INFRARED AND OPTICAL OBSERVATIONS OF

CATACLYSMIC VARIABLES

A Thesis Submitted for the Degree of

Doctor of Philosophy

by

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ABSTRACT

This thesis presents infrared and optical photometry of the binary light curves of several cataclysmic variables. The results are discussed in terms of the accepted model of cataclysmic variables, comprising a Roche lobe filling late type secondary and a white dwarf primary. The secondary star loses matter from the inner Lagrangian point and this matter forms an accretion disc around the white dwarf.

Our observations have shown that sometimes the late type secondary dominates the infrared luminosity of the binary. With further accurate observations over many cycles such systems will provide an excellent opportunity for the analysis of ellipsoidal variations in late type stars.

In other systems the accretion disc spectrum, which current theories predict should vary as $v^3$, dominates the luminosity of the system from the ultraviolet right through to the near infrared. Then our observations, combined with ultraviolet and further optical measurements, allow us to discover the size and outer rim temperature of the accretion disc.

Alternatively a combination of the disc spectrum, dominating at short wavelengths and the spectrum of the late type secondary, becoming bright at long wavelengths is observed. Observations of the light curves, simultaneously at infrared and optical wavelengths, then enable us to show that the results can be modelled in terms of an accretion disc of standard brightness distribution being eclipsed by a late type secondary. This provides support for current disc theories.

Finally our observations out to 3.6 $\mu$m combined with 2 - 2.5 $\mu$m spectrophotometry of one system have shown clearly the presence of a dust cloud around the binary and allowed us to find the temperature of this dust. Similar observations of other systems will be of interest.
ACKNOWLEDGEMENTS

I would like to take this opportunity to thank the many people who have assisted me during my research work at Leicester. Firstly my supervisor Dr. R.F. Jameson for his help, encouragement and guidance, and Dr. A.R. King and Dr. J. Frank for invaluable discussions. Secondly, Dr. J. Abolins, Dr. D.J. Adams, Dr. D. Axon, Dr. J. Bailey, Dr. B. Giles, Dr. J. Hough and P. Lawson for assistance in making the observations. Finally I wish to thank Mrs. N. Corby for her splendid typing of the manuscript and my father for drawing many of the diagrams in this thesis.
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CHAPTER ONE

INTRODUCTION

Cataclysmic variables are close binary systems with orbital periods of a few hours. One component is a white dwarf surrounded by a gaseous disc rotating in the orbital plane of the binary. The other component, most likely a main sequence dwarf, overflows its Roche lobe. Matter flows from the inner Lagrangian point of this secondary component towards the disc, producing the so called 'hot spot' upon collision. Eventually matter from the disc accretes onto the white dwarf component. Occasionally the hot component of the system i.e. the white dwarf and/or the inner regions of the disc, brightens producing the 'outburst' of the system. The magnitude and frequency of such outbursts determines the classification of each system into the subgroups, nova, recurrent nova, dwarf nova or nova-like variable.

Cataclysmic variables have been observed visually, and both photometrically and spectroscopically at optical wavelengths for many years. Visual observations, mainly by large numbers of amateur astronomers, have documented the 'outburst' light curves of the brighter systems. Photometric observations have concentrated on studying the light curves of those systems showing eclipses and looking for changes in their binary periods. More recently interest has centred on searching for periodicities on the time scale of seconds, in the rapid light variations exhibited by all cataclysmic variables.

This thesis presents our work to date on a project to photometer the binary light curves of cataclysmic variables at near infrared wavelengths, J(1.2 μm) and K(2.2 μm). The study of the infrared light
curves of close binary systems has been an interest of the Leicester infrared group for several years. The inspiration for this particular project came from observations by the group of AM Herculis in July 1977. By chance an observing trip to the Infrared Flux Collector on Tenerife coincided with a flare in the 'hard' X-ray emission from AM Herculis. Interest in this object was aroused and the binary light curve was measured at both 1.2 μm (J) and 2.2 μm (K). The results, Jameson et al. (1978), were exciting, and sparked off interest in the possible results of a study of other cataclysmic variables, at infrared wavelengths.

Research into the previous work done on cataclysmic variables showed that the vast majority of the observations had been at optical wavelengths. It soon became clear that the infrared offered potential for a new insight into these systems and also that virtually no results of infrared measurements had been published. The only infrared observations prior to this study were an independent set of light curves of AM Herculis (Neugebauer et al., 1978) and infrared colours of a number of cataclysmic variables observed by Szkody (1976, 1977).

At optical wavelengths the light curves of cataclysmic variables are dominated by radiation from the bright spot and the central (hot) regions of the disc. Spectroscopically these systems show a continuous spectrum with emission lines (Balmer lines, He I, He II and Ca II) from the disc superimposed. The spectrum of the secondary star is only seen in systems with periods greater than six hours.

At infrared wavelengths we would expect the bright spot and central regions of the disc to be faint. Instead radiation from the secondary, the outer regions of the disc and any material ejected from the binary system should dominate, for the following reasons. In the majority of cataclysmic variables the secondary star is thought to be a
late (K or M) type dwarf. Thus it should be relatively bright, compared to its optical luminosity, at infrared wavelengths. Current disc models (see Chapter 2) predict a temperature gradient across the disc declining, as $T \propto \sqrt{\frac{1}{r}}$, from the central region around the white dwarf outwards. Thus if the discs are large, i.e. of the order of the size of the primary's Roche lobe, the outer regions of the disc should emit much of their black body radiation in the near infrared. Lastly any gas ejected from the binary system will be ionized by the UV radiation from the system and therefore be visible at infrared wavelengths by virtue of its free free radiation. Any dust in this circumstellar shell will emit thermal infrared radiation.

At the beginning we had no idea what the relative contribution of each of these components would be to the infrared luminosity of the system. Obviously one would expect the importance of each component to vary from one system to another just as at optical wavelengths. By combining our results with published optical observations we hoped to derive more detailed models of the systems we studied. In particular it was anticipated that our observations would allow us to estimate the temperature of the outer disc region and thus the size of the disc for some systems, or alternatively the spectral type of the secondary for others.

Cataclysmic variables divide into five subgroups:- novae, recurrent novae, dwarf novae, nova-like variables and the AM Herculis types or polars. It was decided not to confine our observations to any particular subgroup for two reasons. Firstly, all initial observations were to be made with the 60 inch Infrared Flux Collector at the Cabezon Observatory, Tenerife (IRFC). With this size telescope, only a small number of the cataclysmic variables, visible from this site, are sufficiently bright that the study of their binary light curves in the
Infrared is feasible. We did not therefore wish to restrict our choice further by the selection of a single subgroup. Secondly, when a number of systems from a range of subgroups had been observed a comparison of the results on the various systems might shed some light into the causes of the different outburst characteristics. More recently, since it has been clear our results are of interest, observations have also been made using the larger Anglo Australian Telescope (AAT) and the new United Kingdom Infrared Telescope (UKIRT). This is allowing us to extend our studies to a greater number of systems.

Observations

At the start of this programme it was intended that we should only measure the infrared light curves of cataclysmic variables and that these observations should be compared with published optical data. As a result the first binary light curves obtained were solely in the infrared. The system was followed for one complete period at one wavelength and subsequently for another period at a second wavelength. However it soon became apparent that there existed problems in comparing this data with the optical curves. One feature of cataclysmic variables is that even at quiescence they change in brightness from night to night, and although the light curves retain the same basic features they vary considerably in detail from one cycle to the next. These effects are more marked in some systems than others but generally make accurate correlations between results obtained at different times impossible, particularly when considering the colours of the system. The optical data also had a much higher time resolution, of the order of 1 to 5 seconds, rather than the ~35 second resolution of the infrared curves. Since cataclysmic variables show variability on a time scale of seconds and major features on a time scale of a few
minutes the differences in the time resolution also affected the comparisons.

In the light of this experience the Leicester infrared photometer was modified to incorporate an optical channel. The revised version of the photometer is described in Chapter 3. With the new system simultaneous measurements can be made at one infrared and one optical wavelength. We are now, therefore, able to observe simultaneous optical and infrared light curves with the same time resolution in both channels. This allows direct comparisons to be made and so all variations in the shape of the light curves with wavelength and changes in the colours of the systems over the binary cycle can be studied. A similar photometer is now available at UKIRT.

The results from this programme will be described in detail in the subsequent chapters of this thesis. However in addition to this project several sidelines which have been studied have proved interesting and these will be briefly described in the rest of this chapter.

UV Observations of AE Aquarius

Observing time with the International Ultraviolet Explorer (IUE) produced several ultraviolet spectra of AE Aquarii. AE Aquarii is probably best described as a very unusual dwarf nova. A typical dwarf nova shows simple outbursts of ~ 4 magnitudes every 30-300 days. AE Aquarii produces erratic outbursts of about 0.3 magnitude which follow one another on a time scale of minutes or hours producing a chaotic light curve. Occasionally the flares can be as great as 2 magnitudes (Zinner, 1938). The spectroscopic period of AE Aquarii is 9 hrs 53 mins but no photometric variations have been found to repeat with this period. The optical spectrum shows the absorption lines of a dwarf K2 star (Warner, 1976) together with the emission lines of the hydrogen Balmer
series and the H and K lines of ionised calcium.

AE Aquarii was chosen for observation with IUE because it shows rapid variations and thus would certainly vary optically over the IUE shift of 8 hours. This would allow us to attempt to correlate optical brightness variations with any changes observed in the UV spectrum. The UV spectra of AE Aquarii obtained, show strong emission lines (Lyα, He II and variously collisionally excited alkali-like resonance transitions) on a relatively weak continuum. In fact the UV continuum is not weak for a dwarf nova (it is of the same order as that observed for EX Hydræ by Bath et al., 1980) but the emission lines are unusually strong. Analysis of these spectra has produced a model in which the lines originate from two distinct regions. Lines of lower ionization states (Mg II, Ca II and some Lyα) arise from collisional-radiative processes in optically thin regions of the accretion disc. At least half the observed Lyα and all the lines from higher ionization states (He II, NV, CIV and SiIV) are produced in a 'chromospheric' region photoionized by radiation from the hot central parts of the accretion disc. Correlations between the strength of the lines and the optical brightness were found. Details of this work have been published - Jameson et al. (1980) and a copy of this is included in Appendix 1.

IUE has now been used by various observers to study a number of other dwarf novae both at quiescence and outburst. Among the early results were those of Heap et al. (1978) on SS Cyg. Drs. Bath, Pringle and Whelan have begun a survey of dwarf novae with IUE.

**Binaries of opportunity**

Binaries of opportunity are any exciting binaries that draw our attention just before or during a previously planned observing trip and are visible from that observatory. AM Herculis was a binary of
opportunity at the time of its observation.

V861 Scorpii was the first of these objects I observed. At the end of June 1978 an IAU Circular (Polidan et al., 1978) appeared identifying a variable X-ray source (OAO 1653-40) with V861 Scorpii a 7.848 day binary. The primary star in V861 Scorpii was known to be a BOI star and radial velocity curves suggested that the unidentified secondary had a mass in the range 5-12 M\(_{\odot}\). With the discovery of X-rays speculation arose that this secondary was a black hole and great interest was aroused in this star. From Tenerife we measured light curves at 1.2 \(\mu\)m (J) and 2.2 \(\mu\)m (K). These showed the secondary was non stellar, possibly indeed a black hole but it was not possible to be more specific. These results are published (Jameson et al., 1979) and a copy is included in Appendix 1. Subsequently it has been proved that the identification of OAO 1653-40 with V861 Scorpii was in error as was the matching 7.848 day period found in the X-rays. Whether V861 Scorpii is an X-ray source or not is still a matter for debate but interest in the system has died.

The second of these binaries of opportunity was SS433. SS433 is an object of great interest because of the presence of enormously Doppler-shifted emission lines swinging back and forth across its spectrum (Margon et al., 1979a; Leibert et al., 1979; Margon et al., 1979b). Suggested models for SS433 include those of Fabian and Rees (1979) and Abell and Margon (1979) and comprehensive reviews of the spectroscopic data have been given by Murdin et al. (1980) and Margon et al. (1979c). We observed SS433 at infrared and optical wavelengths over the course of a year and have supplemented this data with the published results of Impey (1979) and Wynn-Williams and Becklin (1979). The most striking feature of these observations is the near constancy of the infrared colours while the sources flux varies over a range
The data was folded at trial periods in the range 0.1-50 days using the technique of Bopp et al. (1970). No evidence for the 13.1 day period first reported in radial velocity measurements by Crampton et al. (1980) was found, but an 11.8 day period was present in the infrared curves. The light curves show one broad minimum and one narrow minimum per orbital cycle. A paper reporting our results (Giles et al., 1980) has been accepted by Nature and is included in Appendix 1. SS433 is obviously an object where further detailed photometric studies should be made. Certainly it is important that the existence of the 11.8 day period should be confirmed, which would best be achieved by 3-4 weeks of complete coverage rather than by folding irregularly spaced short data sets. The limited optical data we obtained shows no periodicity.
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CHAPTER TWO

CATACLYSMIC VARIABLES -

A REVIEW

Over the last twenty years there have been numerous reviews detailing our knowledge on cataclysmic variables. Payne-Gaposchkin (1957) and McLaughlin (1960) have given compendiums of the properties of cataclysmic variables during outburst. Joy (1960) and Greenstein (1960) have discussed their spectra at minimum light whilst Kraft (1963, 1966) considered the binary nature of cataclysmic variables. Smak (1969, 1971a) and Faulkner (1974) reviewed the theoretical aspects of the subject while in contrast Mumford (1967) concentrated on the observational results. More recently, there have been two extensive reviews (Warner, 1976; Robinson, 1976a) concerned with collecting together and interpreting the observational data and Payne-Gaposchkin (1977) has compiled an extensive list of cataclysmic variables and their properties. Results prior to 1976 have thus been discussed in great detail and it is intended that this be a general review, concentrating in particular on topics where considerable advances have been made since then.

History

There are three eras in the study of cataclysmic variables. The first period which began about 100 years ago consisted of intensive studies of novae and dwarf novae at their outbursts and led to fairly detailed spectroscopic and photometric descriptions of these phenomena. Observations at quiescence were hampered by the faintness of all these objects at minimum and it was only about 40 years ago that two pioneering
spectroscopic surveys - Humason (1938) of novae and Elvey and Babcock (1943) of dwarf novae, began to unravel their true nature.

The second era opened in the mid 1950's and was the impetus for the detailed studies of cataclysmic variables that have continued ever since. The trigger was the discovery by Walker (1954) that the old nova DQ Herculis was an eclipsing binary with the astonishingly short period of $4^h 49^m$ and the discovery by Joy (1954) that the dwarf nova AE Aquarii was a spectroscopic binary with a period of $16^h 49^m$. (Recent observations have shown the period of AE Aquarii is in fact $9^h 53^m$.) The first binary models of UX Ursae Majoris (Walker and Herbig, 1954) and AE Aquarii (Crawford and Kraft, 1956) together with a prophetic hypothesis by Struve (1955) that all cataclysmic variables were binaries followed quickly and so the present era was born.

**Classification**

The hot, very short period eruptive binaries generally grouped together under the title 'cataclysmic variables' are normally divided into four subgroups: novae, recurrent novae, dwarf novae and nova-like variables. This classification is based entirely on the amplitude and frequency of their eruptions, the characteristics of which are summarised in Table 2.1. The dwarf novae are split into three further groups: U Geminorum stars, Z Camelopardalis stars and SU Ursae Majoris stars, also based on variations in their outburst behaviour.

Novae are only seen to outburst once. Typical outburst amplitudes are 9 to 14 or more magnitudes and eruptions last from 50-5000 days (Bath, 1978). Recurrent novae show smaller outbursts of typically 7 to 9 magnitudes which repeat on average every 30 years.

All dwarf novae show outbursts of 2-6 magnitudes repeating every 10-300 days. While not strictly periodic, the dwarf novae outbursts are
<table>
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<th>Amplitude (mag)</th>
<th>Energy (ergs)</th>
<th>Recurrence Time</th>
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<tr>
<td>Novae</td>
<td>9 - 14</td>
<td>$10^{44} - 10^{45}$ or more</td>
<td>Only one eruption</td>
</tr>
<tr>
<td>Recurrent Novae</td>
<td>7 - 9</td>
<td>$10^{43} - 10^{44}$</td>
<td>10 - 100 years</td>
</tr>
<tr>
<td>Dwarf Novae</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(a) U Gem</td>
<td>2 - 6</td>
<td>$10^{38} - 10^{39}$</td>
<td>15 - 500 days</td>
</tr>
<tr>
<td>(b) Z Cam</td>
<td>2 - 5</td>
<td>$10^{38} - 10^{39}$</td>
<td>10 - 50 days</td>
</tr>
<tr>
<td>(c) SU UMa</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>normal outburst</td>
<td>&gt; 3</td>
<td>$10^{38} - 10^{39}$</td>
<td>10 - 240 days</td>
</tr>
<tr>
<td>supermaxima</td>
<td>~ 0.5 &gt; normal outburst</td>
<td>$10^{38} - 10^{39}$</td>
<td>130 - 400 days</td>
</tr>
<tr>
<td>Nova like</td>
<td>-</td>
<td>-</td>
<td>No eruptions</td>
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quasi periodic, in the sense that mean periods derived from intervals sufficient to contain at least 50 outbursts remain sensibly constant (Warner, 1975). U Gem stars simply show these outbursts and no additional characteristics. As well as outbursts, the light cycles of Z Cam stars are interrupted by standstills lasting from several days to several years, during which intervals the star remains at a brightness intermediate between maximum and minimum light (Bath, 1978).

In the past dwarf novae have often only been divided into these two groups. Only recently have the characteristics which separate the SU UMa stars from U Gem stars been recognised. The SU UMa variables show two types of outbursts, the more frequent short eruptions, which are not outstanding compared with the outbursts of other dwarf novae and the long lasting quasi periodic supermaxima which show periodic superhumps. The superhump period is always a few percent different from the orbital period. These properties will be discussed in more detail later.

The nova-like variables do not undergo outbursts but show irregular light variations of small amplitude. Spectroscopically and photometrically they are similar to the other groups.

Recently a fifth class of cataclysmic variable has been discovered. These are the polars or AM Her type variables. There are four members of this group: AM Her, VV Pup, AN UMa and 2A0311-227. VV Pup and AN UMa were previously classified as nova-like variables and all except VV Pup are X-ray sources. Instead of undergoing outbursts polars stay alternately at high and low states differing by 2-3 magnitudes and the transition from one state to another is gradual rather than abrupt. The system remains in each state for around 100 to 1000 or more days. Polars are also distinguishable from other cataclysmic variables in that they exhibit wavelength and phase dependent circular and linear polarization (Krzeminski, 1977). Tapia et al. (1980) searched for
polarization from over fifty other cataclysmic variables but failed to
detect any. A review of the properties of polars has been given by
Kruszewski (1978).

A list of all cataclysmic variables with known binary periods is
shown in Table 2.2. All cataclysmic variables that have been studied
have proved to be binary systems. Several facts arise from this list.
There is a strong preference for short and ultrashort periods. There
is a strong deficiency of periods between 2 hrs and 3 hrs. Only one
star YZ Cnc falls in this 'zone of avoidance'. T Cr B is the only system
listed with a long period but there are undoubtedly some selection
effects applying at this end of the list due to the difficulty of
detecting small radial velocity changes in faint stars (Warner, 1976).

The various groups:- novae, dwarf novae and nova-like variables
are well spread down the table to the period gap at three hours. This
suggests that the nature of the outbursts is independent of the binary
period and indicates that we must look elsewhere than masses or
separation of the components for an explanation of the different out-
burst timescales. It also suggests that it may be possible to find a
unified model for all cataclysmic variables (Robinson, 1976a).

A survey of the distribution of the various types of dwarf novae
shows interesting implications. The Z Cam stars show a tendency to
group at the long period end of the table although they are intermingled
with U Gem stars. The sample is too small to draw any conclusions. A
potentially more interesting fact is that all dwarf novae with periods
two hours and less, except EX Hya and WZ Sge, belong to the SU UMa
subgroup (Vogt, 1986). Also all SU UMa stars with known orbital periods
belong to the group of ultrashort period binaries ($P < 2$ hours). If we
consider the fourteen cataclysmic variables with $2 \text{ hours} > P > 1$ hour
we find eight SU UMa stars, three polars and one system HT Cas which
### Table 2.2

**Cataclysmic Variables with known Orbital Periods**

<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Period</th>
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<tr>
<td>T Cr B</td>
<td>RN</td>
<td>227.6</td>
<td></td>
</tr>
<tr>
<td>GK Per</td>
<td>N</td>
<td>16h 28m</td>
<td></td>
</tr>
<tr>
<td>BV Cen</td>
<td>DN</td>
<td>14 38</td>
<td>U Gem</td>
</tr>
<tr>
<td>V Sge</td>
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**References**

- Warner (1976)
- Vogt (1980)
- Whyte and Eggleton (1980)
- Warner (1979)
has yet to be classified. The two remaining variables have usually been classed as U Gem stars but are quite atypical dwarf novae.

WZ Sge is characterised by extremely rare and intense eruptions (amplitude $\sim 8$ m) and for a long time was considered a recurrent nova but the spectral appearance during outburst (Crampton et al., 1979) resembles a dwarf nova and there is no evidence for mass loss during outburst. A total of three eruptions of WZ Sge have been observed. Both time intervals between consecutive outbursts (32.5 yr) coincide within 0.5% which could indicate a semi-periodicity of the outbursts, as for the supermaxima of SU UMa stars. During the December 1978 outburst superhumps were detected, whose period exceeds the orbital period by 1% (Bohusz and Vdalski, 1979 and references therein). The similarity to the SU UMa type of dwarf nova is remarkable and many authors (e.g. Patterson, 1979a; Warner, 1979; Vogt, 1980) now classify WZ Sge tentatively as a member of this subgroup.

The other ultrashort period dwarf nova in question is EX Hya. This unique variable shows a coherent oscillation with a 67 minute period, and a long life time (Vogt et al., 1980) in addition to its 98 minute orbital period. This will be discussed further in Chapter 4. The outbursts of EX Hya are rare and of low amplitude ($\sim 2$ mag) and the behaviour of the 67 minute cycle during outburst is still unknown. If the 67 minute oscillation were identified with superhumps, we may conclude that EX Hya is stuck in a permanent supermaximum which would also explain the small amplitude and short duration of its outbursts, i.e. we would be seeing short eruptions on the background of a permanent supermaximum (Vogt, 1980). If this interpretation is correct, and therefore we extend the SU UMa subgroup to stars with long and very long cycles, then all ultrashort period dwarf novae are SU UMa stars. Since there are no SU UMa stars with periods greater than three hours, a study
of SU UMa systems may give insight into the riddle:— Why do cataclysmic binaries have a discontinuity in their period distribution?

Any correlations between orbital period and outburst properties are important in finding a solution to this question. Three facts emerge from Table 2.2 (Warner, 1979).

1) All novae and nova-like variables have periods > 3 hours (excluding the strange 18 minute binary AM CVn).

2) Among the dwarf novae those with P > 3 hours are all U Gem or Z Cam stars whereas those with P < 2 hours are all SU UMa stars.

3) The polars are the only group that bridge the gap.

The SU UMa phenomenon is obviously relevant to any discussion of this question, though how this behaviour is related to the ultrashort binary period is not evident. It should be noted that the SU UMa supermaxima are in addition to normal dwarf nova behaviour (Warner, 1975).

The latter is not affected by differences in binary period. Whatever the cause of the gap and the SU UMa type behaviour it remains as yet an intriguing mystery.

Recurrence Rate

Searching for a way to predict and thus observe the outbursts of dwarf novae many people have looked for a relationship between cycle length and amplitude that would apply to all systems.

Considering both dwarf novae and recurrent novae, Parenago and Kukarkin (1934) showed that there was a linear correlation between the logarithm of the mean period and the amplitude of the outburst. They obtained the relationship

\[ A = 0.63 + 1.667 \log P \]

where A and P are the mean amplitude (in magnitudes) and the mean period respectively (Glasby, 1970). This relationship was derived from the
observations of only six dwarf novae and two recurrent novae. Since then a revised equation has been derived based on further observations.

\[ A = 2.28 + 1.85 \log P \]  
(Glasby, 1970)

The fact that a common cycle-amplitude relationship was found, was taken as proof that although the scale of the outburst in dwarf novae and the more spectacular recurrent novae are different, the underlying mechanisms were the same. Kopylov (1957) however obtained two independent relations for dwarf novae and recurrent novae which were totally different.

At present there is considerable doubt whether a uniform cycle-amplitude relation exists for dwarf novae or recurrent novae singly, yet alone a common relation for both classes. Payne-Gapashkin (1977) has demonstrated that it does not. The problem with any such relations is that the paucity of observations make it easy to fit any linear relation reasonably well. What is more probable is that such cycle-amplitude relations exist for individual systems.

Steiner (1978) has derived a relation between the eruption amplitude and the interval between the present and next eruption for three recurrent novae. He finds

\[ m = a + b \log t(i, i+1) \]

Here the constants \( a \) and \( b \) change from one star to the next. A similar relation has been found to hold over 240 cycles of the dwarf nova SS Cyg (Glasby, 1970).

Recently Bath and Shaviv (1978) have suggested that all novae are recurrent. They conclude that there are two classes of novae:- those possessing a main sequence companion to the white dwarf and having a recurrence period of \( \sim 10^5 \) years (classical novae), and those possessing red giant companions with a recurrence period \( \sim 30 \) years (recurrent novae). The large difference between the two cases implies
that novae, though all recurrent, probably do not form a continuous sequence but divide into two classes. It is suggested that the difference in recurrence period between the two classes is produced by the differing binary mass transfer rates in the quiescent state, this being higher in the systems with a shorter recurrence period. Warner (1976) cites evidence for giant secondaries in recurrent novae. If this is the case it lends support to the idea expressed earlier that WZ Sge is a dwarf nova, rather than a recurrent nova as was previously believed. No system with a period as short as 82 minutes could conceivably contain a giant secondary!

**Basic Model**

The basic model for cataclysmic variables was first proposed by Crawford and Kraft (1956). The most important feature of this model was the idea that the disc of material around the primary was more likely to have been generated by mass transfer from the secondary than from matter ejected from the primary itself. The most likely cause of this mass loss was that the secondary was a 'contact' component (Kopal, 1955) i.e. it filled its Roche lobe.

This model could not completely explain the observed light curves. To account for a photometric hump seen in their light curves of UX UMa, Walker and Herbig (1954) introduced a bright region into the system situated near the primary. In his model of U Gem, Krzeminski (1965) placed this 'hot spot' on the following hemisphere of the primary. Objections to this model led Warner and Nather (1971) and Smak (1971b), to independently propose a more complete and physically reasonable model, which has become the standard model for cataclysmic variables. Fig. 2.1 shows a schematic view of this model.

In this model the primary component is a white dwarf. The
Fig. 2.1 Schematic diagram of a typical cataclysmic binary. The diagram shows the case where the white dwarf is the more massive of the two stars (so its Roche lobe is the larger). The opposite case also occurs.
secondary, a late type dwarf in most systems, overflows its Roche lobe so matter flows from the Inner Lagrangian point towards the primary star. This stream of material carries a large amount of angular momentum and forms a gaseous disc around the primary which rotates in the orbital plane of the binary. This disc is a major source of optical continuum radiation. The density of the matter in the disc is sufficiently high for a collision to take place between the stream coming from the secondary and the outer part of the disc. As a result a bright spot is formed in the outer disc region and this bright spot is the second important contributor to the optical continuum radiation (Robinson, 1976a). The kinetic energy of impact of the stream maintains the brightness of the spot and variations in the rate of mass transfer cause the brightness of the spot to vary on timescales from years to seconds (the flickering activity observed in the light curves is attributed to inhomogeneities in this gas stream (Warner, 1976)). Eventually matter from the disc accretes onto the white dwarf component. Occasionally the hot component of the system i.e. the white dwarf and/or the inner parts of the disc brightens by one of two orders of magnitude producing the outburst of the system.

The model for polars differs slightly. In these systems the white dwarf is thought to be degenerate with a magnetic field \( B > 10^8 \) gauss. The magnetic field effectively channels the accretion flow onto its magnetic poles and accretional X-ray emission is produced. Cyclotron radiation is likely to be the dominant source of the optical and infrared light. More recently ideas have been expressed that the white dwarf in some dwarf novae is also magnetised, although with a smaller field. Patterson (1979b) explains coherent oscillations observed in the light curves AE Aquarii as arising from the rotation of an accreting magnetized white dwarf, with a surface field of \( 10^6 - 10^7 \).
If this model is correct it might also be applied to the other cataclysmic variables which show coherent oscillations. This will be discussed in more detail later.

Warner (1976) has derived three relations for this basic model. These are a mass-period relation for the secondary, a radius-period relation for the secondary and a period-luminosity relation for the secondary. These equations are derived by the following reasoning.

Kepler's third law gives the relationship between the separation of two bodies in orbit around their common centre of mass and the period of that orbit.

\[ 4\pi^2 a^3 = G(M_1 + M_2)P^2 \]  

where \(a\) is the separation between centres of the stars, 
\(P\) is the orbital period, 
\(M_1\) and \(M_2\) are the masses of the primary and secondary stars respectively.

In the basic model for cataclysmic variables the secondary fills its Roche lobe. The size of this Roche lobe can be represented by a radius \(R^2\), which is the radius of a spherical star having the same volume as the Roche lobe. This radius has been tabulated by Kopal (1959) as a function of the mass ratio. Paczynski (1971) shows that it can be represented to within 2% of its value by the following formulae

\[ \frac{R_2}{a} = 0.38 + 0.20 \log q \quad \text{for } 0.3 < q < 20 \]  

\[ \frac{R_2}{a} = 0.4622 \left( \frac{q}{1+q} \right)^{\frac{1}{3}} \quad \text{for } 0 < q < 0.8 \]

where \(q\) is the mass ratio \(M_2/M_1\).

The majority of cataclysmic variables with known mass ratios lie in the range covered by equation (3).

By combining equations (1) and (3) we can obtain a value for the
density of the secondary.

\[ \rho = \frac{M_2}{4/3 \pi R_2^3} \]  \hspace{1cm} (4)

equation (3) gives

\[ R_2^3 = a^3 (0.4622)^3 \left( \frac{q}{1+q} \right) \]

substituting for \( a^3 \) from equation (1) gives

\[ R_2^3 = (0.4622)^3 \left( \frac{q}{1+q} \right) \frac{G(M_1+M_2)P^2}{4\pi^2} \]

substituting back in equation (4) we have

\[ \rho = \frac{3M_2(1+q)4\pi^2}{4\pi (0.4622)^3 q G(M_1+M_2)P^2} \]

\[ \rho = \frac{3\pi P^{-2}}{(0.4622)^3 G} \]

\[ \rho = 1.4304 \times 10^9 P_{(s)}^{-2} \text{g cm}^{-3} \]  \hspace{1cm} (5)

Grossman et al. (1971) give a density \( \rho = 120 \text{g cm}^{-2} \) for a star with \( M_2 = 0.085 M_\odot \), which is the minimum mass for a hydrogen burning dwarf (Graboske and Grossman, 1971). Equation (5) therefore shows that for \( P > 0.96 \text{ hour} \) the secondary can be a normal main sequence star, but for shorter orbital periods it must be a helium star, a non nuclear burning dwarf or a degenerate star. For secondaries of spectral type later than FO, the secondaries must be evolved in systems with \( P > 10 \text{ hours} \).

Warner (1976) gives a radius–mass relation for the secondary based on stellar models for the lower main sequence calculated by Copeland et al. (1970) and Grossman et al. (1971) together with observed masses and radii.

This is
This expression is reasonably accurate for the mass range $0.2 < \frac{M_2}{M_\odot} \leq 1.5$ and probably acceptable for masses down to $0.085 M_\odot$. Equation (6) gives an expression for $R_2$

$$R_2 = 0.959 \frac{M_2}{M_\odot}$$

substituting this in equation (5)

$$\frac{1.4304 \times 10^9}{P^2} = \frac{3M_2 (M_\odot)^3}{4 \pi (0.959)^3 (M_2)^3 (R_\odot)^3}$$

$$\left( \frac{M_2}{M_\odot} \right)^2 \frac{4 \pi (0.959)^3 R_\odot^3}{3 M_\odot} = \frac{P^2}{1.4304 \times 10^9}$$

giving

$$\frac{M_2}{M_\odot} = 3.342 \times 10^{-5} P(s)$$  \hspace{1cm} (7)

This mass-period relation for the secondary is valid for mass ratios $0 < q < 0.8$. The relation relies on the assumed mass-radius relation for the lower main sequence which in turn depends on stellar models.

Equations (6) and (7) give a period radius relation for the secondary.

$$\frac{R_2}{R_\odot} = 3.205 \times 10^{-5} P(s)$$  \hspace{1cm} (8)

This period-radius relation allows us to obtain a relationship between the orbital period and the luminosity of the secondary for those systems which contain a dwarf secondary ($P \lesssim 10^h$). Equation (8) can be re-written

$$\frac{R_2}{R_\odot} = 0.1154 \frac{P(h)}{10^8}$$

Recent radii determination by Bopp et al. (1974) together with the
absolute magnitude-radius relation given by Allen (1973) give, to a reasonable degree of accuracy, the relation

$$\bar{M}_V = -12.5 \log \frac{R}{R_\odot} + 5.5 \quad 4 < \bar{M}_V < 15$$

which gives an approximate period-luminosity relation for the secondary

$$M_V = -12.5 \log P(h) + 17.5$$

Observations at minimum light

The spectra of cataclysmic variables at minimum light were first observed by Humason (1938) (novae) and Elvey and Babcock (1943) (dwarf novae). Although of low resolution and in spite of the long exposures (2-3 hours) which were needed, these surveys showed the basic properties of the spectra of these systems. In most cases the spectra contained broad bright Balmer lines of hydrogen, weaker He I and He II emission and bright H and K lines of singly ionized calcium superimposed on an apparently continuous background. Later surveys, mostly with the improved resolution of the 200 inch telescope (Kraft, 1958, 1962; Greenstein 1960) confirmed this early work and added more details.

The emission lines were found to be broad in some cases and narrow in others and to be double in a few systems. The $\lambda 4650$, CIII-NIII group of lines was discovered in emission. Broad absorption lines were found in three objects (WZ Sge, DI Lac, UX UMa) while the absorption spectra of G or K stars were found in a number of others.

Warner (1976) has collected together all available descriptions of the spectra of cataclysmic variables and includes an extensive bibliography. The spectrum of the secondary star (broad absorption lines of a late type star) is only visible in systems with orbital periods $> 6$ hours. The emission lines show orbital radial velocity
variations and in some systems are doubled. This indicates that the emission comes from a rapidly rotating region surrounding one of the components of the binary system. Where the absorption spectrum of the secondary is visible its velocity variations are out of phase with those of the emission lines showing that the rotating region (or disc) must surround the primary (white dwarf) component. The splitting of the emission lines into two distinct components indicates that the mass transfer produces a disc rather than an amorphous cloud (Robinson, 1976a).

The first detailed photoelectric studies of cataclysmic variables at minimum light were made by Grant (1955) and Walker (1957). The wide range of possible inclinations of these systems, together with variations in the strength of the contributions of the components, leads to large differences in the appearances of the light curves. There is no true typical light curve for cataclysmic variables. At optical wavelengths the major contributors to the light are the disc and hot spot, the late type secondary only becoming important in systems with long orbital periods. The universal feature of these stars is the rapid light variations superimposed on the orbital variations. The light curves of systems with photometric periods (these periods may result either from eclipses or merely the repeat of some feature such as a hump) divide into two types.

In type I systems the luminosity of the spot is comparable with or brighter than that of the disc. A hump lasting about one half of the period and centred at the phase when the spot is seen face on, is observed. If the orbital inclination is favourable for an eclipse to occur, it will consist primarily of the occultation of the spot by the secondary component, with secondary effects due to the occultation of the disc (Smak 1971a). U Gem is a good example of an eclipsing type I
system whilst VW Hydri is a type I system whose orbital inclination is not high enough for an eclipse to occur. Z Cha is a type I system in which the inclination is high enough for the eclipse of the white dwarf to be seen as well as the eclipse of the bright spot.

In type II systems the luminosity of the spot is low compared with the luminosity of the disc, e.g. UX UMa. The shoulder is therefore less pronounced and the eclipse, if present, is caused primarily by the occultation of the disc (Robinson, 1976a). The occultation of the spot is a secondary effect. Since the flickering present in the light curves of cataclysmic variables originates from the unstable bright spot it is more evident in type I systems than in type II systems and disappears during eclipse in type I systems. Examples of these two types of light curves are shown in Fig. 2.2.

Fundamental properties

Cataclysmic variables are one of the most numerous types of stars in the galaxy (Gorbatsky, 1975). Warner (1974a) estimates that the total space density of cataclysmic variables is \( \sim 1 \times 10^6 \) pc\(^{-3}\) with dwarf novae and ordinary nova contributing roughly equal numbers.

Colours

The two colour diagram for the mean colours at minimum light is shown in Fig. 2.3 (Warner, 1976). The majority of cataclysmic variables fall near the blue end of the black body relationship in the region where quasi-stellar objects are also to be found. These are also redder objects as is to be expected from the appearance of late type absorption spectra, in the spectra in some of these systems. There is some correlation of B-V with orbital period arising from this appearance of the secondary spectrum for periods greater than 6 hours but the
Fig. 2.2 Typical light curves of Cataclysmic Variables
Fig. 2.3 Two-colour diagram for cataclysmic variables. (after Warner 1976)
relationship is very loose.

**Absolute Magnitudes**

Values for the absolute magnitudes of cataclysmic variables derived over the last thirty years vary widely. The generally accepted values are those of Payne-Gaposchkin (1957) for nova, $M_V = +4.0$ for fast novae and $M_V = +4.7$ for slow novae, and $M_V = +7.5$ for dwarf nova derived by Kraft and Luyten (1965). Warner (1976) obtains $M_V = -0.8$ to $0.8$ for recurrent novae which makes them considerably brighter than other cataclysmic variables. He suggests that the explanation for this is that all recurrent novae possess giant secondaries which are responsible for luminosity of these systems at minimum light. This is in agreement with the recent ideas of Bath and Shaviv (1978) described earlier. The only recurrent nova with a known orbital period is T Cr B, with a period of $227^d.6$ and it stands apart from the other cataclysmic variables, all of which have periods of less than one day. If all recurrent novae contain giant secondaries then their expected periods would be of the order of $10^s$ of days (a 1 $M_\odot$ primary with a K5III secondary has a period of 16 days while a 1 $M_\odot$ primary with a K5I secondary has a period of 462 days). In view of the difficulty in detecting small radial velocity changes in faint systems and in observing photometric periods in long period systems, this would explain why the periods of the other recurrent novae remain unknown.

**Luminosities**

There is evidence for a substantial spread in the luminosity of dwarf novae at minimum light, with systems having longer periods being the brightest. Kepler's law states that systems with longer periods will have larger dimensions, sufficient to contain earlier and more
luminous dwarfs than the smaller systems of shorter orbital periods.

Warner's (1976) period luminosity relation for the secondary

$$M_V = -12.5 \log P(h) + 17.5$$

predicts that at $P = 5$ hours $M_V,2 = 8.8$. Hence in dwarf novae which have $M_V = 7.5$, we expect that the secondary spectrum should just be visible in systems with $P \sim 5$ hours and increase in prominence for longer orbital periods. This is observed.

**Masses**

Although all cataclysmic variables are binary stars, direct determinations of their masses are difficult to obtain because of the complexities of these systems. Only one system, EM Cyg, was known to be both an eclipsing binary and a double lined spectroscopic binary until Wade (1977) announced the detection of the secondary in U Gem. A recent report (Annual Report of the Director of the Hale Observatories, 1978-1979) gives a tentative value for the radial velocity semiamplitude $K_2$ in U Gem as, $K_2 = 290 \text{ km s}^{-1}$. This is subject to change when all the data has been analysed. Thus as present EM Cyg remains the only system where the masses can be directly determined from spectroscopic and photometric data although this should shortly be possible for U Gem.

Robinson (1974) has calculated the masses of the components of EM Cyg to be $M_1$ (white dwarf) $= 0.70 \pm 0.18 \, \text{M}_\odot$ and $M_2$ (red star) $= 0.90 \pm 0.17 \, \text{M}_\odot$. Z Cam is also a double lined spectroscopic binary (Kraft et al., 1969) and the presence of a single hump per period but absence of definite eclipses suggest $i \sim 60^\circ \pm 8^\circ$ (Robinson, 1973). A good estimate of the inclination together with the doubled spectral lines allow us to calculate the masses of the components. Values of $M_1 = 1.20 \, \text{M}_\odot$ and $M_2 = 0.85 \, \text{M}_\odot$ have been obtained (Robinson, 1976a). Thus direct measurements of the masses are only available for two cataclysmic
variables. However indirect techniques for calculating the masses have been developed by both Warner (1973, 1976) and Robinson (1973, 1976b) and these can be applied to a number of systems. Robinson's method is less widely applicable than Warner's method but requires fewer assumptions. There is an encouraging consistency in the revised (1976) masses calculated by these two methods (Robinson, 1976a) and between them and the direct determinations but Warner's method has been criticised by Ritter (1976).

Robinson's method can be used for cataclysmic binaries with known periods of less than about 10 hours for which either the mass ratio or the mass function and orbital inclination are known. It makes use of the following relation (Robinson, 1973)

\[ M_2^2 = \left( 0.966 \times 10^{-8} P^2 (1+q')(0.38-0.2 \log q') \right) R^3 \] (9)

where \( P \) is the orbital period in seconds,

\( M_2 \) is the mass of the late type secondary in solar units,

\( q' \) is the mass ratio \( M_1/M_2 \)

\( R \) is a constant taken as 0.93.

Robinson (1973) obtains this equation by using the same ideas as Warner (1976) uses to calculate his mass-period relation. Plavec (1968) and Paczynski (1971) show that the mean radius of the Roche lobe of the secondary star is given by

\[ R_2 = a(0.38 + 0.2 \log M_2/M_1) \] (10)

Kepler's third law gives

\[ 4 \pi^2 a^3 = G(M_1 + M_2)P^2 \]

substituting in equation (10) for \( a \) gives
Stellar model for the lower main sequence gives a mass radius relation of the form

\[ \frac{R}{R_\odot} = \frac{R}{M} \]

Robinson (1976b) uses a value \( R = 0.93 \) which is slightly different to the value used by Warner (1976). Then equation (11) becomes

\[ \frac{R}{R_\odot} = \frac{R}{M} \]

\[ R^3 = \frac{G M_2 (1+q') P^2 (0.38 - 0.2 \log q')}{4 \pi^2} \]

with \( M_2 \) in solar masses

\[ \dot{\omega} = \frac{0.996 \times 10^{-8} (1+q') P^2 (0.38 - 0.2 \log q')}{R^3} \]

This is equation (9) that Robinson uses to calculate his masses.

Paczynski (1971) states that equation (10) and thus this equation is valid for mass ratios \( 0.3 < q < 20 \).

If the system is a double lined spectroscopic binary so that the mass ratio is known equation (9) gives the masses immediately. For single lined spectroscopic binaries where the orbital inclination is known, the mass function

\[ M_2 \sin^3 i = \frac{P K_1^2}{(1 + q)^2} \]

where \( K_1 \) is the observed semi-amplitude of the primaries radial velocity curve; \( i \) is the orbital inclination, is combined with equation (9) to give the masses.
Robinson's method is based on three assumptions. The first is that the radius of the late type star is equal to the mean radius of its Roche lobe. Paczynski (1971) states that equation (10) is correct to within 2%. The second is that the lower main sequence obeys the linear mass-radius relation. A linear relation is a good fit to current models although various authors have obtained a variety of values for \( R \) (see Robinson, 1976b). Robinson (1976b) chose \( R = 0.93 \) as a mean value. The last assumption is that the secondaries in cataclysmic variables obey this mass-radius relation. This is not true of systems with long orbital period but evidence indicates it is valid for periods less than 10 hours (Robinson 1976a).

Warner's method also applies only to cataclysmic variables with lower main sequence secondaries since it also involves the linear mass-radius relation. It makes use of the properties of the gas disc and is based on a relation expected by theory (Kruszewski, 1967; Flannery, 1975; Lubow and Shu, 1975) between \( K_1/V_\text{d} \text{sini} \) (\( K_1 \) being the radial velocity of the primary and \( V_\text{d} \text{sini} \) the projected velocity of the ring around it) and the mass ratio. Warner (1973) uses a simplified particle trajectory argument to show this relation.

He considers the case where a particle after leaving the \( L_1 \) point conserves its angular momentum about the primary and takes up a circular orbit around the primary. Calculations of Warner and Peters (1972) show that although angular momentum is not conserved in the true case the difference is small.

Consider a particle in orbit around the primary of mass \( M_1 \). Centrifugal versus gravitational force gives

\[
V^2(r) = \frac{GM_1}{r}
\]

Conservation of angular momentum about \( M_1 \) gives
\[ V(r) = \frac{2\pi f^2(q)a_1^2}{p} \]

where \( f(q) \) is the distance from the centre of the primary to \( L_1 \) in units of \( a_1 \) and may be found from the tabulation given by Plavec and Kratochvil (1964) and \( a_1 \) is the radius of the primary's orbits about the centre of gravity of the system.

\[ V_{GM} = \frac{2\pi f^2(q)a_1^2v^2}{p} \]

Kepler's third law gives

\[ 4\pi^2a_1^3 = GM_1(1+q)p^2 \]

The separation of the components \( a \) and the radius of the orbit \( a_1 \) are related by

\[ a_1M_1 = a_2M_2 \]

and

\[ a_1 + a_2 = a. \]

\[ a_1 = a \left( \frac{q}{1+q} \right) \]

So substituting

\[ V = \frac{2\pi a_1}{pf^2(q)} \left( (1+q)^2 \right) q^3 \]

The amplitude of the radial velocity curve of the primary \( K_1 \) is

\[ K_1 = \frac{2\pi a_1 \sin i}{p} \]

and the projected radial velocity of the disc deduced from the width of the emission line is \( V_{ds} \). Thus equations (12) and (13) give

\[ \frac{K_1}{V_{ds}} = \frac{q^3 f^2(q)}{(1+q)^2} \]

Showing that \( K_1/V_{ds} \) is simply a function of \( q \). Warner (1973) calibrated
this function using systems which are double lined spectroscopic binaries. Since $K_1 / V_{dsini}$ is measured from the disc spectrum, $q$ can be found for most systems.

Once the mass ratio is known, Warner then uses three basic relations: Kepler's third law, Paczynski's (1971) expressions for the radius of a sphere of the same volume as the Roche lobe of the secondary (equations (2) and (3) of this chapter) and the mass-radius relation for the lower main sequence.

Kepler's third law is

$$4 \pi^2 \frac{a^3}{T^2} = GM_1 M_2 P^2$$

while Paczynski's expressions are of the form

$$\frac{R_2}{a} = f(q)$$

where $f(q)$ is defined by either equation (2) or (3) depending on the mass ratio.

Equation (14) is of the form

$$\left( \frac{R_2}{R_\theta} \right) \frac{R_\theta}{a} = f(q)$$

substituting in Kepler's law gives

$$4 \pi^2 \left( \frac{R_2}{R_\theta} \right)^3 \frac{R_\theta}{f(q)} = GM_2 \frac{M_\theta}{M_\odot} P^2$$

$$\left( \frac{R_2}{R_\theta} \right)^3 \frac{M_\theta}{M_2} = \frac{GM_2}{4 \pi^2 R_\theta^3} \left( \frac{1+q}{q} \right) P^2 f(q)$$

$$\left( \frac{R_2}{R_\theta} \right)^3 \frac{M_\theta}{M_2} = 1.0 \times 10^{-8} P^2 f'(q)$$

The value of $f'(q)$ can be found from equation (2) or (3) and the mass radius relation of the lower main sequence allows one to find $M_2$.

Using this method Warner is able to calculate the masses of the
components in essentially all cataclysmic variables with known orbital periods. A table of his results is given in Warner (1976). The most striking feature is the total independence of the morphology of the eruption on the mass of either star. These results differ from his earlier results (Warner, 1973) due to an improvement in the mass-radius relationship used. The masses are markedly higher than masses obtained for single white dwarfs (Weideman, 1975). Ritter (1976) questions the accuracy of the measurements from which values for $V_{\text{dsini}}$ and hence $q$ are obtained. He states that a wide variety of results for $V_{\text{dsini}}$ for individual systems can be found in the literature and Warner (1973) did not use all the available values. As well as differences in the values obtained for $V_{\text{dsini}}$ by different authors he finds that there are systematic differences in values found by the two alternative methods, i.e. the measurement of the separation of doubled emission lines used in the calibration of the function and the measurement of the half width of a single line. He concludes that Warner's method cannot therefore provide reliable mass ratios. However the consistency between Robinson's and Warner's results suggests otherwise.

Secondary Component

The secondary is a late type star which fills its Roche lobe and so loses matter through the Inner Lagrangian point. The secondary must be a dwarf star in the majority of systems (i.e. $P < 10^6$) otherwise it would exceed the size of the Roche lobe for such a close binary. The shorter the period the smaller and less luminous the secondaries become leading to the period-luminosity relationship (Warner, 1976) for the secondary given above. Since the luminosity of any type of star changes with spectral type (Allen, 1973), there is also a qualitative relationship between the period of the system and the spectral type of
the secondary viz. the shorter the period the later the spectral type of the secondary. Thus whilst the secondaries whose spectra are observed are G or K type the shorter period systems will have M type secondaries. Recently the spectrum of the secondary of U Gem (P = 4.2 hours) has been observed, making it the shortest period system where the spectrum of the secondary has been seen. Its spectral type is M4.5 (Wade, 1979; Stauffer et al., 1979).

Primary Component

The primary component accreting mass is generally accepted to be a white dwarf. This conclusion is not based on its spectrum which is rarely, if ever, seen. Broad shallow hydrogen absorption lines can be seen in the spectra of DI Lac, UX UMa and WZ Sge at all times and in the spectra of many dwarf novae during their eruptions (Elvey and Babcock, 1943). Although these absorption lines have often been interpreted as coming from a white dwarf, the more likely explanation is that of Warner (1974b) and Nather and Robinson (1974a), who suggest that the absorption lines come from the inner regions of the accretion disc and that their width (sometimes exceeding 100 Å) results from pressure broadening and Doppler broadening.

Since we do not see the primary we must look for indirect evidence of its nature. The absolute magnitudes of cataclysmic variables \( M_V = +4 \) for novae and \( M_V = +7.5 \) for dwarf novae) imply that the components must be either lower main sequence or degenerate stars (Warner, 1979). From the orbital periods observed for these systems together with calculated masses for the primary it is found that the primary component must be a compact object (white dwarf or neutron star) and the calculated masses suggest it is more likely to be a white dwarf. All calculated masses lie below the 1.4 \( M_\odot \) theoretical upper limit on
the mass of a white dwarf. The splitting of the disc emission lines indicates Keplerian velocities in agreement with those calculated for orbits around a white dwarf.

Powerful evidence for a white dwarf primary component comes from observations of Z Cha and OY Car. Both these systems, which have ultrashort orbital periods and large inclinations clearly show the presence of a compact object. In both systems, about half the light at minimum comes from an object of dimension $\sim 10^9$ cm. This is the size of a white dwarf. Each also contains a hot spot with dimensions $\sim 10^9$ cm which is seen to be separately eclipsed, (Warner, 1979).

Further evidence for a white dwarf comes from the rapid oscillations seen in cataclysmic variables especially in dwarf novae during outburst. These oscillations have periods ranging from $\sim 9$ to 120 sec. From the dimensional relationship $t \propto (Gp)^{-\frac{1}{2}}$ for gravitationally controlled processes it is found that the mean densities of the objects involved in producing these oscillations lie in the range $2 \times 10^3 - 2 \times 10^5$ g cm$^{-3}$. These values show that cataclysmic variables must contain a degenerate object. It is proposed that the oscillations are due to non radial pulsations in the outer envelope of the white dwarf (Warner and Brickhill, 1978; Papaloizou and Pringle, 1978). However for some systems an alternative explanation that the oscillations represent the rotation period of the primary has been suggested. Whichever model is finally adopted an ordinary dwarf star could not produce oscillations with the observed periods either by rotation or pulsation. This is firm evidence that the primary in cataclysmic variables must be a compact object.
The disc

The disc in cataclysmic variables splits into two regions, the line emitting region at the edge of and above and below the disc and the main body of the disc which emits continuum radiation. The presence of broad absorption lines in the spectra of some cataclysmic variables indicates that the discs are optically thick. In eclipsing systems, the emission lines are usually less affected during eclipse than the continuum indicating that the lines originate in a larger region than the continuum radiation (Williams, 1980). The formation of emission lines in the optically thick disc is usually attributed to the presence of a chromosphere or temperature reversal near the surface (Warner, 1976) producing the line emitting region. Recently Williams (1980) proposed an alternative theory where the emission lines of cataclysmic variables are generally formed as a natural consequence of the fact that the outer parts of the accretion disc are optically thin in the continuum, but thick in the lines.

The emission lines have been used in two alternative methods of calculating the radii of the discs in cataclysmic variables. The first method involves measuring the separation of the peaks in the hydrogen emission lines of those systems which are double lined spectroscopic binaries, while the second uses the full width measurement of these hydrogen emission lines. Flannery (1975) states that only the low density outer regions of the disc produce significant hydrogen line emission and it is the radius of this outer region which is calculated from the hydrogen line peaks. Measurement of the full width of the emission lines gives a smaller radius corresponding to the radius outside which the bulk of the line emission is produced (Robinson, 1976a).

Measurement of the full width of the hydrogen emission lines has been used by Warner (1973) and Piotrowski (1975) to estimate disc radii.
This method has the advantage that it allows disc radii to be calculated for nearly all cataclysmic variables. The radii calculated by this method are only lower limits and must be viewed with caution since the widths of the emission lines are poorly defined. The results show that $r_d/a$ ($r_d$ is the disc radius, $a$ is the separation of the components) is a function of the mass ratio $q$ and values of $0.1a < 0.3a$ are obtained for the radii. The calculated radii and their dependence on $q$ are in good agreement with values obtained by the theoretical models of Flannery (1975) and Lubow and Shu (1975). Such model discs correspond only to the inner, high density, optically thick disc region.

Measurement of the double peaks of the emission lines produces much larger radii than the values of $0.1a < 0.3a$ obtained by Piotrowski (1975) since the optically thin line emitting region is included. In the case of SS Cyg and Z Cam the discs calculated by this method appear to overflow their Roche lobes. In fact tidal effects are expected to truncate the disc near the primary's Roche lobe (Papaloizou and Pringle, 1977; Paczynski, 1977) but the Keplerian approximation, used for the rotation of the disc in the calculations, will overestimate the radius of any disc that fills or nearly fills its Roche lobe. This method is likely to give disc sizes closer to the true radii but it can only be applied to the few systems which are double lines spectroscopic binaries.

Observations of U Gem and Z Cha, two of the best studied dwarf novae show that the size of the disc varies on a timescale of days. Smak (1971b) showed that although the brightness of U Gem returned to normal about 10 days after an outburst, the bright central region, which expands by some 30% during the initial stage of the outburst, was still contracting some 100 days later when the next outburst began. The effect of an outburst is therefore 'remembered' by the system for at
least 100 days. A similar effect has been seen in Z Cha (Warner, 1974b). From the eclipse profile and its variation between the quiescent and outburst state it was observed that prior to eruption only the white dwarf and inner disc regions radiated strongly in the optical (in addition to the bright spot) but during the eruption the whole disc began to radiate strongly out to a radius of about \(10^{10}\) cm.

**Disc Model**

A standard model for the discs in cataclysmic variables has been developed. Discussions of this model can be found in papers by Lynden-Bell (1969), Shakura and Sunyaev (1973), Lynden-Bell and Pringle (1974) to name but a few.

In cataclysmic variables mass outflow from the secondary through the Lagrangian point forms a stream which is initially in free fall towards the primary. This material is likely to have so much angular momentum that it cannot fall directly onto the primary. Instead it forms a differentially rotating disc, the circular velocity at any point being approximately Keplerian, composed of material which gradually spirals inwards as viscosity transports its angular momentum outwards.

The accepted models for this disc consider a steady state optically thick disc. The advantages of the assumptions of steadiness i.e. accretion rate \(\dot{M}\) = constant and optical thickness are that the predicted spectra and temperatures are independent of any uncertainties in the viscosity. With such a model radiation pressure is also unimportant. Each element of the disc can then be considered to radiate like a black body. These assumptions completely determine the radial temperature dependence of the disc.

A simplified version of this disc model is derived here. The differences between this and the standard model are then discussed.
Consider a ring of disc $\Delta R$ at a radius $R$ from the centre of the disc. The mass of the white dwarf at the centre of the disc is $M_1$, the inner disc radius $R_1$ and the accretion rate $M$. The gain of potential energy of material $M$ falling through distance $\Delta R$ is

$$PE = \frac{MGM_1 \Delta R}{2R^2}$$

The virial theorem states that half of this potential energy will be converted into kinetic energy. The rest is emitted by the disc.

$$\frac{MGM_1 \Delta R}{2R^2} = 2\sigma T^4 \frac{2\pi R \Delta R}{2}$$

The temperature of the disc is therefore

$$T^4 = \frac{MGM_1}{8\pi\sigma R^3}$$

$$T = \left(\frac{MGM_1}{8\pi\sigma}\right)^{\frac{1}{4}} R^{-\frac{3}{4}}$$

The temperature of the disc as a function of radius is

$$T(R) = T^* R^{-\frac{3}{4}}$$

where

$$T^* = \left(\frac{MGM_1}{8\pi\sigma}\right)^{\frac{1}{4}}$$

The emission by ring $\Delta R$ at frequency $\nu$, $dI_{\nu}$ from one side of the disc

$$dI_{\nu} = 2\pi R \Delta R B_{\nu}(T)$$

The total disc emission from one side of the disc at frequency $\nu$, the spectrum of the disc, is the integral of all such elements.

$$I_{\nu} = \int_{R_1}^{R_{out}} 2\pi R B_{\nu}(T) dR$$

$$= \int_{R_1}^{R_{out}} 2\pi R 2\nu^3 \frac{dR}{c^2 (e^{\frac{\nu}{kT}} - 1)}$$

substitute

$$T = T^* R^{-\frac{3}{4}}$$
\[ I_\nu = \frac{4\pi R_\nu^3}{c^2 (e^{\frac{hv}{kT^*R}} - 1)} \]

Substitute
\[ x = \frac{hv}{kT^*R} \quad \text{and} \quad R = \left( \frac{kT^*}{hv} \right)^{4/3}, \]

\[ I_\nu = \frac{16\pi (kT^*)^{8/3}}{3c^2 h^{5/3}} \int_{x_1}^{x_{out}} \frac{x^{5/3}}{(e - 1)} \, dx \quad \text{per steradian} \]

\[ I_\nu = \nu^3 \]

The spectrum of the disc thus varies as \( \nu^3 \). This integral can easily be computed. The form and value of the integral with \( x_1 \) set to zero are shown in Fig. 2.4 and Table 2.3. As long as \( x_{out} \) is large while \( x_1 \) is small the integral is virtually constant and therefore independent of \( \nu \).

The accretion luminosity of such a disc is

\[ L = \frac{M_1 MG}{2R_1} \]

The flux \( dF_\nu \) from one side of the disc from a ring \( AR \) is

\[ dF_\nu = I_\nu d\Omega \]

\[ dF_\nu = 2\pi R \Delta R \cos i \frac{I(R)}{D^2} \]

where \( i \) is the orbital inclination and \( D \) the distance to the system.

The total flux from one side of the disc is therefore

\[ F = \cos i \int_{R_1}^{R_{out}} R(R)2\pi RdR \]

The bolometric luminosity of one side of such a disc is

\[ \frac{1}{2} L_{bol} = \pi \int_{R_1}^{R_{out}} 2\pi R I(R) dR \]

The distance of the system is thus

\[ D = \left( \frac{L_{bol} \cos i}{2\pi F} \right)^{1/2} \]
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This simplified version of the disc differs from the standard disc model in the expression for the temperature as a function of radius

\[
\text{Simplified model} \quad T(R) = \left( \frac{\dot{M} G M R^2}{8 \pi \sigma} \right)^{1/4} \left( \frac{R}{R_1} \right)^{-1/2} \left( 1 - \left( \frac{R_1}{R} \right) \right)^{1/2}
\]

\[
\text{Standard model} \quad T(R) = \left( \frac{3 \dot{M} G M R^2}{8 \pi \sigma} \right)^{1/4} \left( \frac{R}{R_1} \right)^{-1/2} \left( 1 - \left( \frac{R_1}{R} \right) \right)^{1/2}
\]

The factor of \(3^{1/4}\) comes from the consideration of the transport of angular momentum outward due to viscosity. The extra term in the dependence of \(T\) on the radius \(R\) is only important when \(R \approx R_1\) and comes from considering the inner boundary conditions of the disc.

The 'hot spot'

The 'hot spot' is the name given to the shock front formed by the impact of the stream of material from the \(L_1\) point on the gas disc. 'Hot spot' is something of a misnomer since its temperature is certainly lower than that of the central regions of the disc. A more accurate name is bright spot, as Robinson (1976a) uses. Krzeminski's (1965) early model of U Gem placed this bright spot on the primary. The later models of Smak (1971b) and Warner and Nather (1971) moved it to the outer edge of the disc. Present interpretation of observations places the spot slightly inside the outer disc radius.

In systems of high orbital inclination the line emission from the bright spot produces a third peak in the hydrogen line profile. The position of this peak varies with orbital phase, producing an \(S\)-wave emission component that is superimposed on the stationary double peaks from the disc, in trailed spectrograms. In systems with a lower orbital inclination, the spot emission cannot be distinguished as a separate component in the line profiles, but still gives the line a
variable asymmetry. When compared with the emission components originating in the disc, the emission components coming from the spot are usually weaker (e.g. U Gem; Kraft 1962, 1963).

Radial velocity data implies that the radius vector of the spot is slightly smaller than the outermost radius of the disc, i.e. the spot is formed somewhat inside the disc. Presumably the stream from $L_1$ easily penetrates the low density outer regions of the disc. In some systems (Smak, 1971a) the spot components show a much flatter decrement than that of the lines from the disc (e.g. U Gem; WZ Sge). This implies that the radiation comes from a region of higher optical thickness (Gorbatzy, 1965; Kunkel, 1976). Thus a picture arises of the bright spot as an optically thick region slightly inside the edge of the disc. Being optically thick it is a source of continuum radiation. The luminosity is maintained by conversion of kinetic energy in the colliding gas stream. The continuum radiation from the bright spot is seen as the characteristic hump in the light curves of cataclysmic variables such as U Gem. The size of this hump indicates the relative contributions of the disc and the bright spot to the continuum radiation. The hump is only visible for half the orbital period or less, which indicates that absorption by the disc is important.

Observations show that the bright spot is responsible for the flickering seen in the light curves of cataclysmic variables. The amplitude of the flickering is larger in systems such as U Gem and VW Hydri which show large humps, than in systems like UX UMa which has a very small amplitude hump. The amplitude also varies around the orbital cycle. This can be seen clearly in light curves of U Gem. The amplitude of the flickering is largest at the top of the hump and disappears during eclipse (the eclipse is attributed to an eclipse of the bright spot). The persistence of flickering outside the hump shows
that the source of flickering, the hot spot, is not entirely obscured when it is behind the body of the disc. This flickering has been interpreted as arising from inhomogeneities in the gas stream (Warner, 1976).

Mass Transfer and Mass Loss

In the accepted model of cataclysmic variables the secondary star fills its Roche lobe and thus loses matter from the inner Lagrangian point. This matter forms the disc around the white dwarf and is gradually accreted onto it. The mass transfer rate is very important in determining the properties of cataclysmic variables. The luminosity of the disc and bright spot, the mass of the disc and the outburst frequency are all directly related to mass transference.

To date two methods have been used to calculate mass transfer rates. Warner (1976) obtains mass transfer rates by considering the luminosity of the bright spot. He argues that its luminosity derives from the conversion of the kinetic energy of the inter-star stream into heat. By considering that the luminosity of those systems with dominant bright spots is derived from this mechanism, he uses the known average luminosities of novae and dwarf novae to obtain mass transfer rates. The values obtained are $1 \times 10^{18}$ gm s$^{-1}$ for dwarf novae and $1 \times 10^{19}$ gm s$^{-1}$ for novae. In view of the approximate nature of his calculations these mass transfer rates may be considered as rough estimates only.

The second and more widely applied method is to calculate the mass transfer rate from orbital period variations. Since the dominant lines in the spectra of most cataclysmic variables are the broad lines from the outer edges of the disc it is impossible to use spectroscopic observations to search for period changes. Attempts to find variations in orbital periods have therefore concentrated on systems showing eclipse
behaviour. The short periods result in a large number of cycles per year and so, in spite of difficulties in measuring exactly the maximum of the hump or the position of mid eclipse, because of flickering and changes in the shape of the curves from cycle to cycle, period changes \( \frac{dP}{dt} \approx 10^{-11} \) are detectable.

There have been numerous discussions on the period variations in cataclysmic variables (e.g. Pringle, 1975; Smak 1972, 1971a; Mumford, 1967), which express contradictory views as to the nature, size and even to the existence of period changes in a range of systems. There is no doubt however that period variations do exist in some but not all systems. These changes are complicated for most systems, varying in both sign and rate (Smak, 1972). In UX UMa and RW Tri it has been suggested that the period changes are approximately sinusoidal with periods of years (Mandel, 1965; Nather and Robinson, 1974). The periodicity of the variations is believed by many authors but has not been conclusively proved. The suggested period in the case of UX UMa is \( \approx 29 \) years so frequent observations over 60-100 years are needed before doubts can be erased.

In all the better studied systems period variations are alternating in character (Smak, 1972). The observed rates are typically \( \frac{d\ln P}{dt} = \pm 10^{-10} \) to \( \pm 10^{-8} \) d\(^{-1}\). To interpret these period changes purely as a result of mass transfer between components is somewhat naive. There are three important mechanisms which are responsible in varying degrees for the period variations (Smak, 1971a). The first is mass exchange between the components. Changes in the rate of mass transfer would affect the rate of period variations. The second is mass loss from the system and the third is variations in the orbital momentum due to the exchange with the rotational momentum of the stars and disc.

To learn anything about the mass transfer rate we must ignore the
latter two mechanisms and consider that mass exchange between the components is alone responsible for the period variations. In this case we obtain mass transfer rates of $\lesssim 3 \times 10^{-7} \, M_\odot \, y^{-1}$ (Pringle, 1975). We can then calculate the mass of the disc. If the outbursts of dwarf novae are accepted as accretion events, then the decay timescale for the outburst light curves (a few days), corresponds to the viscous timescale in the disc. Thus if matter flows continuously through the disc, the average mass of the disc would be $\sim 10^{-6} \, M_\odot$.

On the other hand, if the transferred matter is accumulated in the disc between outbursts, which occur about every 100 days, then the maximum mass of gas in the disc is $\sim 10^{-7} \, M_\odot$ (Lin and Pringle, 1977).

These mass transfer rates and hence the calculated disc masses are only approximate since, as stated above, other mechanisms are involved in the period changes. Indeed the changes of sign of the period variations can only be accounted for if the third mechanism, the exchange between the rotational momentum of the disc and stars and the orbital momentum is important (Smak, 1971a). That much work is needed before a reliable general method of calculating the mass transfer rate is obtained, is shown by the gulf between the results of the two methods.

Mass loss from classical or recurrent novae at outburst is well established. It is seen as a shell around the nova and is clearly visible in the spectra taken during outburst and sometimes in direct photographs taken after outburst. Spectra of dwarf novae taken during their outburst have failed to show evidence of any outward moving material (e.g. Walker and Chincarini, 1968), and this has been used as evidence for the absence of any outburst related mass ejection. The continued integrity of the circumstellar disc in the dwarf novae during outburst (e.g. Warner, 1974b), as opposed to the probable total destruction of the disc during nova explosions (Sparks and Starrfield,
1973), is evidence that the explosions of dwarf novae are less
ergetic. However Robinson (1973) has found evidence of material
surrounding Z Cam. He suggested that since mass loss is not seen
during outburst it must be a continuous process. However Warner
(1974c) has interpreted the material as arising from mass loss during
outbursts and amounting to $\sim 1.5 \times 10^{18} \text{ g ms}^{-1}$. This amount of mass
loss ($\sim 10^{-9} M_\odot$ per outburst) would not be visible in the spectra
taken during outburst and so reopens the whole question of mass loss
from dwarf novae. Although there is no convincing evidence of any
significant mass outflow from any type of cataclysmic variable outside
outburst (Smak, 1977) it is possible that all novae and dwarf novae
lose material during outburst.

Outburst Light Curves

One of the great unsolved mysteries of cataclysmic variables is
why systems of similar periods show such different outburst behaviours.
The dwarf nova U Gem, nova DQ Her and nova like variable UX UMa all
have binary periods between 4 and 5 hours, yet show very different
outburst characteristics.

Novae are only seen to outburst once. The optical brightness
increases by $> 9$ magnitudes in a few days with a much slower decline.
Fig. 2.5 shows a typical outburst light curve. Spectra taken at outburst
imply that matter is ejected from the system. Spectra taken pre and
post outburst suggest that the disc which is present prior to the
eruption but destroyed during the outburst is re-established within ten
years (Gallagher and Starrfield, 1978). After falling $\sim 3\frac{1}{2}$ magnitudes
from visual maximum, the nova enters the transition region. At this
time many nova show oscillations with amplitudes of up to two magnitudes.
The start of the transition region marks the time when the ejected shell
Fig. 2.5 Schematic light curve of a nova, showing typical stages. The time scale is not uniform throughout; it has been magnified in the early stages. After McLaughlin (1936)
becomes thin, allowing the inner photosphere (formed by continuing mass ejection) to be seen (Warner, 1976). The majority of nova outbursts have only been observed at optical wavelengths. The optical light curves of all novae are similar in shape but vary greatly in their decline rate. For novae in our Galaxy and Andromeda it has been shown that there is a tight statistical correlation between the decline rate and the maximum visual luminosity (Arp, 1956; Rosino, 1964; Pfau, 1976). The dramatic and systematic differences in nova light curves led to the theory that the evolution of optical light is representative of the bolometric luminosity, resulting in the conclusion that fast novae radiate less total energy than slow novae, in spite of higher peak luminosities and ~3 times higher ejection velocities (Payne-Gaposchkin, 1957).

The first UV and IR observations of a nova, FH Ser 1970, revised accepted ideas. The UV data (Gallagher and Code, 1974) showed that the optical decline was almost exactly compensated by a redistribution of flux into the ultraviolet. FH Ser thus maintained a constant luminosity for ~60 days after maximum despite a factor of 10 decline in the visual flux. Almost simultaneously with the end of the UV observations Hyland and Neugebauer (1970) detected thermal infrared emission from FH Ser. Infrared photometry through 110 days after maximum (Geisel et al., 1970), shows that the peak infrared luminosity was at the same plateau level as found earlier from the integrated UV and optical fluxes. The flux levels of the various observations are shown in Fig. 2.6. After day 100 the infrared flux began to decline. It is not known whether this represents a turn off of the nova or a change in the envelope conditions.

As a result of these observations Gallagher and Starrfield (1976) examined the available optical data to determine if a period of constant
Fig 2.6 Smoothed energy budget for FH Ser as a function of time based on ultraviolet and optical data of Gallagher and Code (1974) and the infrared measurements of Geisel et al. (1970). (after Gallagher and Starrfield, 1978)
luminosity is characteristic of all nova. They made a moderately good case for the existence of such a constant luminosity phase in all novae.

Recurrent novae show outbursts of smaller amplitude, 4 to 9 magnitudes as opposed to 8-15 magnitudes for classical novae. The amplitudes appear smaller simply because recurrent novae are brighter at minimum light when their light is dominated by the giant star. The average recurrence period is \( \approx \) 30 years.

Dwarf novae show small eruptions, 2 to 6 magnitudes, repeating on a timescale of 10's of days. The outbursts last 4-8 days and between eruptions their brightness varies continuously by a few tenths of a magnitude. The width and amplitudes of the outbursts of all dwarf novae and the intervals between eruptions vary considerably.

The outburst light curve of the prototype of the U Gem class is shown in Fig. 2.7 (Glasby, 1970). Generally two types of maxima, long and short, are seen, the former being usually the brighter of the two. Statistical studies of SS Cyg (a U Gem type) by Sterne and Campbell (1934) and of U Gem by Greep (1942), show that bright maxima are usually followed by an unusually long interval before the next outburst, and that this outburst is likely to be smaller than usual. This gives the impression that there is a constant source of energy for outbursts, but it is not necessarily all released each time.

In general the light curves of Z Cam stars are like those of the U Gem stars. The amplitudes of their outburst are in the main smaller and their outburst periods are shorter (Glasby, 1970). Occasionally after maximum they do not fade to minimum but remain at an intermediate, almost constant brightness, for a period of a few days to more than a year. After a standstill the system will normally return to minimum although occasionally the star may brighten to outburst. The light curve of the prototype Z Cam is shown in Fig. 2.8. These standstills
Fig. 2.7 Light curve of U Geminorum (Glasby 1970)

Fig. 2.8 Light curve of Z Camelopardalis (Glasby 1970)

Fig. 2.9 Light curve of SU Ursae Majoris (Glasby 1970)
are quite unpredictable, both in their occurrence and their length.

As well as standstills Z Cam variables are also characterised by prolonged periods of completely erratic light variations (Glasby, 1970). This behaviour is obviously important for our theories of dwarf novae outbursts. As yet it is not understood why certain systems undergo standstills while others with similar physical conditions do not (e.g. Z Cam and SS Cyg; Lortet, 1969). Observations indicate that at standstill the system is just halted at a normal stage of decline (Szkody, 1976a).

The prototype of the third group of dwarf novae is SU UMa. Its light curve is shown in Fig. 2.9. At a glance it is very similar to that of U Gem, but detailed studies have recently revealed striking differences. The definition of this group should probably be as follows (Vogt, 1980).

a) Two and only two types of outburst (normal and supermaxima) whose widths as measured midway between maximum and minimum brightness differ by more than a factor 5.

b) Short cycle lengths of normal eruptions compared with those of supermaxima. The cycle for supermaxima is quasi-periodic following a linear ephemeris for 10–20 cycles with a standard deviation of only 5–10% of the corresponding period.

c) Periodic superhumps during supermaxima of typical period 1.5–2 hours and an amplitude of 0.2–0.3 magnitudes (the period decreases during the course of the outburst).

In general supermaxima last 15–20 days. The amplitude of the superhumps is 0.2–0.3 magnitudes in all systems regardless of their orbital inclinations. These superhumps have not been found in any dwarf novae during normal outbursts or even 'long outbursts'. In systems with known orbital periods the superhump period is always a few percent
different from the orbital period (VW Hyi: Haefner et al., 1979; Vogt, 1974; V436 Cen: Vogt, 1980; Vogt, 1979; Z Cha: Vogt, 1980; Bailey, 1979a; WX Hyi: Bailey, 1979b; Marino and Walker, 1978; Schoembs, 1979). The superhump periods are a few percent greater than the orbital periods (e.g. 3% for VW Hydri) except for V436 Cen where it is a few percent less. The supermaxima are also periodic, the periodicity being maintained for 10 to 20 cycles. Each system shows two or three characteristic supermaximum periods (VW Hyi: Bateson, 1977; WX Hyi: Marino and Walker, 1978; SU UMa: Isles, 1975; AY Lyr: Howarth, 1977).

This property of the supermaxima is not mimicked by the long eruptions of other dwarf novae. Vogt (1980) tested the occurrences of the long eruptions of U Gem and SS Cyg for periodicities. The width of these long eruptions only exceeds that of the short ones by a factor of about 2. The third type of outburst seen in SS Cyg, the 'anomalous' outbursts with a slow rise and decline, were not included so that the closest possible analogy to the SU UMa stars was obtained. No periodicity was found.

Patterson (1979a) has shown that there is a linear dependence of the superhump amplitude on the mean light intensity of the star. This strongly suggests that the superhumps arise from the principle light source of the system. Warner's (1974b) observations of Z Cha during supermaximum showed that the luminosity originates from the inner parts of the accretion disc/white dwarf region. If one accepts that supermaxima share a common origin with superhumps, then models of the superhumps are restricted to origins in the white dwarf/inner disc vicinity. This rules out the model of Schoembs (1977), Vogt (1977) and Haefner et al. (1979), who attribute the superhumps to a bright spot on the surface of the red star produced by matter which is ejected from the white dwarf/
inner disc region at the start of the outburst.

The most feasible model for superhumps was suggested by Papaloizou and Pringle (1979). They proposed that the orbits of SU UMa stars are slightly eccentric and that this gives rise to periodic mass transferece with a period slightly longer than the orbital period. This periodicity is only apparent during supermaxima when a prolonged increase in the mass transfer rate occurs. In a recent paper explaining the 67 minute periodicity in EX Hya they show how this model works (Papaloizou and Pringle, 1980). The mass transfer rate varies due to a pulsation in the secondary which is excited by tidal interaction due to a favourable commensurability between orbital and pulsation periods.

The other two groups of cataclysmic variables do not show eruptions. Various theories have been put forward to explain the lack of outbursts from nova-like variables. It has been postulated that they are either old novae whose eruptions went unrecorded in some distant past or alternatively Z Cam stars in greatly extended standstills. The latter is more plausible since their spectra resemble those of dwarf novae at outburst but the question will never be settled until the cause of the eruptions in other systems is found (Burrell and Mould, 1973; Warner and Van Citters, 1974; Nather and Robinson, 1974b; Robinson et al., 1974).

The long term variability of the other non eclipsing group, the polars, is again different. Their brightness shows two states differing by 2 to 3 magnitudes. The transition from one state into another is gradual rather than abrupt.

Observations at Outburst

The spectacular nature of the eruptions of classical and recurrent novae has ensured very complete studies of their spectra during
outburst. Most of these studies relate to the changes in the structure of the ejected shell and will not be discussed here. An excellent recent review of classical novae is that of Gallagher and Starrfield (1978). The outbursts of dwarf novae being less spectacular have attracted less attention but their frequency has allowed observations to be built up over many years. References to the spectra of individual dwarf novae at maximum light can be found in Warner (1976) and Joy (1960).

At or near maximum many dwarf novae show broad H and He absorption variously filled in with emission. Others show only continua or Balmer emission. In some systems the absorption lines are visible only before or after maximum but disappear at maximum. The emission lines seen at maximum are of the same strength and are probably from the same origin as those seen at minimum, namely the outer regions of the disc. This suggests that this outer region is not disrupted during outburst. The broad absorption lines originate from the inner parts of the disc. That they are seen only during outburst in many systems indicates that the inner disc plays an important role in outbursts.

Since dwarf novae outbursts apart from supermaxima are not predictable there are few photometric observations of their eruptions, particularly the rise to maximum light. Most observations of eruptions are visual estimates by amateur astronomers. UBV photometry of maximum light shows a reddening of the colours (e.g. Krzeminski, 1965; Bailey, 1980). In the case of SS Cyg and VW Hyi for which numerous observations are available, Bailey (1980) has shown that the colours become very much redder during the rise to maximum light and gradually return to near their quiescent values during the fall. The rate of change of the colours is much faster on the rise.

Based on the observations of amateur astronomers Bailey (1975)
has found a relationship between the orbital period of dwarf novae and the mean decline timescale (T) of their outbursts. His result is based on observations of eight systems. He defines T (in days) as the time taken for the luminosity to fall by one magnitude from maximum. His data are well fitted by the relation \( T = 9.2P \), where T and P are both in units of days. Bailey suggests that this relation could be used to deduce the orbital periods of further systems but it has far more important implications. If the existence of such a relation is proved by studies of a larger number of systems, it implies that the eruption light curves of dwarf novae are controlled by the binary orbital parameters which would place constraints on outburst models.

Observations have shown that the central regions of the disc are responsible for the increased luminosity during eruptions (e.g. Warner's (1974b) observations of Z Cha). Only relatively small changes occur in the bright spot. Krzeminski (1965) found that, during outbursts of U Gem, the intensity of light contributed by the hump remained constant to within a factor of two. Vogt (1974) found that the hump of VW Hyl during an ordinary outburst behaved in just the same way. Other evidence came from observations of the flickering. Grant (1955) observed that the flickering of SS Cyg remained constant in intensity units during outburst. Later (Robinson 1973a) showed that amplitude of the flickering in Z Cam increased by a factor of two as the star brightened the first 1.5 mag and then decreased until at maximum it was little greater than the value at minimum light. The fact that the bright spot undergoes only small changes during eruptions explains the changes seen in the light curves of eclipsing systems. In most systems such as U Gem the eclipses gradually disappear during outburst. Since they are eclipses of the bright spot whose luminosity hardly alters, while the disc becomes very much brighter, this is explained by the decrease in
the contribution of the bright spot to the total luminosity. Only in systems such as Z Cha, where an eclipse of the white dwarf/central disc region as well as the bright spot occurs, are eclipses seen at maximum light.

**Origin of the Outbursts**

The eruptions of novae involve a far greater energy than those of dwarf novae. This can be seen from Table 2.1. Although it would be pleasing to explain the different outburst by the same mechanism it is generally agreed that this is unlikely.

In novae the outburst observations are dominated by the ejected shell of gas making it difficult to see the underlying binary structure. However it is accepted that the eruptions occur in the white dwarf and there are at present two theories for the source of this vast energy (Gallagher and Starrfield, 1978).

1) Thermonuclear reactions at the bottom of an accreted hydrogen-rich envelope on a white dwarf.

2) Energy produced by an episode of runaway mass accretion onto a white dwarf.

There is at present a doubt as to whether this latter mechanism could produce enough energy on the timescales observed, while the thermonuclear runaway theory has no such problems. At present this is the favoured mechanism for nova outbursts.

In the case of dwarf novae the situation is less clear. It is much easier to produce the lower outburst energies observed. At first the red star was thought to be responsible for the outbursts after Krzeminski (1965) interpreted his observations of U Gem during outburst as indicating a brightening of the secondary. Walker and Chincarini (1968) made radial velocity observations of SS Cyg during outburst and
concluded that the primary was the centre of the eruption. However their radial velocity curve was not unique and so controversy raged. Later observations by Walker and Reagan (1971) of SS Cyg decided this point in favour of the primary and the current model of U Gem, proposed independently by Smak (1971b) and Warner and Nather (1971), permitted the reinterpretation of Krzeminski's observations in terms of a brightening centred on the primary. Current observations, e.g. Warner's (1974b) observations of Z Cha have proved without doubt that the outburst takes place on the white dwarf or in the inner regions of the disc.

There are two basic models for the outbursts. The first is that the eruption occurs in the white dwarf due to a thermonuclear runaway in the hydrogen-rich material accreted onto the white dwarf. This is the same model as that proposed for novae and is favoured by Szkody (1976). However Bath (1976) points out that, with present theories, typical timescales for such events are $10^4 - 10^5$ years. This makes the model untenable for the repeated outbursts of dwarf novae unless the timescales can be reduced.

The second model is that the outburst occurs in the disc as a result of sudden gravitational energy release due to intermittent accretion of material onto the white dwarf from the surrounding disc. The available evidence lends support to this theory (Robinson, 1976a; Bath, 1978). Warner's (1974b) observations of Z Cha are the strongest evidence. Changes in the eclipse profile during outburst indicate that prior to eruption, only the white dwarf and inner disc regions radiate strongly in the optical (together with the bright spot) while during the eruption the whole disc starts radiating as a strong optical source out to about $10^{10}$ cm. This sudden brightening of the disc is exactly the behaviour an accretion powered eruption would produce (Bath, 1978).
Such accretion models predict that the central regions of the disc should become hot enough to radiate a large fraction of the total infall energy in the soft X-ray region. Just how strong a source is produced depends critically on the maximum accretion rate produced. A recent HEAO-A2 'soft' X-ray survey of about 20 dwarf novae during outburst failed to detect X-rays from any systems except SS Cyg and U Gem (Cordova et al., 1980). Accretion models must now show whether the observed energies of outburst can be produced without detectable 'soft' X-ray emission.

If we accept that bursts in the accretion flow through the disc onto the white dwarf are responsible for the outburst we must then explain why this accretion occurs in bursts rather than continuously. Two methods of modulating the accretion flow have been suggested. The first is that the mass transfer from the main sequence secondary occurs periodically (e.g. Papaloizou and Bath, 1975; Bath, 1977). These bursts of mass transfer are caused by instabilities in the red star which Papaloizou and Bath (1975) and Bath (1975) have shown to exist with the required recurrence times. Alternatively Osaki (1974) has proposed that the disc itself (continuously accreting from the red component) undergoes some form of instability which results in the infall of material normally stored in the outer disc regions. The standstills observed in Z Cam stars are interpreted as more or less continuous accretion of matter from the disc. The form of the disc instability has not been discussed.

The accretion model for the outburst is certainly the most viable. Much work is needed however to produce a detailed model which can explain such phenomena as Z Cam standstills and the supermaxima of SU UMa stars as well as ordinary outbursts.
Short Period Oscillations

Rapid coherent oscillations have been observed in the light curves of twenty-two cataclysmic variables. These stars are listed in Table 2.4 together with the periods of their oscillations. The list includes dwarf novae, novae and nova-like variables so the oscillations must be considered as a typical property of cataclysmic variables. The group labelled 'occasional oscillations' show low amplitude, short period oscillations at some times and not others. Most of the occasional vibrators are dwarf novae and show oscillations only during outburst. This has led to speculation that the cause of the oscillations and of the outbursts are related. Such a theory does not explain the oscillations in stars such as UX UMa which never erupts but is an occasional oscillator. Coherent oscillations have never been found in dwarf novae at minimum light, except in the case of WZ Sge, which, as has been explained earlier is a somewhat unusual system. The only explanation that allows us to continue to believe that the outbursts trigger the oscillations is to believe that systems such as UX UMa are stuck at permanent outburst (Warner and van Citters, 1974; Nather and Robinson, 1974b). This does not explain why the oscillations come and go but it should be noted that sometimes during a dwarf nova outburst the oscillations have been seen to disappear (Warner, 1974b).

The coherent oscillations exhibit a number of characteristics (Robinson, 1976a; Nather, 1978).

1. The periods are short. The shortest period is 9.75 sec in SS Cyg (Kiplinger, 1978) and the longest is 121 sec in AM CVn (Warner and Robinson, 1972).

2. The oscillations maintain coherence (stay in phase) for intervals of time that are long compared with the period. This coherence is one of the characteristics which distinguish them from the
Table 2.4
Cataclysmic Variables known to show Coherent Oscillations

Occasional Oscillations

<table>
<thead>
<tr>
<th>Star</th>
<th>Periods(s)</th>
<th>Eruption</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS Cyg</td>
<td>9.75</td>
<td>Yes</td>
</tr>
<tr>
<td>RU Peg</td>
<td>11.6 - 11.8</td>
<td>Yes</td>
</tr>
<tr>
<td>Z Cam</td>
<td>16.0 - 18.8</td>
<td>Yes</td>
</tr>
<tr>
<td>EM Cyg</td>
<td>16.6</td>
<td>Yes</td>
</tr>
<tr>
<td>V436 Cen</td>
<td>19.5 - 20.1</td>
<td>Yes</td>
</tr>
<tr>
<td>CN Ori</td>
<td>24.3 - 25.0</td>
<td>Yes</td>
</tr>
<tr>
<td>SY Cnc</td>
<td>24.6 - 32.0</td>
<td>Yes</td>
</tr>
<tr>
<td>RR Pic</td>
<td>26.2, 28.7, 36.9</td>
<td>Yes</td>
</tr>
<tr>
<td>KT Per</td>
<td>26.7 - 26.8</td>
<td>Yes</td>
</tr>
<tr>
<td>YZ Cnc</td>
<td>26.99</td>
<td>Yes</td>
</tr>
<tr>
<td>Z Cha</td>
<td>27.7</td>
<td>Yes</td>
</tr>
<tr>
<td>VW Hya</td>
<td>28.0 - 413.0</td>
<td>Yes</td>
</tr>
<tr>
<td>UX Uma</td>
<td>28.5 - 30.0</td>
<td>No</td>
</tr>
<tr>
<td>CoD-42°14462</td>
<td>29.0</td>
<td>No</td>
</tr>
<tr>
<td>AH Her</td>
<td>31.5 - 38.8</td>
<td>Yes</td>
</tr>
<tr>
<td>RX And</td>
<td>35.5</td>
<td>Yes</td>
</tr>
<tr>
<td>V Sge</td>
<td>47.7,15.9(2nd harmonic)</td>
<td>No</td>
</tr>
<tr>
<td>V533 Her</td>
<td>63.6, 303</td>
<td>Yes</td>
</tr>
<tr>
<td>AM Cvn</td>
<td>112.8 - 121.0</td>
<td>No</td>
</tr>
</tbody>
</table>

Continual Oscillations

<table>
<thead>
<tr>
<th>Star</th>
<th>Period(s)</th>
<th>Eruption</th>
</tr>
</thead>
<tbody>
<tr>
<td>WZ Sge</td>
<td>27.87, 29.01</td>
<td>Yes</td>
</tr>
<tr>
<td>DQ Her</td>
<td>71.07</td>
<td>Yes</td>
</tr>
<tr>
<td>AE Aqu</td>
<td>33.08</td>
<td>Yes ?</td>
</tr>
</tbody>
</table>

References: Nather (1978); Warner (1976); Patterson (1979b); Warner (1979).
rapid flickering and the quasi periodic oscillations which will be discussed later.

3. The oscillations have low amplitudes ranging from 0.04 mag in DQ Her (Walker, 1958) to 0.0008 mag in Z Cam (Robinson, 1973). The low amplitudes are at least partially caused by extinction within the disc and are only a lower limit to the modulation of the oscillations at their source.

4. The oscillations are sinusoidal.

Three objects exhibit continuous oscillations. It should be noted that such continuous oscillations have been observed from many single white dwarfs though with longer periods (Nather, 1978). One of the continuous oscillators AE Aqr shows more pronounced oscillations during flaring of the system. The amplitude of the oscillation generally averages 0.2-0.3% but often exceeds 1% during flares. In the continuous oscillators the period is remarkably stable. Recent calculations (Patterson et al., 1978a) have found a value of $Q = \left| \frac{1}{P} \right| = 3 \times 10^{12}$ for DQ Her. This stability rivals that of pulsars (Katz, 1975). A similar limit $Q = 8 \times 10^{11}$ had been observed for AE Aqr (Patterson, 1979b). In contrast the periods of the oscillations in the occasional vibrators can change rapidly as can the amplitude of the oscillations. Typically they take a few hundred cycles to get out of step.

Warner and Brickhill (1978) found a remarkable correlation between changes in the period of the oscillations and variations in the brightness of the system. The maximum period corresponded to maximum brightness. Nevo and Sadeh (1978) found the same correlation and expressed it as a period-relative luminosity relation,

$$\log P = b - a \log \frac{I}{I_{\text{min}}}$$

where $a$ and $b$ are constants which change from one star to another and
is the brightness of the system relative to its mean brightness at quiescence. They also comment that in dwarf novae at outburst the oscillations are observed on both the ascending and descending branches of the eruptions.

Warner (1974b) found a second relation, namely that there was a correlation between the apparent amplitude of the oscillations (when they reach maximum amplitude) and the apparent brightness of the star at minimum light, which implies approximately constant maximum intrinsic amplitude of the oscillations.

\[ \Delta m = 0.033 \times 10^{0.4(M-M_{\text{min}})} \]

where \( \Delta m \) is the oscillation amplitude (in magnitudes),

\( M \) is the apparent magnitude at the time of oscillation,

and \( M_{\text{min}} \) is the normal (mean) magnitude of the system between outbursts.

Another important property has been observed in the oscillations of UX UMa and DQ Her. During their eclipses a 360° phase shift is seen in the oscillations. This phase shift is negative in the case of UX UMa (Nather and Robinson, 1974b) and positive in the case of DQ Her (Warner et al., 1972). It is gradual rather than abrupt starting and finishing with the beginning and end of the eclipse. This phase shift was at first thought to be smooth and continuous in both systems but more recent data has suggested that in DQ Her the phase shift is somewhat more complex and perhaps discontinuous (Patterson et al., 1978a).

There are two theories for the origin of these coherent oscillations: non radial pulsations of the white dwarf and accretion onto a rotating white dwarf with a dipole magnetic field.

Nather (1978) favours pulsations of the white dwarf as the explanation for the oscillations. This model has the advantage that it accounts for the coherent oscillations seen in single white dwarfs.
Another benefit is the ease with which white dwarf pulsations produce pure sinusoidal light variations as observed. The length of the oscillation suggests the pulsating mode is non radial rather than radial. Nather (1978) cites the observed phase change in UX UMa as further evidence for non radial rather than radial pulsations. His argument is that the oscillations actually seen are the outer portion of the (optically thick) disc in which the vibrating white dwarf is embedded. As the disc is progressively obscured the oscillation undergoes a smooth change of phase which can be understood if the oscillations originate as waves of brightness travelling around the outer layers of the star. This is the model of Papaloizou and Pringle (1978). As the eclipse progresses the oscillations peak at successively different times as smaller and smaller portions of the disc remain in view.

The second model is the rotating magnetic white dwarf. Patterson (1979b) uses this to explain his observations of AE Aqr. He rejects the model of a pulsating white dwarf because he observes very large and non periodic changes in the amplitude and waveform of the oscillations over a short timescale (factor of 5 in 1 sec). He argues that a single stable period together with such changes is never seen in pulsating stars. The rotating magnetic white dwarf model can explain such changes. Two magnetic poles with independently varying accretion rates or independently varying obscuration effects could cause large amplitude changes while the period caused by the rotation of the white dwarf remained stable. This model is the same as the model for AM Her type stars but with a smaller magnetic field. The fact that no circular polarization has been observed from AE Aqu (Tapia et al., 1980) puts an upper limit on the magnetic field $B < 10^8$ gauss.

In AE Aqu two oscillation components are seen, 33.08 sec and 16.54 sec. The model proposes that the 33 sec period is the rotation
period of the white dwarf. Unless the magnetic poles are exactly on
the star's equator they will present different aspects to the observer. If
the disc is optically thick its visible surface will only be
illuminated by one pole giving the 33 sec oscillation. The very strong
16 sec component is interpreted as seeing the inner edge of the disc
which will be excited by both poles.

The rotating magnetic white dwarf model has long been favoured
as an explanation for the 71 sec oscillations of DQ Her because of
their extreme stability. No 142 sec component is observed. The 71 sec
period is interpreted as the period of the white dwarf with only
the bright region caused by one pole being seen (Patterson et al.,
1978b). The phase of the oscillations undergoes a regular variation
with the binary motion, the most spectacular part of this being the
large phase shift during eclipse. The amplitude of the oscillations
decreases during the eclipse (Petterson, 1979). The 360° phase shift
is explained by a gradual eclipse, and re-emergence of the emitting
region. The duration of this phase shift roughly equals the duration
of the eclipse itself which supports the theory that the oscillating
light observed does not come directly from the white dwarf but is
reflected off the disc (Petterson, 1979). This is further supported
by the 'wavelength dependent phase shift' observed by Chanan et al.
(1979). The sign of the observed phase change can only be explained
if the bright spot is on the inner edge of the accretion disc as
suggested by Rees (Bath et al., 1974) or the back side of the disc
(Patterson et al., 1978b). However there is no direct evidence for a
magnetic white dwarf in DQ Her, AE Aqr or any cataclysmic variables
except the polars.

Although the rapid rotator model can explain the observed
oscillations in DQ Her and AE Aquarius it cannot account for the two
distinct, closely spaced periodicities seen in the light curves of the third continuous oscillator, WZ Sge (Nather, 1978). On one occasion both periods were present simultaneously, beating with each other (Robinson et al., 1978). It may be necessary to invoke different mechanisms to explain the oscillations observed in various systems. A wide range of properties is certainly seen but to find a single explanation would certainly be a more satisfying conclusion.

In addition to these coherent oscillations, quasi periodic oscillations have been observed in 6 dwarf novae (Robinson and Nather, 1979; Patterson, 1979b). They have also been observed from Sco X-1 (Robinson and Nather, 1979). Quasi periodic oscillations are only observed from the dwarf novae during outbursts and in Sco X-1 when the system is bright. Typically they have amplitudes in the range 0.005 - 0.01 magnitude and coherence times of 3-5 cycles of the oscillation. They are seen at the peak of the eruption and in the decline, but not on the rising branch. When they do appear they can last a long time (see for 5 days in RU Peg and 10 days in VW Hyi). Since the dwarf novae in which quasi periodic oscillations have been found, are the brightest in their class, these oscillations must be considered a normal property of dwarf novae. Presence of quasi periodic oscillations does not depend on the subclass to which the dwarf nova belongs or the morphology of the eruption. If it is confirmed that these oscillations are seen in Sco X-1 (further observations are needed: - Robinson and Nather, 1979), then it seems likely that the same mechanism causes the bright states of Sco X-1, the supermaxima of SU UMa stars and the ordinary eruptions of dwarf novae. Since these oscillations are outburst related the white dwarf/inner disc must be responsible. Their extreme instability argues against rotation or pulsation of the white dwarf since the time scales for period changes for these mechanisms are far longer than just
a few cycles.

The characteristic periods of these quasi periodic oscillations are considerably longer than the periods of the coherent oscillations in the same systems (Van Horn et al., 1980) (e.g. 31.5 sec versus 9.75 sec in SS Cyg; ~ 50 sec versus 11 sec in RU Peg). It has been suggested that the quasi periodic oscillations are oscillations of the accretion disc triggered either directly or indirectly by the increased flux of mass through the accretion disc which causes the outbursts, (Van Horn et al., 1980; Robinson and Nather, 1978; Patterson et al., 1977).

Recently Cordova (1979) has observed pulsed 'soft' X-ray emission from two dwarf novae. SS Cyg and U Gem show enhanced 'soft' X-ray emission (0.1 - 0.5 keV) during optical outburst. Extended HEAO-1 pointings on these two sources showed that a large fraction of this emission is pulsed. For SS Cyg the average 'soft' X-ray pulsation amplitude observed was 30%. This was in contrast with the upper limit of 10% to the 'hard' X-ray (2-2.5 keV) pulsed component. This implies that the origin of the oscillation is in 'soft' X-rays, and the implication of such a large pulsed amplitude is that the oscillation itself must be an intrinsic part of the X-ray production mechanism.

The SS Cyg pulsations were found to be remarkably sinusoidal. The amplitude of the pulsation was observed to change by a factor of six within fifteen pulses with no effect on the pulse phase. The phase itself showed both slow variations and rapid jumps. According to Cordova the behaviour of these 'soft' X-ray pulsations in SS Cyg resembles the coherent visible oscillations observed in many cataclysmic variables. On the other hand the 'soft' X-ray pulsations from U Gem show a similar behaviour to the quasi periodic oscillations observed in
the visual from a few dwarf novae on the decline from outburst.

X-ray Emission

The possible detection of 'soft' X-rays (Rappaport et al., 1974) from the dwarf nova SS Cyg during outburst aroused much excitement and led to speculation that all cataclysmic variables would be found to emit X-rays. Warner (1974d) produced a model in which the required X-ray flux was produced in the bright spot, where the stream of material from the secondary interacts with the accretion disc. Pringle (1977) showed however that although the observed 'soft' X-ray flux could be produced in the shock at the bright spot, only a very small fraction of the X-rays would emerge without being absorbed in the surrounding disc and stream. Most of the energy liberated at the bright spot would be thermalised and emerge as optical or ultraviolet radiation. He proved instead that an alternative model suggested by Bath et al. (1974) would emit the observed flux of X-rays. In this model Bath et al. showed that although the accretion disc is not hot enough to produce 'soft' X-rays, such a flux could be expected from the boundary layer (Lynden-Bell and Pringle, 1974) where the accretion disc grazes the surface of the white dwarf.

There has been a vast amount of interest in the possibility of X-rays from cataclysmic variables which has not been matched by the number of detections. To date few cataclysmic variables are listed as X-ray sources. 'Soft' X-rays have been detected from AY Lyr, MV Lyr, SS Cyg and U Gem. 'Hard' (> 2 keV) X-rays have been detected from EX Hya, SS Cyg, U Gem, GK Per, 2A0526-328, AM Her, AN UMa and 2A0311-227 (Warner, 1979).

We (Watson et al., 1978) carried out a search for 'hard' X-rays from 47 of the brightest dwarf novae using data from the Ariel V Sky
Survey Instrument. Only SS Cyg and EX Hya gave positive results.

'Soft' X-ray emission from SS Cyg and U Gem is known to be enhanced
during outburst and so HEAO-A2 carried out a 'soft' X-ray survey of 20
dwarf novae during outburst (Cordova et al., 1980). It failed to
detect X-rays from any systems except SS Cyg and U Gem.

Two models of X-ray production in cataclysmic variables are now
accepted. One model applies only to the emission from polars and the
other applies to all the other cataclysmic variables which have been
detected as X-ray sources.

Three of the four polars (the exception being VV Pup) are 'hard'
X-ray sources. The first to be discovered was AM Her which was
identified with the X-ray source 3U1809+50 (Giacconi et al., 1974)
by Berg and Duthie (1977). Their identification of the peculiar blue
variable AM Her with a 'hard' X-ray source led ultimately to the
distinguishing of a new type of variable, 'the Polars'. AN UMa and
VV Pup were classed as Polars on the bases of their optical and
polarization variability. Only recently has AN UMa (Hearn and Marshall,
1970) been detected as an X-ray source. The fourth Polar 2A0311-227
was first detected at X-ray wavelengths (Cooke et al., 1978) and optical
identification was made by Griffith et al. (1979) and Hiltner et al.
(1979).

The X-ray light curve of AM Her shows periodic variations with
the same period as the optical light curves. The adopted model for
Polars where the white dwarf is degenerate with a large magnetic field
provides a natural explanation for the observed X-rays. The magnetic
field channels an accretion flow of material from the disc onto the
poles and accretional X-rays are produced.

For other cataclysmic variables the accepted model is that the
X-rays are produced by shocks in the boundary layer as mentioned earlier.
Pringle (1977) had shown that the boundary layer could emit 'soft' (0.1-1.0 keV) X-radiation with the 'soft' X-ray flux sensitively dependent on the accretion rate. Observations of 'hard' X-rays from SS Cyg (Ricketts et al., 1979), U Gem (Swank et al., 1978) and EX Hya (Watson et al., 1978) raised doubts as to the viability of this model until Pringle and Savonije (1979) showed that the model could also account for observed 'hard' X-ray fluxes. Their theory predicts that at optical quiescence an appreciable fraction of the X-ray flux from the boundary layer should be 'hard' X-rays, although the intensity may well be too low to be detectable with the present generation of X-ray detectors. During an optical outburst the accretion rate increases and the boundary layer becomes optically thick to the 'hard' X-rays which become thermalized and so are emitted as 'soft' X-rays, leading to an enhancement of the 'soft' X-ray flux. In view of the recent non-detection of 'soft' X-rays from many dwarf novae during outburst (Cordova et al., 1980) detailed calculations of flux levels are needed to support this theory.

Cordova et al. (1978) observed a large amplitude modulation during optical outburst in the 'soft' X-ray flux from SS Cyg with a period $\sim 9s$. This is similar to the period of the coherent oscillations observed in the optical (Patterson et al., 1978). A modulation has also been seen in the 'soft' X-ray flux from U Gem during outburst (Cordova, 1979). Such oscillations are often seen in dwarf novae at outburst and may be produced by non radial pulsations in the surface layers of the white dwarf (Papaloizou and Pringle, 1978) as was mentioned earlier. The detection of pulsations in the 'soft' X-ray emission, if this model of the oscillations is correct, is support for the boundary layer model as the source of these X-rays (Pringle and Savonije, 1979).
Associations

Possible similarities between cataclysmic variables and other variable stars has been the topic of much discussion. Kraft (1962) proposed that cataclysmic variables were evolved from W UMa stars. His conclusion was based on similarities between the space distribution and proper motions of both groups. Mass loss was indicated as the main cause of the transformation from W UMa system to eruptive binary (Gorbatsky, 1975). Calculations by Webbink (1976) suggest that W UMa systems evolve into single white dwarfs not cataclysmic binaries.

It has been noticed that there is an analogy between X-ray bursters and cataclysmic variables (Baan, 1977; Sunyaev and Shakura, 1977; Brecher et al., 1977). Brecher et al. showed there are many similarities between the optical outbursts of SS Cyg and the X-ray bursts of MXB 1730-335. They conclude that this lends support to the association of X-ray burst sources with mass transfer systems containing a compact object with an accretion disc rotating around it. Only from time to time does the condition for accretion arise and then we have an X-ray burst when the central object is a neutron star or a dwarf nova outburst when the central object is a white dwarf. Similarly, if the compact object has a strong magnetic field or physical conditions in the disc are such that the accretion occurs not in pulses but continuously, there occur X-ray binary pulsars for neutron stars and Polars for white dwarfs (Kruszewski, 1978). Bath (1978) has also pointed out the similarity between cataclysmic variable models and the models of galactic X-ray sources. Indeed much of the accretion disc theory now being applied to cataclysmic variables was developed as an explanation for the observed properties of X-ray stars.

In their discussion of cataclysmic binaries Whyte and Eggleton (1980) include a number of objects which, while they might be related,
are not usually included in this class. Their definition of cataclysmic variable is wider than most. It includes all systems believed to contain both an evolved compact star (usually a white dwarf) and a red/yellow dwarf. Their basic criteria is that the period of the system be less than 24 hours and that one component is presumed to be evolved and compact. Several interesting stars fall into their net. These include V471 Tau and PG 1413+01, both of which consist of a white dwarf and a non-lobe filling secondary. They suggest that such systems may be progenitors of cataclysmic binaries.

Another interesting system which is often included in lists of nova-like variables is V Sge. Being both a double lined spectroscopic binary and an eclipsing binary it has been well studied. The derived secondary mass seems rather large for a system of short orbital period \( P = 12.34 \) hours. The primary appears to be a Wolf Rayet star of unusually low mass (Herbig et al., 1965) but it may be explicable as a core-helium burning remnant which has lost mass to its companion. Currently mass transfer (via stellar wind rather than Roche lobe overflow) appears to be in the direction from the primary (Wolf-Rayet) to the secondary, i.e. in the opposite direction to the mass flow in cataclysmic binaries, but the primary could become a carbon oxygen white dwarf without losing much more mass. Whyte and Eggleton (1980) have suggested this system might represent an earlier stage in the evolution to cataclysmic binaries than systems like V471 Tau.

Recent Developments

Until recently our ideas about cataclysmic variables were based solely on observations at optical wavelengths and many questions were left unanswered. During the last five years or so interest has increased tremendously, partly because of the detection of X-ray from a few
systems, and developments in technology have made it possible for observations to be made at a far larger range of wavelengths. X-ray observations are continuing with more and more sensitive detectors. Ultraviolet satellites have extended observations to this wavelength range. In particular the International Ultraviolet Explorer (IUE) is being used to take spectra and do spectrophotometry of a large number of cataclysmic variables (e.g. Bath et al., 1980). Observations at infrared wavelengths were started by Szkody (1976b, 1977) who obtained infrared colours of a number of systems and we ourselves have observed the infrared light curves of several systems.

The extending of the wavelength range of the observations has brought a vast amount of new material to the study, and should enable models for individual systems to be produced in far more detail than has previously been possible. We might then obtain an answer to the ultimate question - Why is such a range of behaviour seen in systems whose components are so similar?
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CHAPTER THREE

INSTRUMENTATION AND
OBSERVING TECHNIQUES

The majority of the observations described in the subsequent chapters of this thesis were made with the Leicester infrared photometer attached to the 1.5m Infrared Flux Collector at the Cabezon Observatory, Tenerife. The basic infrared photometer is of a standard design and has not changed greatly over the last five or so years. Infrared instrumentation and in particular the various stages in the development of the current Leicester photometer have been described in detail in the theses of previous members of the group, namely, Longmore (1975), Akinci (1978) and Abolins (1980), and therefore will not be described in full here. In this chapter a brief description of the photometer will be given, concentrating mainly on the changes made in the past three years, in particular the addition of the optical channel which is so important in our study of cataclysmic variables. This will be followed by an outline of our observing techniques.

Photometer

Fig. 3.1 shows the current Leicester infrared/optical photometer. Its rather ungainly appearance is due to the addition to the basic photometer of several facilities over the years. This has resulted in its growing appendages.

The radiation beam, which is collected immediately from the secondary mirror, passes through the hole in the centre of the offset guide mirror and impinges on a 45° dichroic mirror. The dichroic
Fig. 3.1 Infrared Photometer
mirror reflects the infrared beam but transmits the visible radiation. The infrared beam is reflected to a second 45° mirror which is the sky chopper. After this second reflection it passes to the outer window of the cryostat, which is situated above the chopper, and thence to the infrared detector. Below the dichroic mirror there is a 45° plane mirror which can be positioned either in or out of the transmitted optical beam. When the mirror is in the beam, the optical light is reflected to the primary eyepiece. When the mirror is removed from the beam, the visible radiation passes straight down into the optical photometer. The offset guide mirror allows light from the centre of the field of view of the telescope to pass into the photometer, but reflects the rest of the field to a second moving eyepiece, the offset guide eyepiece.

Both eyepieces are Ramsden eyepieces with illuminated graticules. They have a one inch linear field of view, which for the primary eyepiece corresponds to an angular field of view of 4.4 arc min in a 60" F13 telescope (IRPC). The graticules have a single horizontal hair and two parallel vertical hairs. The former is positioned across the centre of the field of view and the latter are spaced to correspond to the throw of the chopper. This enables the two beams defined by the sky chopping system to be located exactly and consistently in the eyepieces.

The photometer is aligned by first setting the dichroic to 45° and then adjusting the position of the sky chopper mirror until the infrared beam passes vertically and centrally through the aperture of the cryostat. The primary eyepiece is mounted on the side of the photometer perpendicular to the incoming radiation and its position is finely adjusted by four setting screws until the optical beam is centred on one of the two sky chopping positions. The sliding mirror is then moved out
of the beam. The optical photometer is attached to the infrared photometer by means of an X-Y slide which is then adjusted until the optical beam passes through the centre of the aperture of the optical photometer.

When observing the star is first set on one of the sky chopper positions in the primary eyepiece. Since this eyepiece receives no light when the optical channel is in use, the offset guide eyepiece is then adjusted until a bright offset guide star is positioned at the corresponding sky chopper position in this eyepiece. Once the sliding mirror has been moved to allow the optical beam to enter the visual photometer all guiding is done from the offset guide eyepiece.

The sky or focal plane chopper modulates the infrared radiation impinging on the detector. This is done for two main reasons. Firstly it produces an alternating output from the detector since it is easier to amplify AC rather than DC signals and secondly it allows the cancellation of the high background signal which exists at wavelengths \( \lambda > 1 \mu \text{m} \).

The chopper consists of a single mirror vibrating from one position to another at the position of the second 45° mirror of the photometer. It is mounted on the end of a solenoid vibrator manufactured by Ling Dynamics Ltd. It is important that the movement of the mirror should be parallel to the optical axis of the detector since the detector then sees the minimum movement across the primary mirror of the telescope. The maximum throw of the chopper is 40 arc sec. The detector is exposed alternately to two neighbouring patches of sky ("beams"), the first of which contains the object of interest plus an area of bright sky (the source beam) and the second contains just an equal area of sky (the reference beam). The difference between the two beams i.e. the signal from the source of interest alone can then be
obtained by phase sensitive rectification.

The cryostat

The cryostat which houses our infrared detector is shown in Fig. 3.2. The infrared detector used for our observations is an indium antimonide (InSb) photovoltaic device supplied by the Santa Barbara Research Centre (SBRC), USA. Indium antimonide detectors require low temperatures for operation and are usually cooled by being placed in thermal contact with a bath of liquid nitrogen. At normal pressure the temperature of liquid nitrogen is 77\(^\circ\)K but it is usual nowadays to cool the detector to 'pumped' nitrogen temperatures i.e. \(T \approx 63\,\text{K}\) since this improves the sensitivity.

The cryostat maintains the detector at a low temperature by providing a mounting in excellent thermal contact with the pumped liquid nitrogen. It also houses and cools the filters, aperture stops, a Fabry lens and part of the preamplifier circuitry. Cooling of the filters and apertures minimises their thermal emission which the detector 'sees'. The first stage of the preamplifier circuitry is cooled for two reasons. Firstly it reduces the FET gate shot noise and secondly its proximity to the detector means that only short leads are needed thus reducing microphonics and stray capacitances to a minimum. The Fabry lens images the primary over the whole detector surface to reduce noise introduced when seeing, guiding errors and vibrations cause a smaller image to wander randomly over the non-uniform detector surface. Both the cryostat window and Fabry lens are made of CaF\(_2\) which has a transmittance of greater than 80\% from 0.5-10\(\mu\)m.

The filters used are interference filters from the standard UKIRT batch. The cryostat contains four filters \((J, H, K, L)\), four circular apertures of diameter 0.5, 1.5, 2 and 4.5 mm and two slit
Fig. 3.2 Cryostat
apertures. The aperture used for all our photometry was 2 mm. The effective wavelengths and bandwidths of the filters are

<table>
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<th>J</th>
<th>H</th>
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<tr>
<td>$\lambda_{\text{eff}}$ μm</td>
<td>1.25</td>
<td>1.65</td>
<td>2.22</td>
<td>3.8</td>
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<tr>
<td>$\Delta \lambda$ μm</td>
<td>0.3</td>
<td>0.3</td>
<td>0.4</td>
<td>0.7</td>
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The Infrared Detector

Indium antimonide is an intrinsic photodetector with a forbidden energy gap (i.e. valence band to conduction band) of 0.22 eV at liquid nitrogen temperatures and therefore photons $\lambda < 5.5 \mu m$ are required to create an electron-hole pair. An InSb photovoltaic detector consists of adjacent zones of p and n doped material which together form a photo-diode. Infrared photons are absorbed at the junction creating an electron hole pair which is separated by the junction field and appears as charge at the electrodes.

The intrinsic noise of the detector (when background noise is negligible) limits the sensitivity. InSb photo-diode systems have three inherent types of noise; Johnson noise (random thermal electron motion), 1/f or current noise and generation-recombination noise (statistical fluctuations in the rate of generation and recombination of charged particles in the detector caused by charge carrier phonon interactions or by the random arrival rate of photons from the background) (Wolfe, 1985). The generation recombination noise has been reduced to a minimum by cooling the detector. The 1/f noise is a function of the DC current through the detector whereas the Johnson noise current is a function of temperature and detector impedance. Our detector is operated in a Johnson noise limited condition i.e. no DC current through the detector by using the preamplifier design of Hall et al. (1975). The preamplifier is attached to the cryostat to prevent
noise pickup along lengthy transmission cables.

The Johnson noise current is given by $\Delta i = \sqrt{\frac{T}{R}}$ where $T$ is the detector temperature and $R$ is the system resistance. Since the noise decreases as the temperature is lowered the detector is cooled as described earlier. Johnson noise is also reduced if the detector resistance can be increased. This is achieved by the strange process of "J-flashing". The cooled detector is exposed to extremely intense 1.2 μm radiation (usually from an ordinary light bulb, J-filtered) for ~4 minutes. The detector resistance is increased by an order of magnitude or more by this procedure although the mechanism involved is poorly understood.

To obtain the best performance from our detector we follow the procedure described by MacGregor (1977). The detector is cooled to 77 K, flashed, pumped to about 63 K and then flashed again. The sensitivity of the detector improves at each stage.

The Optical Photometer

The design of the optical photometer is shown in Fig. 3.3. It was first added to the infrared photometer in August 1978.

The optical channel is attached to the infrared photometer by means of an X-Y slide which enables the exact alignment of the infrared and optical detectors. The optical beam, which is transmitted through the dichroic mirror in the infrared photometer, passes first to the aperture wheel containing apertures of diameter 1 mm, 2 mm and 4 mm. A 2 mm aperture was used for all our observations. The aperture wheel contains four 2 mm apertures. One is a plain aperture, and the other three contain neutral density filters to reduce the light falling on the photomultiplier tube by factors of 10, 100 and 1000. This allows bright standard stars to be observed without the photon rate being
Fig. 3.3 Optical Photometer
higher than the maximum the tube can measure.

A Fabry lens is situated below the aperture wheel. The Fabry lens images the primary over the whole area of the photocathode to reduce noise introduced when seeing, guiding errors and local vibrations cause a smaller image to wander randomly over the non uniform photocathode area. Below the Fabry lens is situated a filter wheel containing U, B and V filters. The transmission curves of these filters are shown in Fig. 3.4. Only the V filter was commonly used. The other filters were rarely used because the system is non standard at U and B. The U filter is standard but, before reaching the filter wheel the optical beam has passed through a glass dichroic and glass Fabry lens which do not transmit the short wavelength end of the U band. This makes the transmission of the system non standard at U. The B filter was little used because it is slightly non standard. The standard blue filter transmission is shown in Fig. 3.4. Our blue filter transmits more 0.3-0.4 μm radiation than is standard. It has now been replaced with a standard blue filter. The V filter, which is the optical filter that was normally used is standard. The long wavelength cutoff is provided by the response curve of the photomultiplier tube. Both tubes used (see below) had very similar cutoffs and their response curve is shown in Fig. 3.4.

From August 1978 until July 1979 a 9734NB photomultiplier tube made by EMI was used. This was a ruggedised tube aimed at space applications, that happened to be around the infrared laboratory when the idea of an optical channel was first proposed. This tube had a lime soda window and Si11' cathode. The dark current shot noise at 20°C was $2.5 \times 10^{-16}$ Watts and the tube has an anode sensitivity of 50 A/1um 

This tube was not quite sensitive enough for our work and was replaced before the observing trip of August 1979.
Fig. 3.4 Optical Filter Transmission Curves
The second and current photomultiplier tube was a type 9502S tube made by EMI. This tube is aimed specifically at very low light level applications and has a very small dark current. The thermionic emission of the tube is reduced due to special processing. It has an EMI 'S' cathode and a lime-soda window. The quantum efficiency of this tube is similar to that of the 9734NB tube but the dark current shot noise is lower at $3.5 \times 10^{-17}$ Watts and the anode sensitivity is higher, 200 A/lumen. This tube gave the photometer a much improved performance as will be discussed later.

**Signal Processing Electronics**

A block diagram of the signal processing electronics and data recording system is shown in Fig. 3.5 for the infrared signal the arrangement of the Hall preamplifier, phase sensitive detector and integrating digital voltmeter are now standard in infrared photometry.

The optical pulses from the photomultiplier tube pass first to the amplifier/discriminator/line driver which is attached to the side of the photometer to avoid loss of signal down long leads. The pulses are first amplified and then passed to the discriminator. This selects only those pulses greater than a chosen height thus eliminating the noise and most of the spurious pulses caused by ringing. It then converts the accepted pulses to linear ECL pulses (emitter coupled pulses). The line driver converts these negative going pulses to TTL pulses and amplifies them so they can pass down the long cables from the telescope to the optical counter without loss. It also allows the pulse rate to be divided by a factor of 10 or 100, if the star is so bright that the pulse rate is too high for the optical counter to accept without the loss of some pulses. The integration time for both the infrared and optical channels is controlled by a single master oscillator.
Fig. 3.5 Block diagram of the signal processing electronics.
(crystal) in the integrating digital voltmeter. This is tuned to be accurate to 1 part in $10^5$. The two channels are controlled by the same oscillator so that the integrations are truly simultaneous and of the same length at both wavelengths.

The next element in the signal processing electronics is the microprocessor. This is the second improvement made to the system in the last three years. Prior to the acquisition of the microprocessor, the readings for each integration were recorded by hand from the displays on the integrating digital voltmeter and optical counter, together with the time of the integration. With typical integration times of 20 seconds and runs of up to 7 hours of continuous observations on one star, this was hard, tedious work. The microprocessor removes this drudgery.

This integration is started by a signal from the teletype or VDU. The microprocessor passes this signal to the integrating digital voltmeter which begins the integration in both the infrared and optical systems (integrations can also be started directly by a switch on the integrating digital voltmeter in the case of a failure of the microprocessor). At the end of the integration time (which can be set to anything from 1 sec to 99 sec on the integrating digital voltmeter) the microprocessor records the date and time at which the integration occurred, together with the reading in each channel and the difference between these readings and the previous reading in each channel. Since we observe first with the star in one chopper position, then in the second chopper position and then back to the first this difference column immediately gives the star reading with the background and PSD offset subtracted in the infrared. In the optical, the difference column also gives the star reading directly, since one position corresponds to observing the star plus background and the second to just recording
the background. The clock in the microprocessor is based on a master oscillator (crystal). Once the date and time have been set in the microprocessor it will keep time accurately (the 1 Hz crystal signal is accurate to 0.0025%) as long as it is left switched on. The time, readings and differences can be recorded on a digital cassette as well as printed out on the teletype for immediate perusal. The cassette provides a compact, reliable method of transporting the results to Leicester where it can be read directly by the Leicester University Cyber 73 computer.

Other instruments

During the course of this project other infrared photometers have been used for a few of the observations. These are the common user infrared photometers at the AAT, SAAO and UKIRT. Details of these systems are available from the observatories concerned.

OBSERVING TECHNIQUES

Observing Programme

As was mentioned in Chapter 1 it was decided from the start not to restrict our observations to any one subgroup of cataclysmic variables. The number of cataclysmic variables visible from Tenerife and bright enough to be observed with a 60" telescope is limited. Our choice was made purely on the basis of selecting the potentially most interesting systems bright enough for observation bearing in mind the sensitivity of our instrument. The noise limits of our instrument for the various observing trips of this project are shown in Table 3.1. The noise limits for the SAAO and AAT systems are also included.
<table>
<thead>
<tr>
<th>Date</th>
<th>V</th>
<th>J</th>
<th>K</th>
</tr>
</thead>
<tbody>
<tr>
<td>April 1978</td>
<td>-</td>
<td>-</td>
<td>11.5</td>
</tr>
<tr>
<td>April 1979</td>
<td>14.7</td>
<td>12.9</td>
<td>12.0</td>
</tr>
<tr>
<td>August 1979</td>
<td>15.7</td>
<td>13.2</td>
<td>12.1</td>
</tr>
<tr>
<td><strong>SAAO Infrared Photometer on 1.88m Telescope</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>December 1978</td>
<td>-</td>
<td>13.0</td>
<td>11.7</td>
</tr>
<tr>
<td><strong>AAT Infrared Photometer on 3.8m Telescope</strong></td>
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<td></td>
</tr>
<tr>
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<td>16.13^+</td>
</tr>
<tr>
<td>April 1980^*</td>
<td>-</td>
<td>17.40</td>
<td>14.65</td>
</tr>
</tbody>
</table>

^ quoted AAT noise figures

^* operating without focal plane chopper
Selection of Standard Stars

The choice of standard stars for use in the magnitude calibration of our observations was of paramount importance if the best possible accuracy in the absolute photometry was to be achieved. The standards used in this project were mainly from Johnson's lists of standards (Johnson et al., 1966). For the southern hemisphere observations, standards were chosen from the lists of Glass (1974) or Allen (1980, private communication).

The primary criteria when selecting standards are (a) the star should be as near in the sky as possible to the star of interest and (b) the standard should be as close as possible in brightness to the star of interest, to avoid possible systematic error introduced by any non-linearity in the amplifiers. Since infrared standard stars are relatively few in number and are generally rather bright the stars selected did not often satisfy the above criteria well but were always an optimum selection. For simplicity the same standard star was used at both infrared and optical wavelengths. The stars selected were checked for variability by reference to the Catalogue of Bright Stars. Any star suspected of being a variable was immediately discarded.

The Observations

To achieve accurate absolute photometry the standard star should be observed frequently during the night so that the best possible corrections for atmospheric extinction and varying sky conditions can be made. However if this procedure was to be followed and the standard measured every $\frac{1}{2}$ - 1 hour or so rather incomplete light curves would have been produced. The decision was therefore made to sacrifice some of the accuracy of the absolute photometry to achieve complete light curves, and to measure the standard only at the beginning and end of
each run. The length of each run was usually just over one binary period - anything from 1 hour 45 min to 7 hours. Even though corrections for atmospheric extinction (see below) were made based on the observations of the standard before and after each light curve, there may be drifts, estimated as $\pm 0.1$ magnitude, in the absolute photometry due to the long intervals between the measurements. The standards were often some distance from the star of interest so to make these errors due to variations in atmospheric conditions and extinction as small as possible a sub-standard was used. A non variable star of about 8-9 magnitude and within 1° of the star of interest was chosen as the sub-standard. This was measured before and after the run and it was the readings of this star that were used to correct for changing atmospheric extinction. Thus the variations were as close as possible to those of the star of interest. This sub-standard was calibrated against the standard star.

DATA REDUCTION

Heliocentric Corrections and Conversion to Phases

The dates and times of each integration was first converted to Julian days and decimals of a day. Heliocentric corrections were then applied to the times of the observations using the tables of Landolt and Blondeau (1972). The phases of the observations were then calculated from the most recent reliable published ephemeris. Heliocentric corrections are especially important in the calculation of accurate phases for very short period systems.

Conversion to Magnitudes and Fluxes

The readings obtained for the star of interest and the standard star are proportional to the brightnesses of the two stars being compared.
After correcting the measured signals for atmospheric extinction, conversion to magnitudes is achieved by application of the well known formula:

\[ M_\varepsilon(\lambda) = M_{ST}(\lambda) + 2.5 \log_{10} \left( \frac{A_\varepsilon(\lambda)}{A_{ST}(\lambda)} \right) \]

where \( M_\varepsilon(\lambda) \) and \( M_{ST}(\lambda) \) are the magnitudes of the star of interest and the standard respectively at wavelength \( \lambda \) and \( A_\varepsilon(\lambda) \) and \( A_{ST}(\lambda) \) are the readings of the star and standard respectively.

Conversion to flux units followed the absolute calibration of Johnson (1966).

**Atmospheric Extinction**

Extinction of starlight in the Earth's atmosphere is caused by two processes, absorption and scattering by the constituents of the atmosphere. The amount of extinction varies with wavelength and the distance of the object from the zenith i.e. the amount of atmosphere looked through. It is important to correct observations for this extinction. The apparent magnitude \( M(\lambda) \) at any wavelength is a function of the airmass \( M(Z) \) at zenith distance \( Z \)

\[ M(\lambda) = M_0(\lambda) + \Delta M_0(\lambda) M(Z) \]

where \( M_0(\lambda) \) is the magnitude which would be observed outside the Earth's atmosphere and \( \Delta M_0(\lambda) \) is the magnitude loss at the zenith and equals 2.5D(0) where D(0) represents the optical density of the atmosphere for one airmass \( (Z = 0) \). The airmass can be expressed in a simple form when the atmosphere is assumed to have a plane parallel structure. This is a reasonable approximation for zenith distances less than 60°. Then

\[ M(Z) = \sec Z. \]

More complicated formulae apply when \( Z > 60^\circ \) but generally observations are not made at zenith distances \( > 60^\circ \).
The usual procedure for correcting observations for atmospheric extinction is to plot a graph of $\log_{10} (\text{observed signal})$ at zenith angle $Z$ against $\sec Z$ for the calibration star(s). Magnitudes of the object of interest can be obtained directly by using the calibration star signal extrapolated to the appropriate airmass. This procedure was used when reducing our data.

Since following a single star at two wavelengths for a period of hours produces a large number of data points all this data reduction discussed was effected using the Leicester University Cyber 73. The Cyber 73 was also used to produce the final light curves using the Ghost Graphics Package.

Errors

Generally the results of our observations, shown in subsequent chapters, are plotted magnitude against phase with each point representing a single integration in each channel.

The errors on each curve were estimated from similar observations of a comparably faint non-variable star. The errors shown on the light curves are the 1σ errors calculated from these observations.

Two methods have been used on some of the data sets to reduce intrinsic flickering and instrumental noise and thus show the variations more clearly. The first method used was to bin the data i.e. readings from a chosen number of points were averaged into one point. The errors plotted on these binned curves is simply the error on the non-binned data, divided by the square root of the number of observations in each binned point.

The second method used was a smoothing routine. This routine takes a Fourier transform of the data set and convolves it in frequency space with a Gaussian curve. This removes the high frequency variations.
The inverse transform of this new data is then taken. The level of the smoothed curve is set by making the area under the smoothed curve the same as the area under the original data. The degree to which the data is smoothed is altered by changing the width of the Gaussian. The error on the smoothed curve is a function of the standard deviation of the input data and the degree of smoothing applied. Both the smoothing procedures and the error estimates are carried out on the raw data before conversion to the logarithmic magnitude scale.
REFERENCES


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EX HYDRAE

EX Hydræ is a dwarf nova with a binary period of 98 minutes. It thus belongs to the group of ultrashort period variables ($P < 2$ hrs). Most dwarf novae erupt every 20-100 days with typical amplitudes up to 5 magnitudes. EX Hya is an exception in this respect, its outbursts being rare, of small amplitude and of short duration. Outbursts occur every 574 days on average but vary within wide limits (Bateson, 1979). They last less than four days and have typical amplitudes of about 2 magnitudes. Observing these infrequent events is thus difficult and there are no photometric or spectroscopic observations of EX Hya at maximum.

EX Hya has always been classified as a U Gem star since it has never been observed to undergo Z Cam standstills or SU UMa supermaxima. The recent discovery of a 67 minute periodicity (Vogt et al., 1980) together with its strange outburst cycle has led Vogt (1980) to suggest that it should be reclassified as an SU UMa star (this has been discussed in Chapter 2).

PREVIOUS WORK

In contrast to the lack of observations at outburst, EX Hya in its minimum state is fairly well studied, since it is one of the brightest dwarf nova with $V \sim 13.2$.

Spectrum

Kraft (1962) obtained spectra of EX Hya and found doubled disc
emission lines. This indicated that the system is observed at a high inclination and prompted a search for eclipses in its light curves.

The spectra show strong, stationary double hydrogen emission lines with a separation of the components of about 1400 km s\(^{-1}\) (Kraft, 1966). In addition there is a periodically variable weak 'S' wave component. The maximum velocity of recession of the 'S' wave occurs near primary minimum in the light curves and is accompanied by a drop in the continuum intensity. In addition to the hydrogen lines a fairly strong emission line of HeI (\(\lambda 4471\)) and a faint trace of HeII emission (\(\lambda 4686\)) is present. No further spectroscopic studies have been published since these early spectra by Kraft.

**Long Term Variability**

Visual observations of the long term variability of EX Hya are discussed by Bateson et al. (1970). The observations show almost continuous fluctuations between visual magnitude 12.8 and 13.2 with flare-like activity producing a number of peaks with magnitudes 12.2 to 12.6. There are also several distinct sharp minima below magnitude 13.2. These effects are due to short period eclipses on which is superimposed the flare-like flickering. The nature of the rare outbursts suggest that the rise from magnitude 12.8 or 13.0 to as bright as 9.6 or 10.1 on occasion, occurs in less than one day. This is not unusual for dwarf novae. The fall from outburst lasts 2 to 4 days and follows a very brief stay at maximum. This is very steep even for a U Gem type star. Whilst there are other dwarf novae that take only two days for the descent they are those systems, such as AB Dra, that have very short mean cycles. There is no evidence to suggest that EX Hya has a short mean cycle. It is possible that the small peaks resulting from flare-like activity represent secondary maxima of approximately 2.5 magnitudes.
fainter than the bright maxima. This would indicate a very short mean cycle with maxima of very uneven brightness. The duration of these flares is very short and the visual observations are not frequent enough (rarely more than one observation per peak) to prove or disprove this idea. Recently Bateson (1979) has suggested that the outbursts of EX Hya are in fact supermaxima of very short duration.

**Light Curves**

Krzeminski (unpublished) was the first to identify EX Hya as an eclipsing binary. Subsequent photometric studies were published by Mumford (1964, 1967, 1969), Warner (1972, 1973) and Watson and Rayner (1974). The observations show that the light variations are continuous with little or no constant phase. Primary minimum which is sharp and very narrow (\( \approx 3 \) min duration) is visible in each cycle but is variable in both shape and depth (0.3 - 0.8). Prior to primary minimum a small hump is visible in the light curves. This hump is irregular in shape and varies in amplitude from cycle to cycle. The light curves show large amplitude flickering on time scales of \( \approx 10 - 100s \) which has not been found to be periodic on a time scale of a few minutes to seconds. This flickering, frequently \( \approx 0.25 \) in amplitude is present throughout the whole cycle and is probably responsible in part for the changes in shape and depth of primary minimum. An example of a light curve published by Warner (1972) is shown in Fig. 4.1.

The colour changes with binary cycle are also unusual (Mumford, 1967). Most dwarf novae show a blue increase prior to primary minimum at which time the system generally reddens. The U-B colour index usually behaves in an opposite manner with an ultraviolet excess at primary minimum. Mumford (1967) found EX Hya was bluest near primary minimum in April 1965, whilst observation from April 1964 showed it to
Fig. 4.1 Light curve of EX Hydrae (after Warner 1972)
be red at primary minimum.

Warner (1973) and Watson and Rayner (1974) explain the EX Hya light curves in terms of the general model for cataclysmic variables. The general model consists of a white dwarf primary surrounded by a disc of gas formed by matter transferred from the secondary which is a cool dwarf star filling its Roche lobe. A bright spot is formed on the disc at the point of impact of the stream from the secondary. This spot contributes a significant fraction of the light of the system and is responsible for the rapid flickering observed.

Adopting this model Warner (1973) suggests that the amplitude of the flickering indicates that most of the light from EX Hya reaching the observer originates from the bright spot. There are no wide eclipses in which all the flickering disappears, such as those seen in U Gem, which indicates, together with the variable nature of the eclipse, that a partial or grazing eclipse of the bright spot is observed. Warner (1973) attributes the observed variations in primary minimum to changes in the brightness, size, shape and position of this spot. Watson and Rayner (1974) argue that the eclipse depth of $\sim 0.5$ suggests that the hot spot may contribute in the region of one-third to one-half of the total visible light from the system.

Until recently the only piece of evidence to throw doubt on the completeness of this model was the lack of a sizeable bright spot hump in the light curves such as is observed in U Gem and VW Hyi. If the bright spot indeed contributes significantly to the total luminosity of EX Hya a large hump rather than a slight rise would be expected just prior to primary minimum. However an interesting discovery by Vogt et al. (1980) suggests another cause is responsible for the chaotic light curves.
67 Minute Periodicity

Vogt et al. (1980) report extensive photometric observations of EX Hya which cover more than 14 years and 143 hours of observations. They have detected an oscillation in the light curves with a period near 67 minutes. The form of this periodicity is shown in Fig. 4.2. It consists mainly of the periodic occurrence of peaks with variable shape and amplitude and sharp minima midway between the peaks. Averaged over many cycles the modulation is a sine wave with superimposed flickering which is enhanced during the light maxima. The eclipses interrupt the sine wave for a short time. The amplitude of the 67 minute cycle not only shows strong variations from cycle to cycle but the average amplitude has increased during the 14 years of the observations from ~0\textsuperscript{m}.2 in 1962 to 0\textsuperscript{m}.4.

From their observations Vogt et al. (1980) obtained the following elements for the 67 minute cycle.

\[
\text{HJD}(\text{max}) = 2437699.8904 + 0.046546447 \ E^{+5}_{67} +7
\]

with a standard deviation of \(\pm 0.0032\). This scatter is mainly due to intrinsic variations in the light curve shape and also the influence of the eclipse minima from the orbital cycle whenever they coincide with phases near the light maxima of the 67 minute cycle. This 67 minute modulation is a general property of EX Hya having remained coherent over 14 years and being recognizable in all observations which cover a long enough time interval. Only in a very few cases was it not possible to identify a maximum predicted by the ephemeris.

Prior to this, Vogt (1979) had reported the existence of a 48 hour cycle in EX Hya. Observations covering more than one cycle showed that cycles with two humps near phases 0.25 and 0.75 alternated with cycles showing minima at these phases. Observations on consecutive
Fig. 4.2 Light curve of EX Hya (after, Vogt et al. 1980) The maxima of the 67 minute cycle are indicated by the upper arrows, the eclipse minima by the lower arrows.
nights showed that the situation was always inverted after 24 hours i.e. on the first night the humps appeared in the even numbered cycles and on the second in the odd numbered cycles. The transition of the humps from even to odd cycle numbers was never seen. It is now clear that this 48 hour cycle was due to an interaction between the 67 minute modulation and the orbital cycle. Since the ratio between the two periods is very near to 15:22 similar light curves between two eclipses repeat every 15 orbital cycles which is close to 1 day. However, the corresponding hump appearance alternates between even and odd cycles on subsequent nights and only after 2 days is exactly the same configuration achieved. The combination of the variations from the two periods is obviously responsible for much of the non uniformity of the EX Hya light curves.

This 67 minute periodicity makes EX Hya unique among cataclysmic binaries. It is the only system which shows two independent coherent periodic variations with long lifetimes apart from the oscillations with periods of seconds observed in the light curves of DQ Her, AE Aqr and WZ Sge. However, short lived periods only a few percent different from the orbital periods (where known) are observed in SU UMa stars during their supermaxima (see Chapter 2). This superhump period is known, for at least one system, VW Hyi, to be maintained for 1-2 weeks after the system returns to quiescence, but during the five months that elapse until the next supermaximum no trace of the superhump periodicity is evident in the light curves. In contrast the 67 minute cycle in EX Hya is always present and its period is very different from the orbital period although it is only 2.3% larger than 3/2 of the orbital period.

The closeness of the periods in EX Hya to a 2:3 relationship may indicate that the same physical process is responsible for the superhumps in SU UMa stars as well as for the 67 minute cycle of EX Hya, with
the difference being that the periodicity of this process shows a 1:1 ratio to the orbital period in SU UMa stars but a 2:3 ratio in the case of EX Hya.

During the maximum of the 67 minute oscillation the flickering is enhanced. This has led Vogt et al. (1980) to suggest that the mass transfer is triggered with this period. The most likely trigger mechanism is non radial pulsations of the red star whose fundamental period should be of the order of 1 hour but asynchronous rotation of the red star secondary causing periodic mass transference cannot be ruled out. Papaloizou and Pringle (1980) support the theory that the 67 minute cycle is caused by a variation in the mass transfer rate with that period due to stellar pulsation and that the pulsation is excited by tidal interactions due to a favourable commensurability between orbital and pulsation periods. They show the nature of such instabilities and how they might arise. This is the same model as was suggested by Papaloizou and Pringle (1979) to explain the superhumps of SU UMa stars. It is currently the best explanation for both these phenomena.

Vogt et al. (1979) suggest that an alternative explanation for the 67 minute periodicity and the SU UMa superhumps is a magnetic rotator model. Increased accretion onto the white dwarf is triggered periodically when the white dwarfs magnetic pole faces the main particle stream from the L1 point. In EX Hya this model would involve a strongly magnetic white dwarf with a rotation period of 67 or 134 minutes. However, a lack of detectable circular or linear polarization in the V band (Krzeminski et al. 1980) together with evidence for a substantial disc (Bath et al. 1980) make this model very unlikely.
Period Changes

Until recently the orbital period of EX Hya was believed to be constant. No evidence for a changing period was found by Mumford (1967, 1968, 1969, 1970, 1975, 1976) and Pringle (1975). Only Watson and Rayner (1974) found marginal evidence for a decrease in period. All these conclusions were based however, on just a small number of cycles. Analysing their fourteen years of observations Vogt et al. (1980) found that the period of EX Hya is decreasing and obtained new elements

$$ET(\text{min}) = 2437699.94179 + 0.068233850E - 1.8 \times 10^{-13} E^2$$

where $ET(\text{min})$ is the Heliocentric Julian Date converted to Ephemeris time. EX Hya is thus the first ultrashort period cataclysmic variable for which a period change has been established. The orbital period decreases at a rate $P = -5.2 \times 10^{-12}$. It has not been demonstrated whether this period change is constant and continuous or the result of sudden jump after a time of constant period, or whether it keeps its sign or oscillates as in the case of UX UMa and RW Tri.

X-ray Observations

In 1978 interest in EX Hya was reawakened when we, Watson et al. (1978) identified it as a 'hard' X-ray (2 - 18 keV) source. We searched for 'hard' X-ray emission from 47 of the brightest dwarf novae based on Ariel V Sky Survey Instrument data. Only two dwarf novae were detected: - SS Cyg (already known) and EX Hya.

EX Hya had previously been suggested as a candidate for the Uhuru source 2U1253-28 (Warner 1972, 1973) on the basis of positional coincidence and Warner's theory that the hot spot in cataclysmic variables should emit X-rays. In the 2A and 4U catalogues, the sources
2A1251-290 and 4U1249-28 (which are almost certainly identical; Cooke et al., 1980; Forman et al., 1978) were identified with a cluster of galaxies. Using additional observations and improved positional accuracy obtained after the 2A catalogue we revised the error box, now 2A1249-289. These error boxes and the positions of EX Hya and the centre of the cluster of galaxies are shown in the paper which is included in Appendix 1. EX Hya lies within 3 arc min of the centre of the revised error box and thus is a good candidate on positional grounds. The identification was completed when we showed that the source was variable thus making the cluster of galaxies an unlikely candidate.

Subsequently 'soft' X-ray (0.15 - 3 keV) emission has been detected from EX Hya by the HEAO-A2 experiment (Cordova and Riegler, 1979). The position and variability of the source were consistent with the indenitification of EX Hya. At the same time another experiment on HEAO-1 detected a 2 - 10 keV source with the same position. X-rays were detected from EX Hya only above 0.5 keV and were variable. In less than 1.2 hours the 'soft' X-ray intensity changed by a factor of 3. No correlation with the orbital or 67 minute periods was apparent but the data is too sparse to settle the question.

Few dwarf novae have been observed as X-ray sources particularly at quiescence. EX Hydrae is the brightest source (mean flux \( \approx 1 \times 10^{-10} \) erg cm\(^{-2}\) s\(^{-1}\)) in the 'hard X-ray sky' among dwarf novae at quiescence (Watson et al., 1978). The total X-ray luminosity (0.5 - 10 keV) for EX Hya is estimated to be \( 2.4 \times 10^{32} \times (D/100 \text{ pc})^2 \) erg s\(^{-1}\) (Cordova and Riegler, 1979). The accepted model for the X-ray flux from EX Hya is the boundary layer model of Pringle and Savonije (1972) (see Chapter 2). The presence of an accretion disc together with the lack of detectable circular polarization (Krzeminski et al., 1980) and the lack of any
modulation of the X-rays with the orbital period argue against the magnetic white dwarf model developed for AM Her.

**UV Observations**

Bath et al. (1980) have recently obtained simultaneous optical and UV spectrophotometry of EX Hya at quiescence. In their ultraviolet spectra they observe lines of MgII (2800 Å), AlIII? (1850 Å), HeII (1640 Å), CIV (1550 Å), SiIV (1400 Å), CII? (1340 Å), OI? (1300 Å) and NV (1240 Å). The spectrophotometry is well fitted by the spectrum of a steady state accretion disc (see Chapter 2) with $T_e = 7.0 \pm 1.4 \times 10^4$ K and with $T_{out} < 3.7 \times 10^3$ K implying $R_{out}/R_1 > 50$. This will be discussed in more detail later.

**OUR OBSERVATIONS**

EX Hya was first observed on April 6, 1978 with the 1.5m Infrared Flux Collector on Tenerife at K(2.2 µm). This was before the Leicester Infrared photometer was modified to include an optical channel which allows simultaneous infrared and optical observations to be made. On April 22, 1979 two further cycles of EX Hya were observed, this time simultaneously at V and K. All this data is shown in Fig. 4.3. The error bars shown are derived from observations of non variable stars of similar magnitude. Each point is the difference between a 20 second integration performed in each channel.

The observations were calibrated against the standard star BS 4757 which was observed before and after each light curve. BS 4757 has the magnitudes $V = 2.94; J = 3.03, K = 3.05, (Johnson et al., 1966)$. Heliocentric and atmospheric extinction corrections were applied to all observations. The results are shown plotted by phase using the ephemeris:

$$J.D.2437699.94168 + 0.068233832P$$ (Mumford, 1976).
Fig 4.3 Light curves of EX Hydrae. The top four curves were observed in 1979. The bottom curve was observed in 1978. The error bars are derived from observations of non-variable stars of similar magnitude.
At the time of all these observations EX Hya was observed by members of the Royal Astronomical Society of New Zealand Variable Star Section to be a quiescence \((V \sim 13.2)\) (Bateson, private communication).

Attempts to measure the 1.2\(\mu\) light curve were frustrated by cloud but a colour of \(V-J = 0.7\) was obtained at phase \(\sim 0.3\) on April 24, 1979.

This year further observations of EX Hya have been obtained. The infrared magnitudes of EX Hya were measured on two nights at UKIRT. On 22 April, 1980, H, K, L magnitudes were observed and on 23 April, 1980, J, H, K magnitudes were recorded. These observations were calibrated against the standard stars (Johnson et al., 1966).

BS 4845 on April 22 which has the magnitudes
\[
V = 5.95, \quad H = 4.735, \quad K = 4.56, \quad L = 4.16
\]
and BS 5634 on April 23 which has the magnitudes
\[
V = 4.93, \quad J = 4.21, \quad H = 4.06, \quad K = 3.90.
\]

On 24 April, 1980, the J, H, K magnitudes of EX Hya and a circular variable filter wheel spectrum between 2.025 \(\mu\)m and 2.25 \(\mu\)m were obtained at the AAT using the AAT photometer/spectrometer. These observations were calibrated against the standard stars (Allen, private communication),

BS 5028 for the photometry which has the magnitudes
\[
J = 2.74, \quad H = 2.74, \quad K = 2.73
\]
and BS 5463, \(V = 3.2\) SpC1 FOV, for the spectrophotometry.

The Light Curves

The light curves at both \(V\) and \(K\) show continuous variations with no outstanding features. They do not repeat well from cycle to cycle at either wavelength but careful examination of the light curves shows that primary minimum at zero phase is always present. In addition numerous other significant features are visible but none of these repeat
from cycle to cycle. U, B, V and white light observations of other authors described earlier show a similar nature, with primary minimum always present but many other features sometimes present.

Interpretation

Our 1979 observations gave mean colours for EX Hya of $V-J = 0.7$ and $V-K = 1.5$. These colours fit well the $\frac{1}{2}$ spectrum predicted from the standard accretion disc model discussed in Chapter 2. Fig. 4.4 shows UV and optical spectrophotometry of EX Hya at quiescence by Bath et al. (1980) with our V, J and K mean points added, with 20% error bars. The solid lines are theoretical disc spectra using the standard model and varying the temperature of the outer edge of the disc. The fit of our observations to the theoretical curves is so good that it is tempting to conclude immediately that the disc dominates the emission at all wavelengths producing the observed $\frac{1}{3}$ spectrum from 1225 Å to 2.2 μm.

Before making this conclusion we must consider the possible contributions from other elements of the system to the infrared luminosity. There are two other possible sources, the secondary star which is a late type dwarf and any region around the system of gas and/or dust, if such a region exists. The spectrum of the secondary star in EX Hya has never been observed but an estimate of its spectral class and absolute magnitude can be found from Warner's (1976) relations between the orbital period and the mass and absolute magnitude of the secondary. These relations assume that the secondary is a Roche lobe filling main sequence star.

EX Hya has a binary period of 99 minutes. Warner's relations

$$\frac{M_2}{M_0} = 3.18 \times 10^{-5} P(s)$$
Fig. 4.4 Spectrum of EX Hydrae due to Bath et al. (1979) with our V, J and K mean points added.
and \[ M_{\nu} = -12.5 \log P(h) + 17.5 \]
give \( M_{\nu} \) (secondary) = 14.78 and \( M_2 = 0.19 M_\odot \). This mass implies a spectral type of M5.5V (Allen, 1973) which has the colours \( V-J = 4.45 \) and \( V-K = 5.40 \) (Johnson, 1966). Therefore considering a likely distance of \( \sim 100 \) pc, the apparent magnitudes of the secondary are \( J = 15.3 \) and \( K = 14.4 \). The observed \( K \) magnitude of the system is 11.8 so the secondary only contributes \( \sim 9\% \) of the 2.2 \( \mu \)m flux. Even if the secondary deviates slightly from the main sequence assumptions it is unlikely that it provides more than a small fraction of the 2.2 \( \mu \)m flux. The flux from the secondary could be increased by a strong reflection effect but if this was significant it would be apparent in the light curves.

The other possible source of 2.2 \( \mu \)m flux is a region of emitting material around the system. Spectroscopic and direct photographic studies of classical novae have shown the presence of ejected shells around nova systems and also that this material is ejected during outburst. Evidence for material around dwarf nova systems is sparse. Spectra of dwarf novae taken during their outbursts have failed to show evidence for any outward moving material (e.g. Walker and Chincarini, 1968) and this has often been used as evidence for the absence of any outburst-related mass ejection. Robinson (1973) found evidence for mass loss from the dwarf nova Z Cam and because of the lack of evidence for outburst related ejecta concluded that the mass ejection from Z Cam is continuous. However Warner (1974) has shown that if the material is emitted during outburst, the amount of material involved in the case of Z Cam is too small to be visible in spectra taken during outburst.

The question of material around dwarf novae systems is therefore open. At the time of our 1979 observations we concluded that a contribution at K from such circumstellar material was unlikely for two
main reasons. Material around the system would emit either a free-free spectrum or a black-body spectrum. It is possible that such a contribution could combine with the disc emission at K to produce a $\nu^{\frac{1}{2}}$ spectrum. However our 1979 observations fitted so precisely a disc spectrum that it seemed unlikely that we would have been unlucky enough to find the situation at 2.2 $\mu$m, where a large contribution from circum-system material together with a small contribution from the disc fitted exactly on the disc spectrum predicted by UV, optical and our J observations. Secondly, it is difficult to see how such a contribution could be reconciled with the observed variations in the K light curves and also a large contribution from an ionized shell of gas would be inconsistent with the observed Balmer line intensities.

As a result we concluded that the observed $\nu^{\frac{1}{2}}$ continuum was due to an optically thick accretion disc. In 1980 we have obtained three subsequent sets of colours, on one occasion out to L (3.6 $\mu$m), at UKIRT and the AAT over the space of four nights with the aim of learning more about the outer parts of the accretion disc. None of these colours fit precisely on the $\nu^{\frac{1}{2}}$ spectrum as the previous observations did and the colours and luminosity of the system are seen to vary from night to night.

The observed colours are shown in Table 4.1 together with the 1978 and 1979 observations for reference. No simultaneous V measurements are available. A report of the observations of the Variable Star Section of the Royal Astronomical Society of New Zealand for April 1980 states that EX Hya was at quiescence and that several brightenings to magnitude $V \sim 12.7$ were observed. This is normal behaviour for EX Hya and also occurred during April 1979 when the earlier observations were made.

These 1980 observations are plotted in Fig. 4.5 together with the CVF spectrum from 2 - 2.5 $\mu$m measured at the AAT on 1980 April 24/25.
<table>
<thead>
<tr>
<th>Telescope</th>
<th>Date</th>
<th>J</th>
<th>H</th>
<th>K</th>
<th>L</th>
</tr>
</thead>
<tbody>
<tr>
<td>UKIRT</td>
<td>1980 April 21/22</td>
<td>-</td>
<td>12.62 ± 0.02</td>
<td>12.21 ± 0.02</td>
<td>10.45 ± 0.46</td>
</tr>
<tr>
<td>UKIRT</td>
<td>1980 April 22/23</td>
<td>12.96 ± 0.02</td>
<td>12.54 ± 0.03</td>
<td>12.13 ± 0.02</td>
<td>-</td>
</tr>
<tr>
<td>AAT</td>
<td>1980 April 24/25</td>
<td>12.60 ± 0.01</td>
<td>12.32 ± 0.03</td>
<td>12.16 ± 0.02</td>
<td>-</td>
</tr>
<tr>
<td>IRFC Tenerife</td>
<td>1978 April 6/7</td>
<td>-</td>
<td>-</td>
<td>11.6 ± 12.2 (light curve)</td>
<td>-</td>
</tr>
<tr>
<td>IRFC Tenerife</td>
<td>1979 April 22/23</td>
<td>-</td>
<td>-</td>
<td>11.6 ± 12.2 (light curve)</td>
<td>-</td>
</tr>
<tr>
<td>IRFC Tenerife</td>
<td>1979 April 24/25</td>
<td>12.6 ± 0.1</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 4.1

Infrared Photometry of EX Hya
Fig. 4.5 1980 April Photometry and Spectrophotometry of EX Hydrae.
and our 1979 mean colours. The J, H, K points all show a decrease in flux with wavelength as expected. Since the continuum spectrum of an optically thick disc (see below) must show a Rayleigh-Jeans turndown at frequencies $\hbar \nu \ll K T_{\text{out}}$, one would expect the flux at wavelengths greater than $\sim 2.2 \, \mu m$ to decrease. However HKL photometry obtained at UKIRT on 1980 April 21/22 showed an L ($3.6 \, \mu m$) flux well above the expected level. This trend of the spectrum at long wavelengths is confirmed by higher resolution CVF spectrophotometry obtained at the AAT three nights later.

The CVF spectrophotometry also shows the detection of Brackett $\gamma$ in emission at a level better than $3 \sigma$. Graphical estimates of the flux in this line and in H$\beta$ from the observations of Bath et al. (1980) yield an approximate $B \gamma / H \beta$ line ratio of 0.03. The two observations are of course non-simultaneous and therefore comparisons carry little weight but it is interesting to note that Case B recombination theory, (Osterbrock, 1974), predicts values for this ratio in the range 0.033 to 0.028 for electron temperatures in the range 5,000 - 10,000 K. The LTE line ratio is 0.012 to 0.023 for temperatures in the range 5,000 - $5 \times 10^4$ K.

Our observations show that the infrared colours of EX Hya vary over the timescale of one day. Part of this variation is no doubt due to the fact that the 1980 measurements of EX Hya are the result of point observations taking around 2 minutes per filter rather than mean fluxes averaged over a considerable length of time as in 1979. Since the light curves of EX Hya show continual fluctuations of several tenths of a magnitude at V and K (see Fig. 4.3), over timescales of minutes, some of the changes in the fluxes observed from one night to the next are no doubt due to those light curve variations. Fig. 4.5 also shows that there is a small discrepancy ($\sim 0^m.06$) between the AAT K point and
the flux predicted in the K band ($K \sim 12^{m}.1$) by the CVF spectrum observed the same night. The CVF spectrum gives the true mean level since it represents $\sim 3$ hours of observations, while the K point represents $\sim 2$ minutes of integration, at which time the K flux was apparently slightly lower than the mean level.

At the time of all our observations EX Hya was at quiescence ($V \sim 13.2$) but the J, H, K fluxes observed vary considerably. The mean K flux from the CVF measurement is clearly lower than the mean 2.2 $\mu$m flux $K = 11.8$ observed in 1978 April and 1979 April. Similarly all the 'spot' J and K fluxes from April 1980 are less than or equal to those measured in 1978 and 1979. We therefore conclude that the infrared fluxes can vary considerably with little or no change in the optical fluxes. Such changes are entirely compatible with the idea that the optical thickness of the outer parts of the accretion disc can vary erratically perhaps in response to small changes in the accretion rate. In terms of the parameters of a standard disc (see Chapter 2) this would mean changes in $T_{\text{out}}$ and $R_{\text{out}}$. Variations in the accretion disc are probably responsible for much of the observed night to night changes in the J, H and K fluxes.

The most interesting result of our new observations is the observed shape of the continuum spectrum, with the decrease in flux with increasing wavelength seen from J to K being reversed at wavelengths longer than $\sim 2.2$ $\mu$m. In the absence of non-thermal emission, which has not so far been suspected in cataclysmic variables, this rise in flux towards longer wavelengths must indicate the presence of material at a temperature $\lesssim 1000$ K. This is far too low to be the secondary star, which is presumably undetectable at all wavelengths, being swamped by the disc (and bright spot) at short (UV, optical, near IR) wavelengths, and by this low temperature component at wavelengths $\gtrsim 2$ $\mu$m. A
circumbinary disc could possibly supply this low temperature component but a more plausible candidate is circumstellar dust, presumably originating in mass loss accompanying the accretion process.

The Low Temperature Material

To investigate the nature of this low temperature component, which is most likely to be circumstellar dust, we model the system by combining a disc contribution and a black-body low temperature contribution and adjust the relative strengths and temperatures of both components to give the best fit to the observations. The low temperature component is likely to contribute to the K flux and the size of this contribution can be found from the model.

We have very little information from our observations about the short wavelength spectrum of EX Hya (mainly in J and H) and so use of a full disc spectrum for the disc contribution, which involves a number of free parameters, is not justified. Instead a variety of fits have been performed approximating the disc component with power law spectra and a black-body spectrum.

A total of 25 data points were used for the error-weighted least-squares fits to our observations. These were the CVF points, minus the three points corresponding to BV, the L point and the H and J measurements from the same night as the CVF spectrophotometry. Computations fitting a variety of power laws as the disc spectrum together with a black-body spectrum for the low temperature component showed that the results were not strongly dependent on the power law index in the range 0.8 to 2, yielding $T_L$ (temperature representing the low temperature component) ranging from 420 K to 670 K.

Approximating the disc component with a black-body spectrum produced better fits. The function used for the fitting procedure was
of the form

$$F_\nu = \alpha_1 B_\nu(T_L) + \alpha_2 B_\nu(T_d)$$  \hspace{1cm} (1)

where $\alpha_1$ and $\alpha_2$ are constants and $T_d$ is a temperature roughly characterising the disc. The main importance of this second term is to allow a reasonable fit of the low temperature component ($T_L$).

The best fit obtained using this function and fitting all the readings described above is represented by the curve labelled 'a' in Fig. 4.5. This fit gives values of $T_L = 560 \text{ K}$, $T_d = 6600 \text{ K}$ and $\alpha_1 = 3.6 \times 10^{-17} \text{ sterad}$. The 90% confidence limits for this fit based on the standard $\chi^2$ test are $430 \text{ K} < T_L < 1200 \text{ K}$ and $5700 \text{ K} < T_d < 8000 \text{ K}$.

To take account of the likely variations in the J and H fluxes discussed earlier we artificially increased the errors on these points by a factor of ten so they were given less weight by the fitting procedure. The new best fit using a function of the form (1) is shown labelled curve 'b' in Fig. 4.5. This fit gives $T_L = 730 \text{ K}$, $T_d = 1300 \text{ K}$ and $\alpha_1 = 5.4 \times 10^{-18} \text{ sterad}$. The 90% confidence limits for this fit are $540 \text{ K} < T_L < 1750 \text{ K}$ and $T_d > 4350 \text{ K}$.

We also investigated the effect of the J, H and L points by fitting the CVF points alone. In this case the best fit of a function of the form (1) above gave $T_L = 870 \text{ K}$, $T_d = 6600 \text{ K}$ and $\alpha_1 = 1.6 \times 10^{-18} \text{ sterad}$. This fit, without the J and H points minimises the disc contribution to the CVF readings and so produces an artificially high temperature for the low-temperature component.

The temperature of the disc given by our best fits 'a' and 'b' varies considerably and should not be regarded as a determination of the outer rim temperature of this disc since it is found by essentially fitting a black-body through just two points, J and H. The calculated temperature tells us no more than that the outer disc temperature is of the order of a few thousand degrees.
If we adopt our suggestion above that the low temperature component in the continuum spectrum of EX Hya results from black-body emission from circumstellar dust we can find the size of the dust cloud. The typical size \( R \) of the dust cloud is given by

\[
\frac{R}{1 \text{AU}} \approx \left( \frac{L_{\text{bol}}}{L_\odot} \right)^{\frac{1}{2}} \left( \frac{T_{\text{rad}}}{390 \text{K}} \right)^{-2}
\]

where \( L_{\text{bol}} \) is the bolometric luminosity = \( L_\odot \) for EX Hya (Bath et al., 1980) and \( T_{\text{rad}} \) is the radiation temperature. For equilibrium we require \( T_L \approx T_{\text{rad}} \). Our two best fits, curves 'a' and 'b' of Fig. 4.5 imply \( T_{\text{rad}} = 560 \) and 730 K respectively and therefore typical sizes

\[
R = 7 \times 10^{12} \text{ cm} \quad (a)
\]
\[
R = 4 \times 10^{12} \text{ cm} \quad (b)
\]

which are much larger than the binary separation \( a = 5 \times 10^{10} \text{ cm} \).

We may check the circumstellar extinction resulting from these distributions. If the cloud consists of \( N_g \) dust grains, each of surface area \( \sigma_g \) and all radiating at the temperature \( T_L \) equating fluxes at each wavelength implies

\[
N_g \sigma_g \pi B_\nu(T) = \alpha_1 B_\nu(T)4\pi D^2
\]

where \( D \) is the distance to the system. If the cloud has an effective thickness \( \ell \) along the line of sight and effective radius \( R_1 \) orthogonal to it, the extinction \( A_\nu \) due to these grains alone is (Spitzer, 1978)

\[
A_\nu = n_g \sigma_g \ell = \frac{4 \alpha_1 D^2}{\pi R_1^2} \quad \text{(mag)}
\]

where \( n_g \) is the number density of grains. Measurements of Bath et al. (1980) give \( A_\nu < 0.12 \) so \( R_1 > 1.0 \times 10^{21} \text{ cm} \), where \( D_{100} \) is \( D \) in units of 100 pc. For curves 'a' and 'b' we find
Thus for an expected distance to EX Hya of $D \sim 100$ pc, $R_1 \sim R$ in both cases. Hence a spherical dust cloud of typical size $\sim 1$ AU and a temperature in the range $550 - 750$ K is consistent with all observations. This is the most likely explanation for the infrared excess at wavelengths $\geq 2 \mu$m. Whether this dust has a uniform geometry and density is not known. Robinson (1973) finds that the material ejected from Z Cam is in the form of polar cones.

The dust presumably originates via mass loss from the binary during the accretion process. From our observations we can estimate the mass of this dust cloud. The flux from the dust cloud at any wavelength is given by (assuming the dust cloud is optically thin)

$$F_{\nu} = \frac{N \cdot 4\pi r^2 B_{\nu}(T)}{4\pi D^2}$$

where $r$ is the radius of the dust grains. The mass of the cloud is therefore

$$\text{mass} = \frac{N \cdot 4\pi r^3 \rho}{3} = \rho r \frac{F_{\nu} \cdot 4\pi D^2}{B_{\nu}(T)}$$

where $\rho$ is the density of the dust.

Assuming radii for the dust grains $\sim 0.2 - 0.3 \mu$m and likely densities e.g. silicate we find masses $\lesssim 10^{21}$ g from our fits. This could easily be supplied in plausible time scales by mass-loss rates very small compared to the accretion rate $\sim 10^{16}$ g s$^{-1}$.

The flux from this dust shell may not be constant over long intervals of time. There are two possible causes for variations in the flux from the dust. If the mass loss from the binary system only occurs during outburst rather than continuously the mass of dust in the cloud will vary. However in this case EX Hya is an unlikely candidate since
its outbursts are so rare although mass ejection might possibly be related to the flarelike activity observed. Secondly changes in the inner disc might cause variations in the heating and therefore the temperature of the dust.

**The Disc**

If we assume the contribution of the dust cloud to the 2.2 \( \mu m \) flux is constant we can determine the percentage of the observed 2.2 \( \mu m \) flux that can be attributed to the dust emission for both the 1979 and the 1980 observations. In 1979 the observed K flux from EX Hya was considerably higher than in 1980. This is not attributable to the system as a whole being brighter since on the night in question (Bateson, private communication) the system was at quiescence with \( M_{\text{visual}} \approx 13.2 \). Also as can be seen from Fig. 4.5 on one of the nights in 1980 the J flux was observed at the same level as in 1979, but the K flux was considerably lower. Clearly variations in the infrared colours particularly at K are due to the changing state of the disc. On the night in 1980 when the J flux is high but the K flux is low it appears we are seeing a \( \sqrt{3} \) spectrum from the disc out to J as in 1979, but on this occasion the outer regions of the disc have become optically thin, so a lower flux is observed at K.

It seems that the disc spectrum observed so clearly by Bath et al. (1980) at UV and optical wavelengths extends out to 2.2 \( \mu m \) on occasion but sometimes only to H, J or possibly even shorter wavelengths. In April 1979 we were fortunate enough to observe the system when the disc was large. Taking our best fit 'a' i.e. all points with their measured error bars we find that the dust contributes 13% of the K flux on 24/25 April 1980 and 10% of the K flux from April 1979. If we consider fit 'b' where the errors on J and K were increased to account for possible
variations at J and H we find 30% of the 2.2 μm flux from 24/25 April 1980 was dust emission and 24% of the 2.2 μm flux in April 1979 was due to the dust.

The dust contribution to our 1979 K point, assuming the dust emission to be constant, is around 10 - 24%. With this dust contribution, our earlier conclusion that in 1979 we observed a \( \frac{1}{3} \) disc spectrum from EX Hya extending out to 2.2 μm is still valid since our observations still fit a disc spectrum. It is unlikely that the \( \frac{1}{3} \) disc spectrum ever extends much beyond 2.2 μm since this would force the disc to be larger than the Roche lobe of the primary (see below) but tidal effects are expected to truncate the disc at the Roche lobe (Papaloizou and Pringle, 1977; Paczynski, 1977). From our observed, 1979, disc fluxes we can calculate the size of the disc when it is extended.

Taking the standard disc model, the temperature at radius \( R \) in such a disc is

\[
T(R) = T_\ast \left( \frac{R}{R_{\text{in}}} \right)^{-\frac{1}{2}} \left( 1 - \left( \frac{R_{\text{in}}}{R} \right)^\frac{1}{2} \right)^\frac{1}{4}
\]

(see e.g. Bath et al., 1980)

where \( R_{\text{in}} \) is the inner radius of the disc and

\[
T_\ast = 4.1 \times 10^4 \; \dot{M}_1 \frac{1}{2} \frac{M_1}{10^9 \; \text{cm}} \left( \frac{R_{\text{in}}}{10^9 \; \text{cm}} \right)^{-\frac{1}{2}}
\]

Here \( \dot{M}_1 \) is the accretion rate in units of \( 10^{16} \) g/sec and \( M_1 \) the white dwarf mass in units of \( M_\odot \). For EX Hya at quiescence, \( T_\ast \) has been determined by Bath et al.'s (1980) UV observations to be \( (7.0 \pm 1.4) \times 10^4 \) K. The spectrum of the disc is (as described in Chapter 2)

\[
f_\nu = \int_{R_{\text{in}}}^{R_{\text{out}}} \pi B_\nu \{T(R)\} 2 \; \text{RdR}
\]

with \( B_\nu (T) \) the Planck function and \( R_{\text{out}} \) the outer radius of the disc. Thus one finds
\[ f_v = \frac{1}{v^3} \int_{\frac{5}{3}}^{X_{\text{out}}}{\frac{x}{e^x - 1} \, dx} \]

where \( X_{\text{in}} = \frac{hv}{kT(R_{\text{in}})} \) etc. The form of this integral is shown in Chapter 2. Thus the \( v^{\frac{1}{3}} \) law holds for frequencies \( v \) with \( kT_{\text{out}} \ll hv \ll kT_{\text{in}} \), giving way to a Wien distribution for \( hv \gg kT_{\text{out}} \), and a Rayleigh-Jeans tail for \( hv \ll kT_{\text{out}} \).

Fig. 4.4 shows the UV, optical and IR data fitted with disc spectra having \( T_e = 7 \times 10^4 \) K and three values of \( T_{\text{out}} \): \( T_{\text{out}} = 0, 2170 \) and \( 3000 \) K (the fit of these values of \( T_{\text{out}} \) is not affected by different values of \( T_e \) within the range \((7.0 \pm 1.4) \times 10^4 \) K). If we remember that the marked error bars are 20% and that 24% of the K flux may be emitted by the dust cloud we find that \( T_{\text{out}} = 2170 \) K gives a good fit. If we attribute only 10% of the K flux to the dust emission (fit 'a') we find \( T_{\text{out}} = 1450 \) K. Errors allow \( T_{\text{out}} \) to be in the range \( 0 \) (i.e. \( kT_{\text{out}} \ll hv \)) and \( \sim 3000 \) K.

Equation 1 reduces to \( T = T_e \left( \frac{R}{R_{\text{in}}} \right)^{-\frac{2}{3}} \) for \( R \gg R_{\text{in}} \). With \( T_{\text{out}} = 2170 \) K and \( T_e = 7 \times 10^4 \) K, we immediately find the disc is large, \( R_{\text{out}} = 103 R_{\text{in}} \). Assuming \( M_2 = 0.19 M_\odot \) as predicted by the mass-period relation of Warner (1976) and taking \( M_1 = 1 M_\odot \), we find (using Kepler's law) that the binary separation \( a = 5 \times 10^{10} \) cm. Thus unless \( R_{\text{in}} < 5 \times 10^8 \) cm, which corresponds to the radius of a white dwarf \( 1 M_\odot \) or higher the outer radius of the disc will be greater than the binary separation. Although it is possible for an accretion disc to be as large or larger than the binary separation and still exhibit a \( v^{\frac{1}{3}} \) spectrum since this depends only on local conditions it is extremely unlikely that a smooth \( v^{\frac{1}{3}} \) spectrum from 1225 A to 2.2 \( \mu \)m as observed would result. This is because tidal effects are expected to truncate the disc near the primary's Roche lobe (Papaloizou and Pringle, 1977; Paczynski, 1977). Even if any material further out had a \( v^{\frac{1}{3}} \) spectrum
Paczynski (1971) gives an expression for the average radius of the Roche lobe of the primary as a function of the mass ratio $q$ (mass of secondary/mass of primary) which, if the mass of the secondary is assumed fixed, means the radius is a function of the mass of the primary

$$\frac{r_L}{a} = 0.38 + 0.2 \log \left[ \frac{1}{q} \right]$$

If as suggested by our considerations above we assume $R_{out} = R_L(M_1, q)$ and that $R_{in}$ is given by the radius of a white dwarf of mass $M_1$ (e.g. Chandrasekhar, 1967) we then have a relation between $M_1$ and $q$ for any given $T_{out}$

$$R_{out} = \left( \frac{T_*}{T_{out}} \right)^{4/3} R_{in}(M_1) = R_L(M_1, q)$$

Putting in the errors on $T_*$ we then have a band of allowed values in the $M_1, q$ plane for each value of $T_{out}$. This is shown in Fig. 4.6.

With $T_{out} = 2170$ K the system must have $M_1, q$ lying between the curves labelled '$T_{out} = 2170$ K'. The curve on which the secondary mass has the minimum value 0.085 $M_\odot$ for a hydrogen burning star (Graboske and Grossman, 1971) is also shown. If the system contains a main sequence secondary it must lie to the right of the curve. If instead of $T_{out} = 2170$ K we take $T_{out} = 1450$ K, corresponding to a 10% dust contribution, the upper limit to $M_1$ given by the upper curve labelled '$T_{out} = 2170$ K' becomes instead a lower limit; the corresponding upper limit is greater than the Chandrasekhar mass. If we demand that $R_{out}$ is smaller than $R_L$ the corresponding lower limits on $M_1$ and upper limits on $q$ become tighter.

Fig. 4.6 implies a fairly high white dwarf mass (> 1.1 $M_\odot$ for $T_{out} = 2170$ K, > 1.3 $M_\odot$ for $T_{out} = 1450$ K) unless an extreme mass ratio (q < 0.01) is adopted. This is in agreement with the observational
Fig. 4.6. The relation between the white dwarf mass $M_1$ (solar masses) and ratio $q$ of secondary to primary masses in EX Hya, assuming the radius $R_{out}$ of the disc is equal to the average Roche lobe size.
estimates. Warner (1976, and references therein) gives values of

\[ M_1 > 1.07, \quad q(M_2/M_1) < 0.15 \]

while from recent spectroscopic observations Breysacher and Vogt (1980), find the mass of the white dwarf to lie in the range \( 1.38 < M_1 < 1.53 \) with the lower limit as the most probable case and a mass ratio \( q = 0.13 \pm 0.02 \).

From our estimate of \( M_1 \) we can find the distance \( D \) to the system. Bath et al. (1980) give the relation

\[ D = 650 \left( \frac{R_{\text{in}}}{10^8} \right) (\cos i)^{\frac{1}{2}} \text{ pc} \]

where \( i \) is the orbital inclination. For \( M_1 \) in the range \( 1.1 M_\odot < M_1 < 1.38 M_\odot \) we have \( 5 \times 10^8 \text{ cm} > R_{\text{in}} > 2 \times 10^8 \text{ cm} \). Assuming \( i = 70^\circ \) which is probably necessary to get the primary eclipse observed at \( V \) we find

\[ 76 < D < 190 \text{ pc} \]

If \( i \) is found to be somewhat greater than \( 70^\circ \), \( R_{\text{in}} \) would have to be larger to prevent the system's parallax from being measurable. The estimate of \( M_1 = 1.38 M_\odot \) of Breysacher and Vogt (1980) implies a distance to EX Hya of 76 pc. Comparing EX Hya with other dwarf novae our distance estimate seems reasonable.

**Variability**

Examination of both the \( V \) and \( K \) light curves shows that primary minimum at zero phase is always present. There are in addition numerous other significant features but none of these repeat from cycle to cycle. If we accept that the \( K \) emission comes from the outer regions of the disc which fills the Roche lobe of the primary, (which appears to be the case at the time we measured the light curves), this variability is understandable since one would expect the outer regions of such a disc to undergo many disruptions. Clearly tidal effects will be important
(Papaloizou and Pringle, 1977) as will the impact of the gas stream from the secondary.

**The 67 minute periodicity**

We have tested both our K and V light curves for any sign of the 67 minute periodicity discovered in the light curves of EX Hya by Vogt et al. (1980) and described earlier. The data folded on their ephemeris is shown in Fig. 4.7, where phase 1.0 corresponds to the occurrence of the maximum amplitude of the modulation. As can be seen there is some evidence for the 67 minute period in the V data but very little in the K data. This is consistent with the modulation being caused by radiation from a region rather hotter than the outer parts of the disc.

**Summary**

Our observations of EX Hya have shown that the infrared flux from the system varies reflecting a changing size and rim temperature of the optically thick accretion disc. On occasion a 2.5 disc spectrum is observed to extend out to ~ 2.2 μm, tightening Bath et al.'s limit of $T_{\text{out}} < 3700\ K$ on the temperature of the outer edge of the optically thick region of the accretion disc to $T_{\text{out}} < 3000\ K$. Both estimates are considerably lower than the theoretical limit $T_{\text{out}} > 6000\ K$ obtained by Williams (1980) from LTE calculations of the opacity in the outer regions of a model accretion disc, although this result is somewhat dependent on binary geometry and accretion rate.

Assuming that our disc with $T_{\text{out}} < 3000\ K$ fits within the Roche lobe of the primary we find a mass for the white dwarf $M_1 > 1.1 M_\odot$. The distance of the system is then found to be between 76 - 190 pc.

A low temperature component, $T = 550 - 750\ K$ is observed in the
Fig 4.7 Our K and V photometry of EX Hya folded on the ephemeris of the 67 minute periodic modulation of the light curve (Vogt et al., 1980), with maximum at phase 1.0.
spectrum at wavelengths longer than $\sim 2 \, \mu\text{m}$. All the results are consistent with this low temperature component being a circumstellar dust cloud of radius $\sim 1\text{AU}$. If the ejection of dust from the system is sporadic or the heating of the dust by radiation from the inner disc region varies greatly the estimated dust temperature and the $2.2 \, \mu\text{m}$ flux from the dust will vary. This will in turn affect our estimate of the outer temperature of the disc. Since EX Hya is rarely seen to undergo outburst it seems unlikely that the dust cloud was produced by outburst related mass ejection or that the heating of the dust varies greatly. It is more likely that the dust cloud is the result of continuous mass loss and that the heating flux from the inner disc only changes by small amounts as the result of variations in the accretion rate (except during the rare outbursts).

Two papers have been written describing these results. These are included in Appendix 1.
REFERENCES


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CHAPTER FIVE

VW HYDRI

VW Hydri is the brightest Southern Hemisphere dwarf nova averaging $M_V = 13.7$ at quiescence. It belongs to the group of ultrashort period systems having a binary period of 107 minutes. It is a confirmed member of the SU UMa subgroup undergoing both normal eruptions and the longer brighter supermaxima. As well as being one of the brightest dwarf novae, VW Hyi has a large outburst amplitude, averaging 4-5 magnitudes, together with a relatively short mean interval between eruptions. The mean interval between successive maxima of all types is 27.33 days (Bateson, 1977).

Until a few years ago our knowledge of VW Hyi was restricted to its outburst behaviour. The information available was due to extensive visual observations by members of the Royal Astronomical Society of New Zealand. Most publications on VW Hyi have concentrated on a study of, and a comparison between, the two types of maxima.

PREVIOUS OBSERVATIONS

Spectrum

Warner (1976) reports that spectra taken of VW Hyi at quiescence show very broad doubled hydrogen emission lines. Other spectra taken at quiescence by Vogt (1976) show only H$\beta$ and possibly CIII ($\lambda$4185) in emission. The continuum is very inhomogeneous showing very broad ($\sim 100$ A) depressions around the positions of the Balmer lines.

No spectra have been taken during normal outbursts but spectra have been obtained during supermaximum. These are similar to those
observed during normal maxima of other systems which implies there are no large differences in the physical properties of dwarf novae at normal maximum and supermaximum.

Vogt (1976) reports that spectra observed during supermaximum show very broad absorption lines of the Balmer series and He I (\(\lambda 4471\)). Within two days the equivalent widths of the Balmer lines decreased by about 30%. Schoembs (1979) made a detailed spectroscopic study of the October 1978 supermaximum. Three nights after the beginning of the outburst (BV = 9) the spectrum showed broad shallow H\(\alpha\) and H\(\beta\) absorption lines as expected from Vogt's results. In nine spectra taken twelve nights after the start, (BV = 13.3) the H\(\alpha\) was a doubled emission feature emerging from a shallow and even broader absorption. He I, \(\lambda 5875\), \(\lambda 5015\) and Fe II, \(\lambda 5163\), \(\lambda 5169\), \(\lambda 5316\) were also in emission. This suggested that the normal minimum spectrum had re-emerged but a series of seven spectra on the following night showed no distinct line features except weak He I \(\lambda 5875\) emission. No explanation has been given of this behaviour.

Binary Light Curve

At quiescence a hump in the light curve gives an orbital period of 106.95 minutes. This hump, the typical bright spot hump of cataclysmic variable light curves resembles that seen in U Gem but no eclipse is observed. There is no evidence for a changing period (Bailey, 1976; Vogt, 1974). The hump lasts approximately half a period beginning near phase 0.72, reaching a maximum at phase 0.0 and ending near phase 0.25 and is quite symmetrical. Between humps the light curve falls slowly to a minimum at phase 0.72 (Haefner et al., 1979). In many cycles a more or less pronounced secondary maximum is present near phase 0.5. The relative and absolute amplitude of the hump varies from day to day.
but averages around 40% relative amplitude (Schoembs, 1977) or $0.35$

$0.4$ with exceptional amplitudes of up to $0.55$ (Vogt, 1974). The

variations in the amplitude of the hump are much larger during the

first five days after maximum than at later times but there is no
correlation between the time interval to the next or previous outburst
and the amplitude of the hump (Haefner et al., 1979).

The presence of the hump is explained in terms of the bright spot
model. A small optically thick spot of high luminosity is formed on the
gas disc around the white dwarf component where the stream of material
from the secondary meets the disc. Because the whole hump lasts almost
exactly half a period the spot must be small compared to the size of
the disc (Vogt, 1974). The intermediate hump observed at mean phase

$0.5 \pm 0.05$ is most probably due to backward radiation from the same spot.

Either it can be seen sometimes through the disc, or the perpendicular
extension of the disc combined with the orbital inclination, allow the
limb of the bright spot to be observed occasionally over a quite flat
disc. This would agree with the spot model suggested by Lubow and Shu
(1976). U Gem occasionally shows a similar intermediate hump (Haefner
et al., 1979).

The light curve also shows the presence of rapid flickering. It
has an especially high amplitude during the first five days after an
eruption and is strongly colour dependent showing at U an amplitude
twice that at V. A typical quiescent light curve obtained by Warner
(1975) in white light is shown in Fig. 5.1.

The short eruptions of VW Hyi resemble those of other dwarf
novae. The hump becomes smaller as the system brightens almost or
completely disappearing near maximum light and returning during the
decline with an amplitude similar to that at minimum (Vogt, 1974;
Schoembs, 1977). The absolute intensity of the bright spot remains
Fig. 5.1 Light curve of VW Hydri (after, Warner 1975)
almost constant during the eruption. Interpreting the bright spot as energy released due to the interaction between the gas stream and disc this suggests that the rate of mass transfer does not change greatly during outburst. This appears to exclude Bath's model where outbursts are triggered by increased mass transfer from the secondary while supporting Osaki's model for the outbursts in which material is transferred from the secondary at a constant rate and collects in the disc. Outburst is then triggered by an instability in this disc.

Outburst Characteristics

VW Hyi shows two types of outburst, normal and supermaxima. The two types of maxima are exclusive. There are no intermediate cases (Vogt, 1977). 80% of the eruptions of VW Hyi are normal outbursts. Normal maxima occur every 27.3 days on average and their width, $W_n$, 2 magnitudes below maximum brightness averages 1.4 days (Vogt, 1980). They are not periodic, occurring at intervals between 8 and 50 days (Bateson, 1977). Their mean brightness is 0.8 magnitude fainter than the mean for supermaxima reaching around $M_V = 9.45$.

The supermaxima follow a linear ephemeris for 10-20 cycles and then the frequency switches randomly to another characteristic frequency for a similar length of time. Three such supermaxima periods are observed in VW Hyi (Vogt, 1980). Supermaxima occur every $179^d.35 \pm 12.1$ days on average, the characteristic frequencies varying by $\approx 18$ days. They have a width, $W_s = 12.6$ days and reach a mean magnitude of $M_V = 8.6$.

Normal Outbursts

At minimum light the magnitude and colours of VW Hyi show continuous small variations. The approximate mean colours and magnitudes are $V = 13.7 - 14.3$, $B-V = +0.1$ and $U-B = -0.9$ (Walker and Marino, 1978).

The onset of normal outburst is sudden with a rise of two magnitudes in eight hours or less. Often a dip is seen in the minimum magnitude
immediately prior to an outburst. After the star has risen 1 or 2 magnitudes a pronounced pause lasting on average 2 hours but on occasion up to more than 12 hours is observed. At times the rise ceases completely and at others it merely slows down (Walker and Marino, 1974). The second rise is steep (approximately 0.4 mag. per hour) and peak brightness is reached in little more than 24 hours from onset. The magnitude and colours at maximum are $V \sim 9.45$, $B-V \sim -0.05$ and $U-B \sim -0.55$. There is no stay at maximum, the rise gradually passing through a smooth transition into decline.

Bailey (1980) has combined all the UBV observations of normal outbursts to show the colour changes. Marino and Walker (1978) also describe them in detail. Both $B-V$ and $U-B$ become very much redder during the rise. After the pause $B-V$ becomes bluer but $U-B$ continues to redden for several hours. The system is bluest some hours after maximum and then returns quickly to normal. These colour variations can be explained in terms of the model of dwarf nova eruptions in which the outburst is due to a sudden increase in mass transfer from the secondary (Bath, 1976). In the early stages of such an outburst most of the material will be in the outer cooler disc regions giving rise to the red colours observed on the rise. This is apparently in conflict with the observations of the bright spot during outburst. It may be that it is naive to assume that there is a direct correlation between the mass transfer rate and the observed intensity of the bright spot and that the constant intensity of the bright spot does not exclude increased mass transfer as the triggering mechanism for outbursts. It may also be possible to explain the colour variations in terms of the disc instability model. Clearly a better understanding of the physics of the disc and bright spot are needed before this question can be settled.

**Supermaxima**

The supermaxima of VW Hyi show many of the same features as the normal outbursts but are brighter and flat topped. A steep rise in around one day often with a standstill at an intermediate magnitude is
followed by a period of around thirteen days at maximum. During this time the system declines slowly and this is followed by a steep fall to minimum lasting about three days. As with normal maxima a distinct decrease in minimum magnitude immediately before outburst is sometimes seen (Bateson, 1977). The colour changes show differences from those of the short eruptions. Instead of becoming bluer during the early stages of decline, supermaxima show a slow reddening. At maximum the colours are $B-V = -0.08$ and $U-B = -0.75$ (Vogt, 1974).

The amplitude of the hump which corresponds to the system's orbital motion remains constant in intensity units during the rise to supermaximum as during the short eruptions. For around twenty four hours after this no humps at all are visible while by the third night of a supermaximum, superhumps have appeared. These have developed within twenty hours (Haefner et al., 1979). Superhumps were first discovered independently by Vogt (1974) and Warner (1975). They resemble the humps seen at minimum but repeat with a distinctly different period of 110 minutes. This is 3% longer than the orbital period. Superhumps are never seen during normal outbursts but are a common feature of all supermaxima.

The superhumps appear near maximum light with an absolute amplitude around 35% (Schoembs et al., 1979). During the course of the supermaximum the amplitude of the humps decreases faster than the mean brightness of the system and they change shape from a pronounced peaked structure with a steeper rise than decline, to a flat less structural shape (Vogt, 1974). The amplitude decreases from $0.33$ to $0.08$ (Haefner et al., 1979). During the outburst the superhump period decreases but it does not reach the orbital period by the end of the outburst (Schoembs, 1977; Vogt, 1977; Schoembs, 1979). The period and rate of decrease of the period are identical within observational
errors for different supermaxima (Vogt, 1977).

Vogt (1977) observed VW Hyi for eight nights at the end of the Dec 1975 supermaximum. The system had declined almost to minimum light (0.5 to 0.6 above average minimum light). The orbital hump was present in all the light curves (Schoembs et al., 1979) but with deviations of up to 22% from the predicted position and showed an irregular and distorted shape. Vogt (1977) and Schoembs et al. (1979) suggest that a beat phenomenon between the orbital period and the superhump period was the cause of these effects. The deviation in position and shape of the hump vary systematically with beat phase. This shows that the superhumps persist for at least eight days after decline but with an amplitude too small for them to be detected in their original form. As was described in Chapter Two the best model currently for superhumps is the eccentric orbit model of Papaloizou and Pringle (1979).

Coherent Oscillations

Rapid coherent oscillations have been observed during both normal outbursts and supermaxima. Unlike the oscillations of most dwarf novae which appear at the peak of the outburst, no oscillations are observed until the system is well down the decline stage (Warner and Brickhill, 1978; Haefner et al., 1977). A wide range of periods is observed. Warner and Harwood (1973) report oscillations with a period of 28.15 seconds and a peak to peak amplitude of about 5%. They comment that VW Hyi is the first dwarf nova where the oscillations have been large enough to see without the aid of periodogram analysis. The following year Warner et al. (1974) observed oscillations with periods of 31.0 and 33.6 seconds on the decline from a supermaximum. Haefner et al. (1977) report coherent oscillations with an amplitude of 0.005
and a period that changed erratically between 86 and 90 seconds.

Warner and Brickhill (1978) describe a very interesting phenomenon. On the decline stage from outburst they observed sinusoidal oscillations with a period near 30s. The period was not constant and the amplitude of the oscillations varied considerably. Throughout the observations a remarkable (413 ± 1) second light modulation with an amplitude of 12% was seen. The 30 second oscillations reached a maximum amplitude of 5% at the peaks of the 413 second oscillation and were absent in the troughs.

Haefner et al. (1979) report the detection of a variety of other periods: 193s, 266s, 88s, 28.8s, and 35.7s from observations of several outbursts. All these oscillations have similar lifetimes. They are quite stable within one hour but change erratically in the order of a few percent in timescales of half a night. These timescales are in agreement with those observed by Warner and Brickhill (1974). No other system shows such a range of oscillation periods. The 28 second and 88 second periods have been observed simultaneously (Schoembs et al. 1979). When considering the models suggested for these oscillations (see Chapter Two) multiple periods and this large range of periods favours ideas of non radial pulsations of the white dwarf rather than the magnetic rotator model. Whether non radial pulsations can account for all these periods is not clear.

X-ray and UV observations

A HEAO-1 'soft' (0.18 - 3 keV) X-ray survey of dwarf novae during outburst (Cordova et al., 1980) failed to detect VW Hyi either during normal or supermaxima. A 'hard' (≥ 2 keV) X-ray survey of dwarf novae from Ariel V sky survey data (Watson et al., 1978) also detected no X-ray flux from VW Hyi. Schoembs (1979) reports that VW Hyi shows
no detectable linear or circular polarization at optical wavelengths.

Bath et al. (1980) have observed VW Hyi at ultraviolet wavelengths with IUE and simultaneously at the optical wavelengths while on the decline from outburst. The measured V magnitude was 12.7 compared with the usual quiescent magnitude of 13.4. At this time the optical showed that the broad Balmer absorption lines had almost vanished but the emission lines had not returned. The ultraviolet spectra showed evidence for weak emission at MgII (2800 Å) but no other lines were visible. The continuum flux was well fitted by the spectrum expected from an optically thick steady state accretion disc. (Lynden-Bell, 1969; Pringle and Rees, 1972; Shakura and Sunyaev, 1973).

OUR OBSERVATIONS

Our observations of VW Hyi were obtained at the SAAO 1.9m telescope with the Glass infrared photometer. This does not have the capability of simultaneous optical photometry. The light curves were observed at the following times.

\[ \text{K(2.2 \mu m)} \quad \text{December 5/6, 1978} \]
\[ \text{J(1.25 \mu m)} \quad \text{December 6/7, 1978}. \]

The observations together with the error bars are shown in Fig. 5.2. Each observation is the difference between a 10 sec integration performed in each channel. The error bars were estimated from similar observations of a non-varying star of approximately the same magnitude. Heliocentric and atmospheric extinction corrections have been applied.

The observations of VW Hyi were calibrated against the standard star BS1336,

\[ V = 3.34, \quad J = 1.87, \quad K = 1.32, \quad \text{(Glass, 1974)}. \]

The data are plotted by phase using the ephemeris

\[ \text{JD.2440128.0222 + 0.0742711 P} \quad \text{(Vogt, 1974)}. \]
The J and K light curves of VW Hydri. The error bars are derived from observations of a non-variable star of similar magnitude.
where 0.0 phase represents the time of maximum of the hump in the optical curves. At the time of the observations VW Hyi was at quiescence just prior to an outburst. The outburst was recorded by the Variable Star Section of the Royal Astronomical Society of New Zealand as a normal outburst beginning on 8/9 December, 1978 (Bateson, private communication).

The Light Curves

Fig. 5.3 shows our light curves binned over 5 points to reduce intrinsic flickering and instrumental noise and thus show the orbital variations more clearly. Error bars are marked on each point. The curve through these points is the raw data after smoothing by the computer program described in Chapter 3 with a full width half maximum of the Gaussian of 9 points. The errors on these curves are ± 0.03 at J and ± 0.04 at K.

At optical wavelengths the light curves are dominated by a hump lasting half a period attributed to the bright spot. In the infrared curves this hump is small at J (0.20) and smaller still at K (0.10) indicating that the bright spot contributes a much smaller fraction of the infrared light of the system. Both curves show evidence of a secondary hump around phase 0.4 of amplitude 0.1 at J and 0.07 at K.

Interpretation

The SAAO infrared photometer used for these observations does not have the facility to make simultaneous optical/infrared observations. Visual magnitudes measured by the Royal Astronomical Society of New Zealand Variable Star Observers (Bateson, 1979, private communication) were instead used as estimates of the V magnitude of the system at the time of our observations. Their observations give V = 13.45 on Dec 5
Fig 5.3 The J and K observations of VW Hydri binned to reduce instrumental noise and intrinsic flickering. The curve is the result of smoothing the data using the method described in Chapter 3.
and $V = 13.6$ on Dec 6. Using this data we find $V-J = 1.1$, $V-K = 1.85$ and thus $J-K = 0.75$. On Dec 5 a point measurement was made of the $J$ magnitude of the system in addition to the observations of the $K$ light curve. Our observations alone give $J-K = 0.90$ which is in agreement with the $J-K$ colour obtained for our two light curves which were measured on separate nights. Clearly we cannot rely too heavily on colour indices involving $V$.

$J-K = 0.9$ is the colour expected from a $\frac{1}{2}$ accretion disc. This suggests that we have the same situation in VW Hyi as we observed on one occasion in EX Hya. The period of VW Hyi at 107 minutes is very close to that of EX Hya (98 minutes). It seems likely therefore that our observations of VW Hyi caught the system in the same state as we observed in EX Hya in April 1979, i.e. the light was dominated by a $\frac{1}{2}$ disc spectrum extending out to about $K$ before turning down. Many of the arguments of the previous chapter therefore apply to VW Hyi.

We can again rule out any contribution from the secondary to our $J$ and $K$ fluxes. From the mass-period relation and absolute magnitude-period relation derived for the secondary by Warner (1976), we find that the secondary in VW Hyi has a mass $M_2 = 0.20 M_\odot$ and absolute magnitude $M_V$ (secondary) = 14.36. The mass implies a spectral type of M5 (Allen 1973) leading to $V-J = 4.28$ and $V-K = 5.17$ (Johnson, 1966). Thus for a likely distance of $\sim 100$ parsecs, the apparent magnitudes of the secondary are $J = 15.08$ and $K = 14.19$. The $K$ magnitude of VW Hyi is 11.6 so the secondary only contributes $\sim 6\%$ of the 2.2 $\mu m$ flux.

The question of a contribution from a cloud of material around the system is more difficult to answer. The only infrared observations of VW Hyi are this one set from December 1978. No other infrared observations of VW Hyi have been published. In view of our recent results on EX Hya it would obviously be very interesting to make further
observations of VW Hyi, in particular to extend the wavelengths covered out to L. It seems reasonable to assume that further J and K colours would be likely to show variations in the spectrum just as with EX Hya, indicating a changing size (and therefore outer temperature) to the disc. Any contribution from a cloud around the system, as in EX Hya, should show up clearly at L. We cannot state definitely whether there is a contribution from such material at K in our observed fluxes or estimate the size of such a contribution. We would have been unlucky to observe VW Hyi in the condition where a large contribution at K from the cloud, which would not contribute to the J flux, together with a small contribution from the disc at K, which contributes all the J flux, gave precisely \( \frac{1}{3} \) colours between J and K. In EX Hya, when the disc spectrum was observed out to K, the contribution from the dust to the K flux was \( \frac{5}{3} \times 24\% \).

It seems probable therefore that the observed fluxes represent an accretion disc spectrum extending out to about 2.2 \( \mu \)m, with possibly a small contribution from the dust at K. Unless the accretion rate is considerably less than in EX Hya, the disc spectrum can never extend much beyond 2.2 \( \mu \)m, since this would require the accretion disc to be larger than the Roche lobe of the primary and tidal effects are expected to truncate the disc at the radius of the primary's Roche lobe (Papaloizou and Pringle, 1977). Even if the spectrum of any material outside the Roche lobe has the \( \frac{1}{3} \) form it would not be expected to fit on the disc's \( \frac{1}{3} \) spectrum.

In considering the disc in VW Hyi the bright spot which is such an important contributor to the V light of the system must not be forgotten. Our light curves show that the bright spot hump becomes progressively weaker at J and K. The near absence of the hump in the infrared curves is at first sight somewhat surprising in view of the fact that it contributes about half of the flux at V (Warner, 1976). Spectrophotometry by Bath et al. (1980) at optical and UV wavelengths shows no evidence for a bright spot but this is not surprising since
those observations were obtained on the decline from outburst, when the disc dominates the system's luminosity (Vogt, 1974). Accepting however, that the hump is due to the anisotropic part of the radiation from an optically thick hot spot, the diminished size of the spot at J and K can be simply explained. The ratio of the fluxes from the spot and disc will vary as $\sqrt{2/\sqrt{2}} = \sqrt{3}$. Thus if the anisotropic part of the bright spot light is comparable to that of the disc at 0.55 $\mu$m (Warner, 1976) it will produce only one quarter of the disc's light at 1.25 $\mu$m and one tenth at 2.2 $\mu$m. The maximum amplitude of the hump should then be $0.25\,''$ at J and $0.1\,''$ at K which is consistent with our observations.

As the UV and optical spectrophotometry of Bath et al. (1980) was performed while the system was declining from outburst we cannot use their results to enable us to calculate the size of the disc from our observations which were obtained at quiescence. In particular we cannot carry over their estimate of $T_e > 1.6 \times 10^5$ K as this depends directly on the accretion rate which was presumably higher during their observations than at the time of the infrared measurements at quiescence. However the general similarity in period and infrared light curves between VW Hyi and EX Hya together with the excellent agreement of the J-K colour with that expected for an optically thick accretion disc, strongly suggests that in VW Hyi the disc is also large. Bath et al.'s (1980) estimate of $R_{out}/R_{in} > 90$, using only data out to 7500 Å, already puts $R_{out}$ (near outburst) close to the Roche lobe even for the smallest values of $R_{in}$.

Clearly this is a system whose further observations on a larger telescope will be of great interest. At quiescence infrared colours extending out to L and 2 - 2.5 $\mu$m spectrophotometry would show if there is a dust shell around VW Hyi as with EX Hya. Alternatively if no
shell is apparent such observations would allow us to study the turn
down in the disc spectrum. If such observations were coupled with
UV and optical spectrophotometry at quiescence we would be able to
estimate the size of the disc and calculate the distance to the system.
In addition infrared and optical observations during outburst would
give information about changes in the disc during the course of an
eruption. As VW Hyi shows frequent outbursts of large amplitude it
is an ideal candidate for such a study, since the outburst observations
could be made from a moderate size telescope where time is available to
sit and wait for such occurrences to occur.

Our results on VW Hyi have been published. A copy is included
in Appendix 1.
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J.R. Hind discovered U Gem in 1855. It was the first dwarf nova to be discovered and has continued to be regarded as a representative one. Kraft (1962) found U Gem to be a short period spectroscopic binary and Krzeminski (1964) observed that it was also an eclipsing binary, the period being 4 hr 15 min. U Gem undergoes outbursts of some four to five magnitudes with a period between outbursts of approximately 105 days, (Stauffer et al., 1979). The outbursts comprise an abrupt rise to maximum and a brief stay, followed by a rapid decline so that most of the time the star flickers near its minimum visual magnitude of about 14.0 (Mumford, 1964) with eclipses down to 15.0. Two types of outburst, long and short, are observed. The long outbursts are usually half a magnitude or more brighter than the short. All outbursts observed show steep rises. No anomalous maxima like those of SS Cyg have been observed (Glasby, 1970). Interest in U Gem has recently been reawakened by the discovery that it is both a 'hard' and 'soft' X-ray source.

PREVIOUS WORK

Spectrum

Kraft's (1962) observations of U Gem showed that the visible spectrum at minimum light consists primarily of broad bright Balmer lines and CaII (H-K) lines superimposed on a continuous background. The lines are conspicuously doubled indicating that they must originate in the gaseous disc surrounding the primary component (Smak, 1971). Feebler
emission of the triplet He I lines is also present and occasionally weak He II and Fe II emission lines are seen (Warner, 1976). At outburst bright H and He II emission is observed on a continuous background (Joy, 1960).

The separation of the emission lines corresponds to a rotational velocity of the disc of $V_{\text{d}sini} = 580$ km/s and the amplitude of the radial velocity variations is $K_1 = 265$ km/sec (Kraft, 1962). The radial velocity curves, phased with the photometric period, show that the blue star is eclipsed at primary minimum. An S-wave emission line component from the spot forms blends with the doubled lines from the disc. This results in complex profiles which show definite variations with phase. Smak (1976) states that his spectra show evidence that the S-wave component originates in the stream rather than in the bright spot, since it is visible when the bright spot is totally obscured. The narrowness of the S-wave component indicates, since the velocity of the stream increases steeply with decreasing distance to the primary, that the emitting region in the stream is small. The most obvious explanation for this S-wave region is that, due to radiation from the bright spot, an ionization front is formed in the stream. Because of this component, disc rotational velocities and radial velocities obtained from the emission lines are unreliable.

In spite of the complications from the very strong S-wave contribution attempts have been made to estimate the masses of the components from spectral line measurements. Using their methods described in Chapter Two, Robinson (1976) obtained values of $M_1 = 0.92 M_\odot$ and $M_2 = 0.53 M_\odot$, while Warner (1976) calculated $M_1 = 0.35 M_\odot$ and $M_2 = 0.53 M_\odot$. Smak (1976) obtained a new series of about sixty spectra and using only lines apparently free from blending obtained new disc and radial velocities of $V_{\text{d}sini} = 530$ km/sec and $K_1 = 143$ km/sec. These
allowed him to calculate masses of $M_1 = 0.9 M_\odot$ and $M_2 = 0.35 M_\odot$ with estimated errors of around 30%. In view of the wide spread in the above values all these numbers should be treated with caution.

No lines belonging directly to either star were seen in the spectrum of U Gem until Wade (1977) announced the detection of the secondary. Only a few secondary stars in cataclysmic variables with $P > 6$ hrs had previously been detected, probably because, while the secondaries are most easily observed in the red, the available detectors (photographic plates) were sensitive mainly in the blue. Modern red sensitive image tube spectrographs have made the task of detecting further secondaries possible.

Two papers have been published describing the spectrum of the secondary in U Gem. Stauffer et al. (1979) report that it is immediately apparent that the secondary is an M dwarf. The spectrum shows moderately strong CaH ($\lambda 6385$ Å), a feature sensitive to the star's surface gravity (strong in dwarfs and weak in giants) and at least three TiO bands. They assign a spectral type to the secondary of M4.5 with an error of about half a spectral class. Wade (1979) finds that the secondary lies slightly above the main sequence i.e. it is slightly less dense than a main sequence star of the same colour index and gives it a spectral type of M4.5 or M5. From his results he obtains a distance to U Gem of 76 ± 24 p.c.

**Light Curve**

Eclipses in the light curve of U Gem were first detected by Krzeminski (1964) who found a period of 4 hrs 14.745 min. Since then there have been conflicting views as to whether this period is constant or changing. Mumford (1968, 1970, 1976), Smak (1969), and Warner and Nather (1971) all find evidence for a small increase in the period.
Smak (1972), claims evidence for an alternating period change while
Pringle (1975), who compiled the available data on U Gem and analysed
them in accordance with a procedure to test the statistical significance
of a quadratic term in the light elements, concludes that the evidence
for a period change is not strong. Later Arnold et al. (1976)
applied similar techniques to the data on U Gem, including times of
minima subsequent to Pringle's study, and they found that the period of
the system was increasing. Clearly more data is needed for this matter
to be resolved.

The early light curves of U Gem were published by Mumford (1964),
Krzeminski (1965) and Paczynski (1965) at U, B and V. They all show a
characteristic shoulder lasting half the period from phase 0.6 to 0.1P
that is eclipsed during primary minimum producing a deep eclipse. This
shoulder, attributed to the bright spot, is symmetrical around phase
0.85P (omitting the eclipse). The primary minimum is flat bottomed with
a short ingress and steeper egress. No secondary minimum is visible.
The light curves reveal rapid irregular fluctuations with amplitudes of
a few hundredths of a magnitude and duration of a few minutes. Colour
variations are also seen. The B-V curve is the same as the V curve but
of smaller amplitude, whilst the U-B curve is its mirror image. A UV
excess of about 0.2 magnitude is seen during eclipse (this is similar
to that observed in UX UMa and RW Tri).

Both Krzeminski (1965) and Paczynski (1965) observed U Gem during
outburst. The eclipses retain their shape but become shallower on the
rise to maximum disappearing completely at maximum and returning as the
system fades. As the brightness increases the eclipses occur earlier
than predicted. The intensity of the light contributing to the shoulder
remains constant within a factor of two during eruption. On the rise
and during maximum Krzeminski looked for polarization of the source but
found none. The eclipse widths were found to vary both with colour and the cycle of nova activity. The eclipses are wider in the UV than in B or V and wider immediately after an outburst. At maximum they extend 0.11P and then exponentially diminish to about 0.05P before the next eruption starts.

Warner and Nather (1971) obtained high speed photometric curves of U Gem in white light. A typical light curve is shown in Fig. 6.1. As well as the basic features seen by the other observers, these curves showed clearly rapid flickering with time scales of seconds to minutes and amplitudes from 0.01 to 0.3. The flickering is largest on the hump in the light curve clearly associating it with the bright spot. This flickering disappears at the beginning of the eclipse and reappears after eclipse showing that the bright spot is totally eclipsed.

The Model

On the basis of his photometric data and Kraft's spectroscopic results, Krzeminski (1965) proposed a model for U Gem in which the secondary star was the seat of the outbursts. The eruptions were attributed to rapid, initially asymmetrical expansion of the secondary accompanied by an increase in its surface brightness. Krzeminski's ideas were based on the standard model. The secondary star overflows its Roche lobe and material from the inner Lagrangian point forms a disc around the primary. In their model of UX UMa, Walker and Herbig (1954) introduced a bright spot fixed with respect to the line of centres of the two stars, to account for the photometric hump seen in the light curves and the observed variations in the emission line intensities. Krzeminski assumed that this spot formed on the surface of the primary. The flat bottomed primary minimum was interpreted as a total eclipse of the primary and spot by the secondary star, with part of the light
Fig. 6.1 Light curve of U Geminorum around a complete binary cycle. The abscissa marks are every 200s. Phase is also indicated. (after, Warner and Nather, 1971)
loss being due to a partial eclipse of the disc. Since his observations just prior to maximum indicated, if the eclipses were total, that while U Gem as a whole brightened by a factor of 100 the eclipsed object brightened only by a factor of three, Krzeminski had then to attribute the outburst to the secondary star.

A revised model for U Gem was proposed by Warner and Nather (1971) and independently by Smak (1971). This has become the standard model for cataclysmic variables. The major difference is that the new model places the bright spot on the outer edge of the disc. Warner and Nather (1971) base this on the geometry of the eclipse. Smak (1971), cites evidence from the emission lines, that the density of the disc must be such that the stream from $L_1$ could not pass collisionlessly through the disc and so the spot must form on the outer edge. Primary minimum is then due to a total eclipse of the bright spot and a partial eclipse of the disc. The observations of Warner and Nather (1971) of the disappearance of the rapid flickering during primary minimum indicate that the spot must be totally eclipsed.

From the geometry of the eclipses and the spectra of the system both authors find $i \sim 64^\circ-65^\circ$, and therefore conclude that the primary is not eclipsed. This then leaves the primary/inner disc region free to be the seat of the eruptions. From a theoretical point of view this explanation was more satisfactory, since it was easy to see how accretion onto the degenerate primary might cause the outbursts but in contrast, difficult to understand Krzeminski's model for outbursts in the secondary. In particular it was difficult to see why the variations in the radius of the secondary should be asymmetrical and how they could be so large, without producing considerable variations in the mass transfer rate which would change the luminosity of the spot.

Krzeminski's observations during the outburst of U Gem show that
the height of the hump (in intensity units) and hence the intensity of
the bright spot stay constant throughout an outburst. This is in
keeping with the new model since the energy in the bright spot derives
from the mass transfer and so should not be affected by a brightening
of the centre of the disc. The observed variations in the disc with the
cycle of nova activity are also explained if the eruption occurs in the
primary/inner disc region. The eclipses in U Gem are longest
immediately after an outburst gradually becoming shorter until the next
outburst occurs. During the interval between 20 and 80 days after the
last outburst the brightness of the system at primary minimum steadily
decreases. Both these effects are understandable terms of an eruption
at the centre of the disc causing expansion and brightening of the disc
which then gradually returns to its original state.

X-ray Observations

U Geminorum has been detected as both a 'hard' and a 'soft' X-ray
source during optical outbursts but never during optical quiescence.
Mason et al. (1978) and Cordova et al. (1980) detected U Gem in 'soft'
(0.15-0.5 keV and 0.18-0.43 keV respectively) X-rays during optical
outburst. They report that the source is variable on a timescale of
hours. Mason et al. (1978) state that no 'soft' X-ray emission was
detected prior to optical outburst to a level a factor of 100 below the
maximum flux seen, $3.2 \times 10^{-10}$ ergs cm$^{-2}$ s$^{-1}$. Swank et al. (1978)
detected U Gem in 'hard' X-rays (2-10 keV) during the same outburst
observed by Mason et al., with an intensity 4% of the 'soft' X-ray
intensity giving $2.4 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$. Again the source was
observed to be variable.

No oscillations have been observed at optical wavelengths during
the outburst of U Gem, unlike many other dwarf novae. However, Cordova
(1979) reports pulsations in the 'soft' X-ray flux observed from U Gem during outburst. These oscillations resemble the quasi periodic (rather than the coherent oscillations as in SS Cyg) oscillations seen at optical wavelengths from 6 dwarf novae (see Chapter 2) and possibly originate in the boundary layer which is thought to be the origin of the X-ray emission.

OUR OBSERVATIONS

Our observations of U Gem were made at Tenerife with the Leicester infrared-optical photometer (see Chapter 3). The light curves could not be completed in one night and were observed on the following nights.

K(2.2 μm) and simultaneous V; April 25/26 and April 29/30 1979.
J(1.25μm) and simultaneous V; April 26/27 and April/May 30/1 1979.

The breaks where a change of night occur in the observations are shown clearly by the gaps in the light curves in Fig. 6.2 and Fig. 6.3. The magnitudes of U Gem were consistent at all wavelengths on the nights in question. During the period of the observations the star was at normal minimum (Howarth, private communication). The last recorded maximum (by the British Astronomical Association) prior to these observations was a 'long' outburst centred on March 26, 1979.

The observation of U Gem were calibrated against the standard star BS 3249 which has the magnitudes

V = 3.53, J = 1.09, K = 0.16 (Johnson et al., 1966).

Each point is the difference between a 20 sec integration performed in each channel. The errors shown in Figs. 6.2 and 6.3 were estimated from similar observations of a non varying star of approximately the same magnitude. Heliocentric and atmospheric extinction corrections were applied to the readings but since the standard was measured only at the beginning and the end of each run, drifts of up to 0.1 in the
Fig 6.2 Simultaneous J and V light curves of U Geminorum.
Fig 6.3 Simultaneous K and V light curves of U Geminorum.
absolute photometry are not ruled out.

The data is shown plotted by phase using the ephemeris
JD.2437638.82645 + 0.17690617P (Arnold et al., 1976).

The Light Curves

There have been extensive optical observations of U Gem by a number of authors. These light curves have been described earlier in this chapter. Our V curves shown in Figs. 6.2 and 6.3 agree with previous results, the system being at quiescence at the time of observation with a maximum brightness $V = 14.0$ and a minimum $V \approx 15.0$. In contrast the infrared curves are approximately sinusoidal with total amplitudes $\Delta J = 0.33$ and $\Delta K = 0.30$. The infrared light curves are shown more clearly in Fig. 6.4. Here each point is the mean of five 20 sec integrations thus reducing the effects of instrumental noise and intrinsic flickering. The error bars are shown marked on each data point. The curves through these points are the original data after smoothing by the procedure described in Chapter 3, with a full width half maximum of the Gaussian of 17 points. The errors on these curves are $\sim 0.03$ at both J and K.

Interpretation

U Gem shows a large infrared excess with maximum brightnesses $V = 13.75$, $J = 11.75$, $K = 10.65$. Spectrophotometric observations of Wade (1979) and Stauffer et al. (1979) found that the secondary is of spectral type M4.5 and lies near the main sequence. Since they observe that this secondary is already prominent in the system's spectrum at 0.9 $\mu$m and a M4.5 star has colours of $V-J = 4.0$, $V-K = 5.0$, our large infrared excess is readily explained by light from this star. We therefore conclude that at J and K, light from the secondary dominates
Fig 6.4 The J and K observations from Figs 6.2 and 6.3 binned to reduce instrumental noise and intrinsic flickering. The curve is the result of smoothing the data using the method described in Chapter 3.
and provides the infrared excess of the system.

This conclusion is supported by simple estimates of the possible contribution of the accretion disc and bright spot in the infrared. At optical wavelengths the disc cannot be brighter than the residual flux at primary minimum. Thus \( V \ (\text{disc}) \geq 15.0 \). Taking the disc to have a \( \nu^{\frac{1}{2}} \) spectrum (see Chapter 2), the greatest flux at J and K will be emitted if this spectrum extends out to K and does not turn down beforehand. In this case the disc has the colours, \( J \ (\text{disc}) \geq 14.1 \) and \( K \ (\text{disc}) \geq 13.55 \) and therefore contributes only a very small fraction of the infrared luminosity of the system. Similarly, as the bright spot is expected to be optically thick and have approximately Rayleigh-Jeans colours between V and K, we find \( J \ (\text{spot}) \geq 14.0 \) and \( K \ (\text{spot}) \geq 14.0 \). Since these radiation sources contribute at most a few percent of the J and K light, eclipses of the bright spot or disc, or the spot's anisotropic radiation pattern cannot provide the variations of \( 0^m.33 \) and \( 0^m.30 \) in the J and K curves. Therefore the conclusion must be that the secondary is responsible for the shape of the light curves.

The sinusoidal shape of these curves, with equal depth minima at phase 0.0 and 0.5 together with the almost constant J-K colour throughout the binary cycle, strongly suggest that the shape of the light curves is due to ellipsoidal variations of the secondary, together with the effects of gravity and limb darkening. One might therefore hope, given an accurate orbital solution, to extract considerable information about these effects in late type stars at infrared wavelengths, using a Roche lobe model for the secondary. Before a precise determination of these effects can be made, improved light curves using a larger telescope and following the system for many binary periods to smooth out changes from cycle to cycle are needed, together with a better orbital solution than is available at present. However using
our observations and current orbital parameters we can calculate a first approximation to the ratio of the photometric to geometric elipticity at J and K for the secondary in U Gem.

Merill (1970) has shown that the intrinsic light variations of a distorted star, considering the Roche model, can be described by a series of Fourier coefficients.

\[ L = A_0 + A_1 \cos \theta + A_2 \cos^2 \theta + A_3 \cos^3 \theta + A_4 \cos^4 \theta \]

where \( \theta \) is the phase angle

Maximum light occurs when \( \theta = 90^\circ \) and minimum light when \( \theta = 0^\circ \).

We therefore have

\[ L_{\text{max}} = A_0 - A_2 + A_4 \]

\[ L_{\text{min}} = A_0 + A_1 + A_2 + A_3 + A_4 \]

The difference between maximum and minimum light of our curves is then given by

\[ L_{\text{max}} - L_{\text{min}} = -A_1 - 2A_2 - A_3 \]

The form of coefficients \( A_1, A_2 \) and \( A_3 \) are tabulated by Binnendijk (1974),

\[ A_1 = \frac{-15}{32} \frac{x}{(2+y_5^3)} \frac{r^4_{\Delta_3}}{q} \left(5 \sin^2 i - 4 \sin i\right) \]

\[ A_2 = \frac{-3}{20} \frac{(15+x)}{(3-x)} \left(1+y_5^2\right) \frac{r^3_{\Delta_2}}{q} \sin^2 i \]

\[ + \frac{15}{64} \frac{(1-x)}{(3-x)} \left(3+y_5^4\right) \frac{r^5_{\Delta_4}}{q} \left(7 \sin^2 i - 6 \sin^2 i\right) \]

\[ A_3 = \frac{-25}{32} \frac{x}{(2+y_5^3)} \frac{r^4_{\Delta_3}}{q} \sin^3 i \]

where \( x \) = limb darkening coefficient

\( y \) = gravity darkening coefficient

\( q = M_2/M_1 \) = mass secondary/mass primary

\( i \) = angle of inclination

\( r \) = radius of spherical star of same volume as the Roche lobe of the secondary in units of the separation of the
components a.

$\delta_2, \delta_3, \delta_4$ and $\Delta_2, \Delta_3, \Delta_4$ are structure parameters (see Binnendijk, 1974).

To a first approximation we can discard the coefficients $A_1$ and $A_3$. Binnendijk (1974) tabulates the values of the coefficients for various models and when $N$ is large ($N$ increases as spectral type of the star becomes later and so for the M4.5 secondary in U Gem it will be large) $A_1$ and $A_3$ are very much smaller than $A_2$. The second term in $A_2$ can also be discarded since it is much less than the first term in our case. There are two reasons for this. Firstly it involves $r^5$ rather than $r^3$ and $r < 0.5$. Secondly tables in Binnendijk (1974) show that we would expect $x \approx 1$ and thus the $(1-x)$ term will be very small.

We therefore have to expect a reasonable approximation (20-25% errors)

$$L_{\text{max}} = \frac{3}{10} \frac{(15+y)(1+y^2)}{(3-x)} \frac{r^3 \Delta_2 \sin^2 \iota}{q}$$

Binnendijk (1974) shows that for a Roche model $\delta_2 = 1$ and $\Delta_2 = 1$ ($\Delta_2 = 0.9277$ for convective model).

Taking $L_{\text{max}}$ as the unit of light we then have

$$\frac{3}{10} \frac{(15+y)(1+y)}{(3-x)} \frac{r^3 \sin^2 \iota}{q} = (1-10^{-0.4m})$$

$N$ the ratio of the photometric ellipticity to the geometric ellipticity

$$= \frac{15+x}{15-5x} (1+y)$$

And therefore

$$\frac{3}{2} \frac{Nr^3 \sin^2 \iota}{q} = (1-10^{-0.4m})$$

Smaks (1976) analysis of the spectrometric and photometric data on U Gem gives the most recent determination of the orbital parameters. He finds that the mass ratio $q = 0.43$. Paczynski (1971) has shown that for $q < 0.5$
\[ r = 0.462 \frac{q^2}{(1+q)^\frac{1}{2}} \]
substituting this in the above equation we have

\[ 0.1479 \frac{N \sin^2 i}{(1+q)} = (1 - 10^{-0.4 \Delta m}) \]

To find \( N \) we need to know \( \Delta m \), \( i \) and \( q \). As mentioned earlier our present values of \( \Delta m \) are rather uncertain as are current values for \( i \) and \( q \). The most recent, published values of \( i \) and \( q \) (Smak, 1976) are \( i = 67^\circ \), \( q = 0.43 \) with estimated errors of 30% in the masses used to determine \( q \) and 10% errors in \( i \). His values of \( q \) and \( i \) together with our light curves give \( N_{1.2} \sim 2.99 \) and \( N_{2.2} \sim 2.75 \) for the secondary in U Gem.

A more accurate determination of the component masses in U Gem should shortly be available. A recent report (Annual Report of the Director of the Hale Observatories, 1978-1979) states that Wade, who first detected the secondary in U Gem, has found strong evidence of radial velocity variations in the Na absorption doublet at \( \lambda 8183 \) and \( \lambda 8195 \) Å at the orbital frequency and orbital phase for the M5 type secondary. The report gives a tentative value for the radial velocity semiamplitude of \( K_2 = 290 \) km s\(^{-1}\) but this is subject to refinement when all the data is analysed. These observations will allow a good determination of the component masses which together with further infrared observations will lead to reliable values of \( N_{1.2} \) and \( N_{2.2} \). The determination of these values will be of interest to those studying stellar atmospheres and U Gem serves to show the potential of infrared observations of cataclysmic variables in the study of limb darkening and gravity darkening in very late type stars.

From our observations we can determine the distance of U Gem. If we assume that the secondary is an M4.5V star then its absolute magnitude \( M_V \) is 11.52 (Allen, 1973). Johnson (1966) gives the colours of an
M4.5V star as V-K = 5.02 and so we find $M_K = 6.50$. The mean K colour of the system from our observations is 10.85.

Now

$$M_K = m_K + 5 - 5 \log D_{pc}$$

therefore

$$D = 74 \text{ pc}$$

Wade (1979) finds that the secondary lies slightly below the main sequence on the mean density-colour plane. Our J-K colour, J-K = 1.0, is more appropriate to a red giant (M4.5III) than a main sequence star. The environment of the secondary may alter its atmosphere so that the colour and mean density of the secondary are not consistent with main sequence membership without requiring the interior structure of the star to be evolved. Inevitably there are problems in comparing a component of a close binary system with individual stars. Our distance estimate which assumes the secondary to have the same absolute magnitude as a main sequence star of spectral type M4.5 will therefore be in error. Despite this our value of 74 pc agrees well with Wade's estimate of $76^{+36}_{-24}$ pc which allows for the fact that the secondary lies slightly off the main sequence.

A paper discussing our observations of U Gem has been written and a copy is included in Appendix 1.
REFERENCES


Merrill, J.E. (1970), Vistas in Astronomy 12, 43.


CHAPTER SEVEN

UX URSAE MAJORIS

UX UMa is an eclipsing nova-like variable with an average brightness $V \approx 12.8$. Variability of UX UMa was discovered by Beljawski (1933) on Simeiz plates. Its period was established by the visual observations of Zverev and Kukarkin (1937) who found it had the shortest period known at that time, 4 hr 43 min.

PREVIOUS OBSERVATIONS

Spectrum

The spectrum of UX UMa was first observed by Kuiper (1941) who classified it as a B3 subdwarf due to the presence of broad shallow absorption lines of H and HeI in the spectrum. Later spectroscopic observations by Struve (1948) confirmed the presence of absorption lines and in addition showed $\text{H}\beta$ in emission. He also observed that there were marked differences in the spectrum at different orbital aspects. Linnell (1949) described Struve's spectra as showing strong hydrogen absorption lines before eclipse while after eclipse (until phase 0.35) the spectrum appeared continuous except for weak emission at $\text{H}\beta$.

Walker and Herbig (1954) carried out an extensive spectroscopic study of UX UMa. They describe the spectrum as having the continuum spectrum of a rather weak blue star with broad very shallow absorption lines of $\text{H}\gamma$, $\text{H}\delta$ and $\text{H}\epsilon$ present throughout most of the cycle, except for a short time after maximum light when they are very weak or absent. In addition they observed rather weak $\text{H}\beta$ emission of variable intensity for most of the cycle but the strongest and most nearly permanent line
feature of their spectra was He II λ4685 in emission. Reproductions of Struve's spectra (Linnell, 1949) show that λ4685 was not present in 1948 which suggests that a change in the spectrum occurred between the two observations. A recent description of the spectrum, (Warner, 1976), implies that both the absorption and emission lines are still present.

The variations in the spectrum with eclipse cycle observed by Walker and Herbig (1954) were similar to the results of Struve. The major changes occurred just following minimum light. The wide shallow absorption lines which were visible for most of the cycle disappeared or became very weak following primary minimum. Similarly, the narrow H absorption lines of high quantum number (H8 and higher) seen in about half the cycles observed by Walker and Herbig, disappeared after primary minimum. H3 emission showed no obvious variations with orbital cycle except for a tendency to be stronger between phases 0.4 and 0.7 than near minimum light. Only the emission line of He II λ4685, not seen by Struve, maintained nearly constant intensity throughout the cycle but varied considerably in strength from one cycle to another.

Light Curves

The first photoelectric light curves of UX UMa were observed by Linnell (1949, 1950). They showed a deep primary minimum preceded by an increase in brightness or 'hump'. Primary minimum showed a pause on the ascending branch which was pronounced in most cycles but on occasions was absent. After the pause the system brightened again reaching a value equal to or greater than the value just before eclipse and then returning to normal brightness. No secondary minimum was evident and intrinsic flickering was seen in the light curves. Extensive UBV observations by Walker and Herbig (1954), Johnson et al. (1954) and Krzeminski and Walker (1963) followed. These observations confirmed in
the main Linnell's results and showed that the light curve of UX UMa varied considerably from cycle to cycle.

The typical light curve showed a primary minimum about 1″.1 deep with a standstill on the ascending branch. The brightness of the system gradually decreased from phase 0.1 to 0.7 when the system brightened to a maximum at phase 0.9. No secondary minimum was observed by any of the authors. The standstill on the rise was present to a greater or lesser degree in all the observed curves. The curves varied from cycle to cycle this showing up primarily in the height of the hump (or shoulder) prior to eclipse and in the time taken for recovery to normal light after eclipse.

The major difference between Linnell's (1950) curves and those of Walker and Herbig (1954), Johnson et al. (1954) and Krzeminski and Walker (1963) was in the shoulder following eclipse. In Linnell's curves this shoulder is as bright as or brighter than the shoulder prior to eclipse. The majority of the other curves show the shoulder prior to primary minimum to be about twice the height and length of the rise following eclipse (Walker and Herbig, 1954). However, a few curves observed by Johnson et al. (1954) show a pronounced shoulder following primary minimum, the system being brighter than prior to eclipse, the curves resembling those recorded by Linnell. The two types of curves are shown in Fig. 7.1. In contrast some of the curves observed by Krzeminski and Walker (1963) showed a slow recovery from primary minimum accompanied by an absence of the shoulder prior to minimum light.

The light curves all show clearly the short period intrinsic fluctuations discovered by Linnell. The amplitude of the variations is between 0″.01 and 0″.18 and is larger at U than at V and between phases 0.4 and 0.9. Primary minimum varied in depth with wavelength being deeper at U (1″.2), than B (1″.1), than V (1″.0) and also changes in
Fig. 7.1 Light curves of UX Ursae Majoris on two nights in 1952 (Johnson et al. 1954).
depth and shape from cycle to cycle.

Recent high speed photometric observations in white light by Warner and Nather (1972) have confirmed these results. Their observations show the same sort of slow recovery after minimum light as was occasionally seen by Krzeminski and Walker (1963). The light curves do not show any pronounced shoulder before minimum light. Both these observations and the observations of Krzeminski and Walker indicate that when the system is slow to recover after eclipse this shoulder is small or absent.

The Model

The early observations of Linnell, Struve, Johnson et al. and Walker and Herbig led to a model for UX UMa. This model was first suggested by Linnell and later extended by Walker and Herbig (1954). They proposed a system of two detached stars with a mass of hot material situated well above the surface of the primary and located asymmetrically with respect to the line joining the two stars. The hump preceding minimum light is due to the favourable presentation of this mass and the asymmetry on the rising branch of primary minimum is due to the occultation of the bright region by the secondary star. This hot cloud emits a continuous spectrum which causes the enhancement in the continuum spectrum prior to minimum. The model also postulates an extensive region of cooler gas around the primary which hides the bright region until phase 0.7 although it is not clear if this is seen as a complete disc. These gas regions are responsible for the observed changes in the spectrum with phase. Considering the time of its proposal (1950-1954) this model is remarkably close to the present model for cataclysmic variables.

Warner and Nather explain the observation in terms of the current
model for cataclysmic variables. The presence of the absorption lines in the spectrum (attributed by them to the white dwarf but now thought to be produced in the inner disc region) is evidence that this region contributes a substantial fraction of the light of the system. This must in part be due to the fact that the hump prior to minimum light is unusually small indicating that the bright spot, which is usually a major contributor to the light, is weak. This is supported by the observation that the flickering has a considerably lower amplitude than in other systems indicating that the spot contributes a smaller fraction of the light. The persistence of the emission and absorption lines at reduced intensity during eclipse indicates that the disc, and in particular the inner disc is only partially eclipsed.

The variations in behaviour after phase 0.1 are more extreme than in other cataclysmic variables. When the shoulder before eclipse is small the system is slow to recover from minimum. The implication is that when the bright spot is relatively faint, the slow recovery is seen but when the spot is bright, the depressed light curve after eclipse is augmented by light from the spot. Warner and Nather (1972) suggest that such an effect would arise if UX UMa is observed at a fairly high inclination and there is extra optical thickness of the disc from phase 0.0 to \( \sim 0.3 \). The obscuration caused by this matter after eclipse results in the lag in recovery from minimum which is only offset by unusually high luminosity of the bright spot. The absence of the absorption lines after eclipse is independent evidence for such obscuring material. Warner and Nather (1972) do not determine whether this matter is part of the interstellar stream or is an independent cloud of dense gas. The presence of such a cloud will be discussed again later.
Period Changes

Timings of primary minimum were first made by Zverev and Kukarkin (1937). Observations have shown that the period certainly varies but the nature of this variation is a matter for some debate. Mandel (1965) proposed that the orbital period of UX UMa varies itself periodically with a period of 10,600 days (29.0 yr). Since the first observations in 1937 only about 1.5 periods of Mandel's proposed cycle have been observed. Africano and Wilson (1976) showed that their observations in 1975 fit Mandel's predicted cyclic curve well. They suggest that apsidal motion is responsible for the 29 year period. Likewise Nather and Robinson (1974) report that their eclipse timings fit well to Mandel's hypothesis. They investigate the possibility that the 29 year period may be due to an unseen companion in the system. Although they show this is feasible they have reservations about the likelihood that such an explanation is correct.

However two other papers suggest that although the period is changing it is not a smooth cyclic change. Kukarkin (1977) has reanalysed all epochs of primary minimum up to October 1976 and concludes that one can hardly be sure about the periodicity. A wave and a half can be traced through the observations but it cannot be proved that the wave will repeat. Moreover it is evident that the deviations in the period are not varying smoothly but that abrupt changes occur. These abrupt changes rule out apsidal motion and the presence of a third body as the cause of the period variations. The sum of all the changes both slow and abrupt does however give the general form of a cyclic change, showing the period both increases and decreases. Kukarkin (1977) found that the best fit period to the changes is 10,520 days or 29.2 years which is very close to Mandel's (1965) value.

Observations by Quigley and Africano (1978) support the abrupt
changes found by Kukarkin's analysis. Their 1977 measurements do not fall on the periodic curve of Mandel and in fact tended to fall further from it as 1977 progressed. The period of UXUMa shortened during 1977. A possible explanation of this behaviour, suggested by Quigley and Africano, is that Mandel’s hypothesis may be basically correct but fluctuations in the mass transfer rate may cause short term abrupt changes. Alternatively they suggest that the long term variation in the period may be due to random processes whose combined effect appeared to produce a periodic curve in the past owing to the relatively short time interval over which UX UMa has been observed.

Coherent Oscillations

Warner and Nather (1972) report the detection of oscillations with a period of 29.44 and 28.92 sec respectively in two curves of UX UMa. The oscillations have a mean amplitude of 0.004 and are sinusoidal. The periodicity is not always present. In a comprehensive study of the oscillations of UX UMa, Nather and Robinson (1974) discovered a dramatic 360° phase shift during eclipse. The phase shift is of a sense indicating the gradual loss of one oscillation cycle. The same phenomenon has been observed in DQ Her but in the opposite sense. The phase shift repeats well from cycle to cycle displaying a near linear change from onset until just past light minimum where a lump appears in all of the cycles observed. The amplitude of the periodicity remains constant during the phase shift. The amplitude and period of the oscillations vary from cycle to cycle and on some occasions the oscillations are not present at all.
OUR OBSERVATIONS

Our observations of UX UMa were made at Tenerife. The light curves were not completed in one night and were observed on the following dates.

\[ J (1.25 \, \mu m) \text{ and simultaneous } V \] May 1/2 and May 3/4 1979

\[ K (2.2 \, \mu m) \text{ and simultaneous } V \] April 28/29 and May 2/3 1979.

The break where a change of night occurs in the J and V observations is shown clearly by a gap in the light curve shown in Fig. 7.2. In the K and V curve the observations on April 28/29 extended from phase \( \approx 0.15 \) to \( \approx 0.7 \) and from phase \( \approx 0.9 \) to 1.02. Observations from phase \( \approx 0.57 \) to \( \approx 0.15 \) obtained on May 2/3 are plotted on the same figure. The eclipses were completed in each curve in one night and the magnitude of the system at all wavelengths was consistent from night to night.

The observations of UX UMa were calibrated against the standard star BS4983 which has the magnitudes \( V = 4.26, J = 3.24, K = 2.90 \) (Johnson et al., 1966). Each point is the difference between a 20 sec integration performed in each channel. The errors shown in the light curves are estimated from similar observations of a non-varying star of approximately the same magnitude. Heliocentric and atmospheric extinction corrections have been applied to the results but because the standard was measured only at the beginning and end of each run drifts of up to \( \pm 0.1 \) in the absolute photometry may occur.

The data shown in Figs. 7.2 and 7.3 are plotted by phase using the ephemeris:

\[ J.D.2420238.24245 + 0.1966713 \, P \] (Kukarkin, 1977).

The Light Curves

Our V observations show a very flat curve outside primary minimum with only a small intrinsic flicker. The bright spot hump prior to
Fig 7.3 Simultaneous K and V light curves of UX Ursae Majoris.
primary minimum seen in some of the previous observations described earlier is very small or absent. Primary minimum is very well defined, 1\textsuperscript{m}.0 - 1\textsuperscript{m}.2 deep and is asymmetrical. The rising branch of the eclipse shows a delay in returning to normal brightness. There is no evidence for a secondary minimum. Warner and Nather (1972) observed similar eclipses from UX UMa and suggest that when the system is slow to recover from minimum the shoulder before eclipse is always small or absent.

In the infrared curves there is again no evidence for a secondary minimum. Primary minimum becomes wider and shallower with increasing wavelength being \( \sim 0\textsuperscript{m}.4 \) deep at J and \( \sim 0\textsuperscript{m}.3 \) deep at K. These eclipses appear symmetrical with no slow recovery from minimum as seen in the V curves.

**Interpretation**

As we have discussed earlier, UX UMa has been extremely well studied at optical wavelengths. Our V curves show the same deep, asymmetrical eclipse as has been observed by other authors (e.g. Nather and Robinson, 1974). The asymmetry of the eclipse and the small hump preceding ingress are attributed to the presence of a 'bright spot' where the gas stream from the secondary star strikes the accretion disc surrounding the white dwarf. Nather and Robinson (1974) have produced a qualitative model for the bright spot in which the luminosity of the spot is split into two components; an isotropic component, responsible for the pre-eclipse hump, and also contributing a flux of about 13% of the primary flux in the optical at the hump maximum. The remaining optical flux (i.e. about 90% of the light outside eclipse and hump) must presumably be supplied by the accretion disc.

Bath et al. (1980) have shown that the continuum spectrum of a
'standard' optically thick steady state accretion disc provides a good fit to observations of the ultraviolet/optical continuum of cataclysmic variables. The deep well defined optical eclipses of UX UMa, together with the simultaneous rather shallow infrared eclipses, offer the possibility of trying to fit the VJK light curves by considering the eclipse of a standard disc by a secondary star. This will then test whether the surface brightness distribution as well as the continuum spectrum of such a disc is a reasonable approximation to the real disc. The wide spread of wavelengths offered by simultaneous V, J and V, K photometry is ideal for this programme for two reasons. Firstly the VJK colours of cataclysmic variables can be fitted using a combination of disc and secondary spectra and secondly, the predicted surface brightness distributions at these wavelengths differ markedly. In contrast model disc atmospheres do not as yet produce good fits to the observed UBV colours of cataclysmic variables (e.g. Mayo et al., 1979 and Herter et al., 1979) while the closeness of the effective wavelengths at UBV means that the predicted surface brightness distributions of the disc and secondary are rather similar to each other.

There are two main problems in trying to fit a disc and secondary to our V, J, K light curves. Firstly the contribution of the late type secondary star becomes more important at longer wavelengths (as we have seen for U Gem) and so must be taken into full account when trying to reproduce the VJK colours and light curves. Secondly the bright spot introduces a certain degree of freedom because its physics is not well understood. The eclipse curves and colours provide enough information to separate out the contributions of the secondary and primary (given certain assumptions outlined below) but the bright spot must be dealt with phenomenologically.

Our VJK light curves on their own do not contain enough information
for us to be able to find all the parameters of the system including the
bright spot. In fact they can be quite well fitted considering the
eclipse of a disc alone (with no bright spot) and a secondary
contribution. This is because on the nights we observed UX UMa the
bright spot was relatively weak (Fig. 7.4 shows that at V only a very
small hump was observed prior to primary minimum).

Nather and Robinson (1974) have shown very convincingly however
that the bright spot does exist in UX UMa. Also the shape of our V curve
with a slight hump prior to primary minimum and an asymmetrical eclipse
suggests the presence of a bright spot. To model our light curves we
take bright spot parameters from the discussions in Nather and Robinson
(1974) and then construct our eclipse curves by adding a simulated
bright spot light curve to our disc eclipses. We assume (quite
arbitrarily) the bright spot contribution to have the same VJK colours
as the uneclipsed accretion disc. Within reasonable limits this
assumption does not greatly affect our infrared light curves and our
data cannot rule out moderate variations in shape. To check this
procedure we compare our predicted V curve with one of the white light
curves of Nather and Robinson (1974). It will be seen that a good fit
is achieved.

To model our light curves by adding the bright spot variations
to the eclipse of a standard disc by a secondary star we have to fix a
number of physical and geometrical parameters and we check that these
and other parameters deduced from them are physically reasonable. Our
best fit should not be regarded as definitely determining the parameters
of the system within the estimated errors. Given our assumptions (which
are detailed below) parameters in the quoted ranges (in particular the
best fit parameters) will reproduce the observations within the limits
defined in the next section. It appears that changing the bright spot
variations subject to the constraints imposed by Nather and Robinson's (1974) observations does not have a large effect on our best fitting parameters. It seems likely therefore that the parameters of UX UMa do lie in the quoted ranges but a far more rigorous treatment, particularly knowledge of the physics of the bright spot, combined with more detailed observations over many cycles, is needed before we can confidently determine the exact parameters of the system.

Fitting procedure

To produce theoretical VJK light curves to compare with our observations we add to the bright spot light variations, discussed above, model curves generated by computing the light lost from the occulted area of the disc as a function of orbital phase, assuming the standard temperature distribution of the disc (Bath et al., 1980).

\[ T(R) = T_* \left( \frac{R_{\text{in}}}{R} \right)^{\frac{4}{3}} \left[ 1 - \left( \frac{R_{\text{in}}}{R} \right)^{\frac{1}{3}} \right] \quad (1) \]

where \( R_{\text{in}} \) is the inner disc radius and

\[ T_* = 4.1 \times 10^4 \cdot \frac{M_{16}}{M_1} \cdot \left( \frac{R_{\text{in}}}{10^9 \text{ cm}} \right)^{-\frac{2}{3}} \quad (2) \]

where \( M_{16} \) is the accretion rate in units of \( 10^{16} \) g/sec and \( M_1 \) is the mass of the white dwarf in units of \( M_\odot \).

The disc spectrum is

\[ F_\nu = \int_{R_{\text{in}}}^{R_{\text{out}}} B_\nu(T(R)) \cdot 2\pi R \, dR \]

where \( B_\nu(T) \) is the Planck function and \( R_{\text{out}} \) is the outer radius of the disc.

As we discussed in Chapter 2 the disc spectrum is

\[ F_\nu \propto \nu^{\frac{1}{2}} \]
for frequencies $\nu$ such that $kT_{\text{out}} \ll h\nu \ll kT_{\text{max}}$. For $h\nu \gg kT_{\text{max}}$

the spectrum has the Wien form and for $h\nu \ll kT_{\text{out}}$ a Rayleigh-Jeans form. In Chapter 4 we saw that in EX Hya the $\frac{1}{3}$ law extends all the way from the near UV out to $\sim 2.2 \mu m$ (Sherrington et al., 1980), and this enables one to estimate $T_{\text{eff}}$ and put an upper limit on $T_{\text{out}}$.

In the case of UX UMa we observe colours outside eclipse of $V-J = 0.5$ and $V-K = 0.8$. Previously Szkody (1977) measured infrared colours of $J-K = 0.5$ while we have found $J-K = 0.3$. Szkody's values for $J$ and $K$ are the average of observations on several nights and do not state whether any of these observations were made during eclipse. Considering that UX UMa changes in brightness from night to night and shows different colours during and outside eclipse the discrepancy in these observations is not surprising.

Our observed colours cannot be explained by a $\frac{1}{3}$ disc spectrum extending into the infrared since a $\frac{1}{3}$ spectrum has $V-J = 0.55$ and $V-K = 1.45$. The closeness of the observed $V-J$ colour to a disc spectrum might imply a $\frac{1}{3}$ spectrum extending out to about $J$. This theory will fit the observed colours outside eclipse but for reasons which will be discussed shortly is not correct. The fit is caused by the fact that for binary periods near 4.5 hrs (UX UMa has a period of 4.72 hrs) the secondary star has (as in U Gem) a J-K colour rather similar to a $\frac{1}{3}$ disc, so that a substantial contribution from this star does not spoil the disc-like appearance of the continuum.

For the fitting procedure the secondary is assumed to be spherical of radius $R_2$, moving in a circular orbit of separation (using Kepler's law)

$$a = 9.9 \times 10^{10} \frac{M_2^{\frac{1}{2}}}{M_1} (1 + q)^{\frac{1}{4}} \text{ cm}$$

where $q = M_2/M_1$, the mass ratio ($M_2$ is the secondary mass in units of $M_\odot$).

Taking the secondary to be spherical enables one to find analytically
its projection on the disc (and hence the occulted area) as the intersection of a moving ellipse. This greatly reduces the computing time needed for the fitting procedure. A full Roche model would have the advantage of automatically enforcing the constraints of Roche geometry but would be much more expensive to compute because it is no longer given analytically. We do not use Roche geometry explicitly but the search is confined to only physically consistent binary geometries. In our fitting we use $R_2/a$ to determine $q$ by assuming that $R_2$ is equal to the average Roche lobe radius (e.g. Warner, 1976; Paczynski, 1971). We neglect all limb darkening effects for both the disc and secondary star.

The first step in the fitting procedure is to try to reproduce the quiescent colours of the system outside eclipse by superimposing the continuum spectra of a standard accretion disc and a late-type secondary. The spectrum of the secondary in UX UMa has never been observed. The period of UX UMa is slightly longer than that of U Gem which contains a secondary of spectral class M4.5, so one would expect the secondary in UX UMa to be early M type. The main sequence colours of late K and M type stars were studied until colours were found which, when added to a disc spectrum, could produce the observed colours outside eclipse, although, as yet, the relative contributions of the disc and secondary were unknown. The spectral type chosen was M2. This fixes the colours and mass of the secondary, but its absolute magnitude is not assumed but left as a free parameter. The preliminary least square fit then provides estimates of the temperature $T_{out}$ of the disc edge and the relative contribution of the disc and secondary at all wavelengths. $R_{in}$, which can be taken as the radius of a white dwarf of mass $M_{1\odot}$, is poorly determined by this fit, as it only strongly affects the short-wavelength spectrum of the disc. However this first fit restricts the
values of $T_{\text{out}}$ quite closely as most of the available information is at infrared wavelengths.

The next, and major, step in the fitting procedure is to use the light curves to attempt to fix the geometry of the binary. Model light curves are computed in $V$, $J$ and $K$ by evaluating numerically the fluxes lost from the occulted area of the disc as the secondary moves around a circular orbit of radius $a$, varying the parameters to optimise the fit to the data. Thus, starting from the parameter values suggested by the colour fit we try to adjust the values of $R_2/a$, $i$ and $R_{\text{out}}/a$ to obtain the best agreement to the three light curves simultaneously. This initial fit is simply the eclipse of the disc by a secondary star.

Next we add the bright spot variations to our eclipse curves and compare the resulting composite curves to our observations at $V$, $J$ and $K$. To check that our simulation of the bright spot is approximately correct we also compare our $V$ curve with one of Nather and Robinson's eclipses.

Subsequently we adjust the disc and system parameters, generate new eclipse curves, add the bright spot variations as before and compare the resulting curves with the observed $V$, $J$, $K$ and white light curves. This process is repeated until the best simultaneous fit to all four curves is achieved. In practice a readjustment of the parameters was necessary only once. Had the bright spot contributed a larger fraction of the disc light at all wavelengths the process of convergence to an acceptable fit would presumably have involved more iterations. The effect of adding the bright spot variations to our eclipse curves and adjusting the parameters from those of the best fit with just the disc and secondary, to give the best fit is to change the inclination by $0.5^\circ$. All the other geometrical parameters remain unchanged.

The best simultaneous fit to our $V$, $J$, $K$ observations and the white light curve of Nather and Robinson (1974) is shown in Figs. 7.4
and 7.5. In Fig. 7.4 the data has been binned over 10 points in the case of the V and K curves and over 6 points in the sparser J data to show the fit more clearly. In this figure the dotted curve at V shows the best fit curve without the bright spot variations while the solid curve shows the best fit produced with the bright spot variations included. The dashed curves at J and K correspond to the absolute flux levels predicted by the fit of the composite disc and bright spot curves while the solid curves are the predicted curves shifted to show the agreement in the shape of the eclipses. At K the predicted level (K = 12.0) outside eclipse, in fact agrees well with the observed mean K level outside eclipse. The shift of 0\(^{m}.1\) between this curve and the solid curve probably reflects the effects of varying atmospheric extinction through the night. At J the discrepancy is probably real and can only be eliminated by assuming a secondary brighter at J by \(\sim 0^{m}.3\) than the quoted main sequence colours allow, or by changing the colours of the bright spot.

Fig. 7.5 shows the computed V light compared with a white light eclipse adapted from Fig. 5 of Nather and Robinson (1974). It can be seen that the fit is excellent except that the white light eclipse is slightly deeper than our predicted V curve. As white light is usually rather blue and UX UMa shows a deeper eclipse at U than at B than at V this is to be expected.

The best simultaneous fit to all the light curves yields estimates of \(i = 65^{\circ}\), \(R_2/a = 0.43\), \(R_{out}/a = 0.33\), \(T_{out} = 6500\) K, with the best fit secondary colours being those of a M2V star (Johnson, 1966): \(V-J = 3.37\), \(V-K = 4.27\). We have restricted ourselves to lower main sequence colours for the secondary, implying a relation between V-J and V-K. The fit could have been improved by allowing them to vary independently. We also obtain the estimate that the system in the K band is \(0^{m}.7\) brighter
Fig 7.4 The computed light curves compared with the VJK observations of Figs 7.2 and 7.3.
Fig 7.5 The computed V light curve compared with a white light eclipse from Nather and Robinson (1974).
outside of the eclipse and the hump than the secondary star alone, which enables us to compare the fluxes of the disc and secondary at any wavelength. From the estimate of 1, and $R_{2}/R_{\text{out}}$, we find a ratio of average surface brightnesses of the secondary to the disc of 0.26 at $K$ and much less at $J$ and $V$. Hence there should be no detectable secondary eclipses, as observed.

The evaluation of formal errors for the fit would involve large amounts of computer time. Instead rather pessimistic errors can be easily estimated by considering the results from unsuccessful fits. Tests have shown that varying $R_{\text{out}}/a$ or $R_{2}/a$ by amounts between 5 and 10% and adjusting the other parameters accordingly leads to a clear corruption of the fit, causing either departures of more than $0.1$ from observed eclipse depths or obviously incorrect eclipse shapes. Since $T_{\text{out}}$ affects both the overall colour fit and the eclipse shapes we assert that it cannot be outside the range 5900-8200, the fit at 6500 $K$ being clearly better than at these values. Lastly the acceptable colours of the secondary confine the spectral type to the range K8V-M6V.

The best fit gives us the relative contributions of the secondary star and disc (including the isotropic part of the bright spot flux) and these are shown in Fig. 7.6 together with the observed KJVB values with 10% error bars. It can be seen that the secondary does contribute significantly to the spectrum at $K$, although a disc alone would be fitted to the curves outside eclipse as remarked earlier. Such a disc, however, would need $T_{\text{out}} \sim 2700$ $K$ which, from the temperature-radius relation for the disc, would give a large value for $R_{\text{out}}/R_{\text{in}}$ since $T_{\text{out}} = T_{*}(R_{\text{out}}/R_{\text{in}})^{4}$ (A small $T_{*}$ would cause the Wien turn down to occur at unacceptably long wavelengths.) Since $R_{\text{out}}$ is essentially fixed by the light curves ($R_{\text{out}} = 0.33a$, $a = 9.9 \times 10^{10} (M_{1} + M_{2})^{1/3}$ cm) this means that $R_{\text{in}}$ must be very small. If $R_{\text{in}}$ is very small it implies that
Fig. 7.6 The spectrum of the components of UX Uma. The solid and dotted lines indicate the contributions of the disc (R/Rout = 0.004) and the secondary (M2 V) respectively. The total flux (dashed line) is shown together with the observed K, J, and V values with 10% error bars. The isotropic component from the bright spot is included in the disc contribution.
the dominant optical disc radiation comes from a region very small compared to the orbital dimensions (the size of this region as $R_{\text{in}}$) and the resulting eclipse at $V$ is then always much too narrow, compared with the observations, even if very large radii are assumed for the secondary.

The fitting procedure described above only fixes the relative geometry of the system with the unit of length being taken as $R_{\text{out}}$. We must now check that our estimates are reasonable in that they imply realistic parameters for the system. It should be stated again that this should not be regarded as an absolute determination of the parameters of the system but instead as a check on the disc model. The physical dimensions of the system are found using Kepler's third law (equation 3) which we rewrite as

$$a = 9.9 \times 10^{10} \frac{M_2^{\frac{1}{3}} (1 + q^{-1})^{\frac{1}{3}}}{\text{cm}}.$$ 

Allowing 10% errors on $R_{\text{out}}^2/a$ the condition that the secondary fills its Roche lobe implies $0.9 > q^{-1} > 0.4$ or $1.2 > (1+q^{-1})^{\frac{1}{3}} > 1.1$. The value $R_{\text{out}}^2/a = 0.33$ implies that the disc almost fills the white dwarf's Roche lobe. If the secondary has a mass consistent with our estimates of its lower main sequence spectral type then $0.2 < M_2 < 0.5$, implying $1.0 \times 10^{11} \text{ cm} > a > 0.9 \times 10^{11} \text{ cm}$. (If this restriction on the secondary's mass is dropped and we merely ask that the secondary should be capable of burning hydrogen while the white dwarf does not exceed the Chandrasekhar limit we find $1.4 \times 10^{11} \text{ cm} > a > 0.5 \times 10^{11} \text{ cm}$).

This estimate $a = 0.95 \times 10^{11} \text{ cm}$, gives $R_2 = 0.59 R_\odot$ in reasonable agreement with a lower main sequence (M2V) assignment. With this value of $a$ assumed, our estimates of $i$, $R_{\text{out}}/a$, and $T_{\text{out}}$ give the absolute magnitude of the disc at say $K$ (where $R_{\text{in}}$ has no effect). As the relative contributions of the disc and secondary are given by our fit we can now find the absolute magnitudes $M_K$, $M_K(2)$ of the system and
secondary. With $a = 0.95 \times 10^{11}$ cm we get $M_K = 4.3$, $M_K(2) = 5.0$, this latter value being also in reasonable agreement with the spectral assignment M2V for this star (giving $M_V(2) = 9.27$ while Allen (1973) gives $M_V = 9.99$ for an M2V star).

At the start of our fitting procedure the colours of the secondary were chosen but the absolute magnitude of the secondary was left as a free parameter to be established by the best fit. The absolute magnitude obtained from our fit is in good agreement with the absolute magnitude of a star of the chosen spectral class (Allen, 1973). This gives us confidence in our choice of secondary. The fit to the eclipse curves shown in Fig. 7.4 is the best fit, although it is not good at $J$, that can be obtained if we restrict ourselves to a secondary with main sequence colours. If we had allowed the colours of the secondary to vary from the main sequence a better fit to our observations could be found. We would then however, have no cross check on the values obtained for the absolute magnitude and radius of the secondary. The probable explanation of the discrepancy between the model and the observations at $J$ is that the secondary has colours slightly different from the main sequence. It may be that the environment of the secondary has altered its atmosphere so that the colours are not consistent with main-sequence without requiring the interior structure of the star to be evolved.

The parameters found from the fitting procedure allow us to estimate several others.

The absolute magnitude of the system at $K$, $M_K = 4.3$ together with the observed $K$ magnitude outside eclipse, $m_K = 12.0$ allow us to find the distance if we assume the secondary to be a main sequence star,

$$M_K = m_K + 5 - 5 \log D_{\text{pc}}.$$  

This gives a distance to UX UMa of 340 pc. Interstellar reddening is certainly negligible at $K$ over such a small distance.
From our model we may also estimate the accretion rate in UX UMa.

The separation of the components

\[ a = 9.9 \times 10^{10} M_1^{\frac{1}{2}} (1 + q)^{\frac{1}{2}} \text{ cm} \]

Combining this with equation (1) (the radius-temperature relation for the disc) which simplifies to

\[ T_{\text{out}} = T_* \left( \frac{R_{\text{out}}}{R_{\text{in}}} \right)^{-\frac{3}{4}} \text{ for } R_{\text{out}} \gg R_{\text{in}} \]

and equation (2),

\[ T_* = 4.1 \times 10^4 M_1 M_1^\frac{1}{2} \left( \frac{R_{\text{in}}}{10^9 \text{ cm}} \right)^{-\frac{1}{4}} \]

we have on elimination of \( T_* \) and \( M_1 \) between the three equations

\[ M_1 = 48 \left( \frac{T_{\text{out}}}{6500} \right)^4 \left( \frac{1 + q}{2} \right) \left( \frac{R_{\text{out}}}{0.33a} \right)^3 \]

(4)

With our earlier estimate of \( q, 0.4 < q^{-1} < 0.9 \) and allowing 10% errors on the estimates of \( T_{\text{out}} \) and \( R_{\text{out}}/a \) we find

\[ 180 > M_1 > 24 \]

independently of any assumption about \( a \) and hence about absolute masses.

Taking as before \( 0.2 < M_2 < 0.5 \) and \( 0.4 < q^{-1} < 0.9 \) we find \( 0.1 < M_1 < 0.5 \). This would imply a low mass white dwarf with \( R_{\text{in}} \approx 10^9 \text{ cm} \) and hence a limit on the interstellar reddening (from the VJK colour fit) \( A_V < 0.1 \), which is consistent with the distance estimate of 340 pc.

The derived best fit parameters are listed in Table 7.1 for easy reference.

The total accretion luminosity is (Bath et al., 1980)
### Table 7.1

Parameters of UX UMa from the best fit to the light curves.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inclination</td>
<td>$i = 65^0 \pm 1^0$</td>
</tr>
<tr>
<td>Absolute magnitude of secondary</td>
<td>$M_K(2) = 5^m.0 \pm 0^m.5$</td>
</tr>
<tr>
<td>Adopted colour</td>
<td>V-J = 3.37</td>
</tr>
<tr>
<td>(M2V; Johnson, 1966)</td>
<td>V-K = 4.27</td>
</tr>
<tr>
<td>Secondary radius</td>
<td>$R_2/a = 0.43 \pm 0.04$</td>
</tr>
<tr>
<td></td>
<td>$R_2 = (0.58 \pm 0.09)R_\odot$</td>
</tr>
<tr>
<td>Disc radius</td>
<td>$R_{out}/a = 0.33 \pm 0.03$</td>
</tr>
<tr>
<td></td>
<td>$R_{out} = (3.1 \pm 0.5) \times 10^{10}$ cm</td>
</tr>
<tr>
<td>Secondary Mass (assumed)</td>
<td>$0.2 &lt; M_2 &lt; 0.5$</td>
</tr>
<tr>
<td>White dwarf mass</td>
<td>$0.1 &lt; M_1 &lt; 0.5$</td>
</tr>
<tr>
<td>Binary Separation</td>
<td>$9 \times 10^{10}$ cm &lt; a &lt; $1 \times 10^{11}$ cm</td>
</tr>
<tr>
<td>Temperature of disc edge</td>
<td>$T_{out} = (6500^{+1700}_{-700})K$</td>
</tr>
<tr>
<td>Accretion Rate</td>
<td>$M = (48^{+132}_{-24}) \times 10^{16}$ g s$^{-1}$</td>
</tr>
<tr>
<td>Systems Distance</td>
<td>$D = (340 \pm 110)$ pc</td>
</tr>
</tbody>
</table>
\[ L_{\text{acc}} = 6.7 \times 10^{32} \frac{M_2}{10^9} \left( \frac{M_1}{10^{16}} \right)^{-1} \text{ erg/sec} \]

substituting from equation (4) gives

\[ L_{\text{acc}} = 1.2 \times 10^{34} \left( \frac{T_{\text{out}}}{6500} \right)^4 \left( \frac{R_{\text{out}}}{0.33 a} \right)^3 \left( \frac{R_{\text{in}}}{10^9} \right)^{-1} \left( \frac{M_1+M_2}{0.8} \right) \text{ erg/sec} \]

where the factors in brackets are of order one for UX UMa. Putting in our estimated errors gives

\[ 3.0 \times 10^{34} \text{ erg/sec} > L_{\text{acc}} > 2.3 \times 10^{33} \text{ erg/sec} \]

The total flux at the Earth is given by (Bath et al., 1980)

\[ F_{\text{tot}} = \frac{L_{\text{acc}} \cos i}{2 \pi D^2} = \frac{1.6 \times 10^{34} \cos 65^\circ}{2 \pi (340 \times 3.086 \times 10^{18})^2} \]

\[ F_{\text{tot}} = 3.1 \times 10^{-9} \text{ erg cm}^{-2} \text{ s}^{-1} \]

The total V-band flux observed at the Earth is \(2.5 \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}\).

Hence only \(\sim 1\%\) of the accretion luminosity is radiated in the V-band and the total flux in the region 0.55 \(\mu\text{m} - 2.2 \mu\text{m}\) is about 10% of the accretion luminosity. This illustrates the difficulty in drawing conclusions from the observed flux levels alone although in principle these could be used to estimate the white dwarf mass directly. The errors are however such that any reasonable white dwarf mass (< 1.4 \(M_\odot\)) lies comfortably within them.

\textbf{Conclusions}

Our model gives us a high \((M > 2.4 \times 10^{17} \text{ g s}^{-1})\) accretion rate for UX UMa. This high accretion rate causes the accretion disc to be a major contributor to the system's luminosity at all wavelengths, despite the high orbital inclination. Our best fit involves a secondary having M2V colours and this fit implies an absolute magnitude and radius for
this secondary in good agreement with this spectral type. This supports the idea that in UX UMa the secondary lies close to the main sequence. However our best fit is 0''3 too faint at J and this cannot be improved without spoiling the agreement at V and K since J-K is virtually constant for main sequence types later than K5V. The fit also makes the secondary brighter by 0''7 than quoted values for its type (but well within the scatter on the HR diagram). This suggests one should be cautious about concluding that the secondary is a main sequence star.

Our V curve shows one peculiar feature, the lagging recovery over phase 0.05 - 0.15. This feature is also seen in the white light curves of Warner and Nather (1972) and in some of the curves observed by Krzeminski and Walker (1963). It is not seen in the curves of Nather and Robinson (1974). This behaviour may be caused by orbiting material near the binary plane which has failed to land on the accretion disc. Lin and Pringle (1976) have shown that such material tends to orbit on the following side of the secondary star. This model has previously been suggested by Warner and Nather (1972) to explain the slow egress. Alternatively the appearance of this lagging rise on occasion may just be due to variations in the hot spot contribution. When the slow recovery is seen the hump prior to primary minimum is always very small.

The main gap in our understanding of the light curves of these systems is the lack of any physical model of the 'bright spot'. The fact that in UX UMa its effect is relatively minor allows us to conclude that a steady state optically thick accretion disc does represent fairly accurately the surface brightness distribution of the primary at widely spaced wavelengths. Further observations (particularly in the ultraviolet) will be of great importance in gaining a more complete understanding of the accretion disc.

A paper on this discussion has been written (Frank et al., 1980) and is included in Appendix 1. The computing of this model was done by J. Frank.
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CHAPTER EIGHT

EM CYGNI

EM Cyg is a little studied cataclysmic variable. Differences of opinion exist as to which subgroup it should be classified under. Hoffmeister (1928) was the first to detect the variability of EM Cyg on Sonneberg plates. He found that the brightness varied between magnitude 12.5 and about 14.5 in an interval of 24-27 or so days. His original proposal was that it was an Algol type variation but later (unpublished) observations by Gaposchkin ruled out this possibility. On the basis of their spectra, Burbidge and Burbidge (1953) suggested that EM Cyg was an old nova. The spectra showed broad strong hydrogen emission and a weak emission band of HeII (\lambda4686 A). No absorption lines were visible. Their view is supported by Payne-Gaposhkin (1977) who classes it as 'an ex-nova or potential nova'.

Photographic surveys of EM Cyg have been published by Ahnert (1944), Wachmann (1961) and Brady and Herczeg (1977). In addition, a comprehensive visual study of the almost continuous major fluctuations of this star has been published by von Beyer (1967). He finds that the visual magnitudes of the minima range from near 13.9 to 14.2 while the maxima vary from 12.0 to 12.9. Outbursts occur every 18-25 days on average, though the extreme range is from 9 to 44 days, and have a maximum amplitude of about 2.0 magnitudes. The small amplitude and frequent eruptions led Wachmann (1961) and von Beyer (1967) to suggest EM Cyg is a dwarf nova of the Z Cam class. The classification of EM Cyg as a dwarf nova is supported by the weakness of the HeII \lambda4686 emission compared with the Balmer emission (Robinson, 1974) and Warner (1976).
classes it as a Z Cam variable. However, Brady and Herczeg (1977) who studied 562 photographic plates taken over five observing seasons disagree. While they see eruptions with a mean cycle length varying from season to season (from 19 days during the second half of 1951 to 26 days late in 1953) they find no indication of Z Cam type standstills. This suggests that EM Cyg is a U Gem type system.

PREVIOUS OBSERVATIONS

Light Curves

Walker (1957) obtained the first photoelectric photometry of EM Cyg and found rapid variations or flickering in its light curves with amplitudes up to 0\textsuperscript{m}.24 and timescales of a few minutes. Extensive photometry by Mumford and Krzeminski (1969) produced similar results and they found that EM Cyg is an eclipsing binary, with a period of 6 hrs 58.91 min. Their observations showed that primary minimum varies greatly in shape and depth from cycle to cycle, sometimes being symmetrical and at other times asymmetrical, and in some cases showing pronounced flaring on either the descending or ascending branch. No secondary minimum was observed. Pronounced flickering was in evidence in all the curves. On average primary minimum was 0\textsuperscript{m}.2 in blue light and an irregular hump prior to eclipse was present. Composite light curves at both U and V are shown in Fig. 8.1 taken from Mumford and Krzeminski (1969). The composite ultraviolet curve clearly shows the hump prior to eclipse (phase 0.9) with an amplitude between 0\textsuperscript{m}.1 and 0\textsuperscript{m}.2.

A study by Pringle (1975) shows that the period of EM Cyg is decreasing, although it is not possible to tell whether the change is sinusoidal or monotonic.
Composite light curve derived from observations in ultraviolet light. Ordinate is magnitude difference adjusted to mean value outside eclipse on a given night.

Composite light curve derived from visual-light observations.

Fig. 8.1 Typical light curves of EM Cygni.
Coherent Oscillations

Recently Nevo and Sadeh (1978) observed coherent oscillations from EM Cyg on the ascending branch of an outburst. They found a period for these oscillations of 16.6 seconds making it one of the shortest periods observed. Their observations of the descending branch of another outburst failed, however, to show any oscillations.

Spectrum

The spectra of EM Cyg observed by Burbidge and Burbidge (1953) were of low resolution and showed broad H and HeII bands. Kraft obtained spectra of EM Cyg using the 200 inch Palomar telescope and these have been analysed by Robinson (1974). The spectra at minimum light show strong broad Balmer emission lines superimposed on a blue continuum. Neutral helium lines at 4026 and 4471 Å are weakly present in emission but the CaII K line and HeII λ4686 line are absent. In about one quarter of the spectra the Balmer lines are clearly double peaked with a separation averaging 700 km s⁻¹. A weak metallic absorption spectrum is also visible, heavily obscured and this appears to be a late type spectrum in the G to K range. A spectrum taken at maximum light showed that the absorption spectrum had disappeared. HeII λ4686 emission was nearly as strong as the Balmer lines and CaII K and HeI were observed in absorption with weak emission in the blue wing.

From these spectra Robinson (1974) was able to measure both the emission (disc) lines and the absorption (secondary) lines and from these determine the parameters of the orbit. The values obtained are listed in Robinson (1974). His spectroscopic period agrees, within the measurement errors, with the photometric period of Mumford and Krzeminski (1969). Phase zero of the spectroscopic period was defined as the inferior spectroscopic conjunction of the late type star and this
coincided with zero photometric phase. This confirmed that it is correct to interpret the primary minimum of EM Cyg as an eclipse. The emission line velocities showed a small phase lag relative to the orbit of the late type star. This is probably caused by distortion of the emission lines due to blending with the S-wave component. Thus radial velocities measured from the emission lines will be subject to errors.

Combining available photometric data with his orbital elements from the spectroscopic results, Robinson (1974) determines the radius of the disc, the orbital inclination of the system and the masses of the components. From the splitting of the emission lines, assuming Keplerian motion in the disc, he found that the radius of the disc, $r = 0.4a$ where $a$ is the separation of the primary and secondary stars. This implies that the disc in EM Cyg fits in but essentially fills the Roche lobe of the white dwarf.

The angle of inclination $i$ of the system then follows from the geometry. It must be $> 55^\circ$ for the Roche lobe of the white dwarf to be eclipsed. Robinson maintains that the eclipses are too variable and irregular for the white dwarf itself to be eclipsed and therefore that $i < 67^\circ$. However this condition only holds if you assume that the white dwarf is a major contributor to the light. The depth of the eclipse suggests that the inclination of the orbit should be near this upper limit but Robinson argues that the inclination must be below $64-65^\circ$ because the bright spot is not eclipsed. This conclusion is based on the fact that the flickering does not disappear at minimum and the eclipse does not show a steep ingress and egress reminiscent of the bright spot eclipse of U Gem. Particle trajectory calculations by Warner and Peters (1972) place an eclipse of the spot in EM Cyg at $i \approx 64^\circ-65^\circ$ for the mass ratio obtained from the line measurements. Thus Robinson concludes that $i \approx 65^\circ$. An alternative value for $i$ will be found later

*see footnote p237
from our observations.

Using his orbital elements and \( i = 63^\circ \) Robinson finds masses of \( M_1 \) (white dwarf) = 0.70 ± 0.18 \( M_\odot \) and \( M_2 \) (secondary) = 0.90 ± 0.17 \( M_\odot \).

The methods of determining masses of Warner and Robinson (described in Chapter 2) give \( M_1 = 0.67 \, M_\odot \), \( M_2 = 0.86 \, M_\odot \) and \( M_1 = 0.73 \, M_\odot \), \( M_2 = 0.95 \, M_\odot \) respectively. These are all in fair agreement but all suffer possible errors due to uncertainties in measurements of the spectral lines. These results show that EM Cyg is unusual amongst cataclysmic variables in having a late type secondary more massive than the white dwarf. If the secondary fills its Roche lobe its mass \( M_2 = 0.90 \, M_\odot \) places it on the mass radius relation for the lower main sequence.

**OUR OBSERVATIONS**

Our observations of EM Cyg were made at the 1.5m Infrared Flux Collector at the Cabezon Observatory, Tenerife, with the Leicester infrared-optical photometer. The observations were made on the following nights:

- J (1.25 \( \mu \)m) and simultaneous V August 20/21, 1979
- K (2.2 \( \mu \)m) and simultaneous V August 19/20 & August 21/22, 1979.

The light curves obtained are shown in Figs. 8.2 and 8.3. The K and V light curve (Fig. 8.3) is the composite of observations on two nights.

The break where a change of night occurred in the readings is shown clearly by the gap in the light curve. EM Cyg was close to quiescence with a mean \( V \sim 13.6 \) throughout most of the observations, except for the run on 1979 August 19/20 (shown as phases 0.05 \( \leq P_\odot \leq 0.75 \) on the V, K curves) when the system was somewhat brighter with \( V \sim 13.4 - 13.5 \). This variability is in agreement with the erratic low-amplitude luminosity changes noted by Wachmann (1961) and von Beyer (1967).

The observations of EM Cyg were calibrated against the standard
Fig. 8.2 Simultaneous J and V light curves of EM Cygni.
Fig. 8.3 Simultaneous K and V light curves of EM Cygni.
star BS 7678 which has the magnitudes $V = 5.65$, $J = 4.50$, $K = 4.11$

(Johnson et al. 1966) and was observed before and after each light curve. The data is plotted by phase computed from the ephemeris of Mumford and Krzeminski (1969)

$$J.D.243782.8596 + 0^d.29090942 P.$$  

Each point represents the difference between a 20 sec integration performed in each channel. The errors shown in Figs. 8.2 and 8.3 were estimated from similar observations of a non varying star of approximately the same magnitude. Heliocentric and atmospheric extinction corrections have been applied.

The Light Curves

Fig. 8.4 shows our infrared light curves with the data binned such that each point is the mean of fifteen 20 sec integrations. This was done to reduce the effects of the intrinsic flickering and instrumental noise. The curves through these points are the original data smoothed by the procedure described in Chapter 3, with a full width half maximum of the Gaussian of 35 points. The errors on the smoothed curves are $\pm 0^m.015$ at $J$ and $\pm 0^m.03$ at $K$. These curves show, particularly the $J$ curve, a sinusoidal shape with two nearly equal minima at phase $\approx 0.0$ and $0.5$. At $J$ the minima are $\approx 0^m.22$ deep and at $K \approx 0^m.2$ deep.

Unlike the light curves of Mumford and Krzeminski (1969) our $V$ curves show evidence for a wide, shallow secondary minimum. Phase 0.5 is not well covered by the composite light curves from Mumford and Krzeminski shown in Fig. 8.1. The individual light curves they have published cover only the phases around primary minimum but their composite blue curve which was made principally to establish whether there is a secondary minimum shows no indication of one. However the
Fig 8.4 The J and K observations from Figs 8.2 and 8.3 binned to reduce instrumental noise and intrinsic flickering. The curve is the result of smoothing the data using the method described in Chapter 3.
scatter of points on this curve is too large for a shallow minimum such as we have found to be easily detected. No other light curves of EM Cyg have been published.

Our V curves show two minima which, in contrast with the infrared curves, differ in depth by \( \sim 0.2 \). The deeper minimum, \( \sim 0.35 \), is centred around phase 0.97 and is interpreted as an eclipse of the primary (probably of part of its accretion disc (Robinson, 1974)).

Primary minimum occurs earlier than predicted by the ephemeris of Mumford and Krzeminski (1969) indicating that the period of EM Cyg has decreased over the last 10 years. Primary minimum is preceded by a hump of height around 0.1 centred at phase 0.85 which is presumably caused by the presence of a bright spot where the gas stream from the secondary star strikes the accretion disc. This hump is also discernible in the J and K curves but at smaller amplitude indicating that the bright spot contributes less to the total light in the infrared. The V curves show a flickering of amplitude \( \sim 0.1 - 0.15 \) typical of cataclysmic variables. The error bars on the J and K curves suggest that this flickering may also be present at 1.25\( \mu \)m and 2.2\( \mu \)m but the instrumental noise is too large to determine whether this is the case or not. Since flickering originates in the disc/bright spot proof of the existence or otherwise of flickering at J and K would show whether or not the primary contributes to the infrared radiation of the system.

**Interpretation**

The J and K light curves show a characteristic sinusoidal shape which suggests that in the near infrared the system is dominated by ellipsoidal variations of the late type secondary. These curves are similar to our observations of U Geminorum which have been described in Chapter 6. That the shape of the curves is the result of ellipsoidal variations is supported by the observed colours of the system. V-J is never less than \( 1.3 \) throughout the binary cycle while V-K is never
less than about $1.8$. This implies that $J$ flux (Watts/m$^2$/Hz) is always more than 50% higher than the $V$ flux and the $K$ flux is always about 70% or more higher. In addition, throughout the cycle $J-K = 0.6$ which is very close to the value $J-K = 0.58$ for a K2V star (Johnson, 1966). Allowing for errors of up to $\pm 0.2$ in our value for $J-K$ places the secondary in the range G8V - K6V. We cannot be sure that the secondary in EM Cyg is a main sequence star. Robinson (1974) shows that it clearly lies on the main sequence in the mass radius diagram but points out that unfortunately the evolutionary state of a star is not uniquely determined by its position on the mass radius diagram. He concludes that while the data for EM Cyg are entirely consistent with a main sequence interpretation other evolutionary states may be possible. In view of the lack of any other evidence we shall assume that the secondary does in fact lie on the main sequence.

The interpretation of our observations must be that a secondary of spectral type $\sim$ K2V provides essentially all the $J$ and $K$ light of the system. Consider the case in which the primary makes a large contribution at $J$. The $J-K$ colour of the secondary would be greater forcing it to be later than its observed (Robinson, 1974) G to K spectral class (a M0V star has $J-K = 0.89$). In addition either the $V-J$ or $J-K$ colour indices would disagree with observation for any reasonable primary continuum spectrum. However if future observations of this system were to prove the presence of intrinsic flickering at $J$ and $K$ this conclusion would have to be re-thought and an alternative explanation for our observations found.

It appears that the primary contributes comparatively little even at $V$. A K2V star has the colour $V-J = 1.57$ (Johnson, 1966). EM Cyg displays $V-J > 1.3$ throughout the cycle with $V-J = 1.5$ at primary minimum (phase 0.97). The primary therefore contributes about 40% of the $V$ light outside eclipse and a few percent at eclipse. Its contribution at $J$ and $K$ is very small. This is presumably because it is hot and of small effective area.
The observations of Mumford and Krzeminski (1969) show however that the eclipse of the primary cannot be total. They observe a B-V colour at primary minimum (< 0.65) which is consistently bluer than the B-V = 0.92 colour of a K2V star. Added to this the shape and depth of primary minimum varies considerably from cycle to cycle, which is contrary to expectations in the case of a total eclipse of the primary by the late type star. This explanation implies that the smooth variation in the V curves between the maxima at phases 0.25 and 0.75 is also caused by ellipsoidal variation of the secondary. The contribution of this variation to primary minimum can also been seen from the beginning of a decline at phase 0.8 and the slow recovery from primary minimum between phase 0.1 and 0.2. The decline after phase 0.8 - 0.85 is reversed by the hump due to the bright spot. These features can be clearly distinguished on Figs. 8.2 and 8.3.

Having identified the secondary as a K2V star we are now in a position to estimate the distance of the system. This distance estimate will have a small error if the secondary is found to lie slightly off the main sequence (as for example the secondary in U Gem does). From our arguments above we know that the mean K magnitude \( M_K = 11.7 \) represents solely the light from the secondary star. From Alllen (1973) we find that the absolute magnitude at V of a K2V star \( M_V = 6.3 \).

Adopting \( V-K = 2.15 \) for a K2V star (Johnson, 1966) gives \( M_K = 4.15 \).

\[
M_K = m_K + 5 - 5 \log D_{\text{pc}}
\]

\( D = 324 \text{ pc} \).

From the possible errors in our adopted spectral type (G8V - K6V) we can find the errors on this distance estimate. We find the distance to EM Cyg to be

\( D = 320^{+36}_{-64} \text{ pc} \).
Our interpretation of the wide shallow minimum from phase 0.25 to 0.75 in the V light curve as being due to ellipsoidal variation of the secondary means that no detectable secondary eclipse is observed at any wavelength. Since the secondary contributes significantly to the luminosity of the system this implies that the surface brightness of the primary must considerably exceed that of the secondary or an eclipse of the secondary would be observed. The secondary has an effective temperature of 5000 K (Johnson, 1966) so we must conclude that the average brightness temperature of the primary must be in excess of $10^4$ K at optical and infrared wavelengths for no secondary eclipse to be visible within the estimated errors in our observations. This is probably a lower limit to the temperature estimate at the outer edge of the primary's accretion disc. This temperature estimate is consistent with the observed B–V colours of the system and the increase of the eclipse depth towards shorter wavelengths seen in the observations of Mumford and Krzeminski (1969).

Our estimate of the brightness temperature implies a limit on the effective area of the primary which therefore allows us to calculate limits to the size of the optically thick disc region. Earlier we found that the primary contributes 40% of the mean V flux and therefore two-thirds of the contribution of the secondary.

Thus we have

$$\frac{A_P F_V(T_P)}{A_S F_V(T_S)} = \frac{2}{3}$$

where $A_P =$ effective area of the primary

$A_S =$ effective area of the secondary

$F_V(T_P) =$ surface brightness of primary

$F_V(T_S) =$ surface brightness of secondary.

A K2V star has an absolute magnitude $M_V = 6.3$ (Johnson, 1966).
The flux at V from this star is then

\[ A_sF_V(T_g) = 4\pi (10 \text{ pc})^2 \times 3.81 \times 10^{-23} \times 10^{-0.4 \times 6.3} \]

where \(3.81 \times 10^{-23}\) watts/m²/Hz is the apparent flux at V of a zero magnitude star.

\[ A_sF_V(T_g) = 1.377 \times 10^{11} \text{ W/Hz} \]

Since the brightness temperature we have obtained for the primary is high we can assume that the flux at V is approximately given by the Rayleigh-Jeans tail of the spectrum.

\[ F_V(T_p) = \frac{2\pi K T_{br}}{\lambda^2} \]

\[ F_V(T_p) = 2.87 \times 10^{-10} T_{br} \text{ W/m}^2/\text{Hz} \]

Then

\[ \frac{A_p 2.88 \times 10^{-10} T_{br}}{1.377 \times 10^{11}} = \frac{2}{3} \]

\[ A_p = 3 \times 10^{20} T_{br}^{-1} \text{ m}^2 \]

The effective area of the primary is \(3 \times 10^{20} T_{br}^{-1} \text{ m}^2\). If the major contributor to the primary's light is an accretion disc in the orbital plane of the binary of radius \(R_{\text{out}}\) then

\[ A_p = \pi R_{\text{out}}^2 \cos i \]

Robinson (1974) has obtained a mass ratio \(q = 1.3\) for EM Cyg and Paczynski (1971) gives a relation for calculating the radius of the Roche lobe of binary star components.

\[ \frac{R_L}{a} = 0.38 + 0.2 \log q \]

\[ \frac{R_1}{a} = 0.38 - 0.2 \log q \]

where \(R_L\) = radius of the Roche lobe of the secondary

\(R_1\) = radius of the Roche lobe of the primary

\(a\) = separation of the components
\[ q = \frac{m_2}{m_1} = \text{mass of secondary/mass of primary}. \]

Thus we find that \( R_2 = 0.4a \) and \( R_1 = 0.36a \). From the geometry of the system we then find that the inclination \( i \) of the system must be less than about 73° otherwise the primary would be totally eclipsed which is contrary to our conclusions earlier. Also we know that \( i > 55^\circ \) for an occultation to occur at all (Robinson, 1974). Since we know

\[
R_{\text{out}} = \left( \frac{3 \times 10^{20} T_{\text{br}}^{-1}}{\pi \cos i} \right)^{\frac{1}{2}}
\]

we can then put the limits on \( R_{\text{out}} \).

\[
1.3 \times 10^8 T_4^{\frac{1}{2}} \lesssim R_{\text{out}} \lesssim 1.8 \times 10^8 T_4^{\frac{1}{2}} \text{ m}
\]

where \( T_4 = T_{\text{br}} / 10^4 \text{ K} \).

Robinson (1974) found the binary separation \( a = 1.5 \times 10^6 \text{ m} \), while we found the average brightness temperature of the primary to be greater than or of order \( 10^4 \text{ K} \) so we have \( R_{\text{out}} \sim 0.1a \). This is in conflict with Robinson's estimate \( R_{\text{out}} \sim 0.4a \). However we have calculated the radius of the optically thick disc whilst Robinson's estimate used the velocity splitting of the emission lines which does not necessarily give direct information about the optically thick disc size. From the difference it would appear that there is considerable optically thin line-emitting material orbiting just inside the primary's Roche lobe. The value \( R_{\text{out}} \sim 0.1a \) we have calculated is very close to the minimum value allowed if one assumes that specific angular momentum about the primary is conserved within its Roche lobe (Warner, 1976).

We are now in the position to find the inclination of the system. To cause the near-total primary eclipse we inferred earlier (from the observation that it contributes just a few percent of the V light at
primary minimum), the inclination $i$ must obey
\[ \cos i = \frac{R_2}{(a + R_{\text{out}})} \, . \]

With $R_2 = 0.4a$ and $R_{\text{out}} = 0.1a$ we find $i = 69^\circ$. This is slightly higher than Robinson's upper limit $i = 67^\circ$. However Robinson derived his value for $i$ by assuming that the white dwarf was not eclipsed. He considered this a necessary condition to account for the variable nature of the eclipse since he believed the white dwarf to be a major contributor to the primary's light. However this assumption would mean that the primary makes a large contribution at all orbital phases, in disagreement with our deductions above from the infrared and optical photometry. The restriction on $i = 67^\circ$ can be dropped if, as here, the accretion disc is assumed to be the major contributor to the primary's light. The erratic changes in eclipse shape and depth observed in the optical light curves can be easily accounted for by the near-total eclipse geometry we have inferred, by attributing them to changes in brightness of the disc rim during phases of increased accretion. Using $i = 69^\circ$ we adopt the lowest values from Robinson's mass range since $69^\circ$ is so close to his upper limit to the inclination of $67^\circ$. We therefore find masses for EM Cyg of $M_1 = 0.52 \, M_\odot$ and $M_2 = 0.73 \, M_\odot$. This value for the mass of the secondary agrees rather well with the main-sequence mass one would deduce from the K2V spectral assignment ($M_2 = 0.74 \, M_\odot$; Allen, 1973) strengthening the view that the secondary does indeed lie on the main sequence.

A study of the ellipsoidal variations in EM Cyg would provide information about gravity and limb darkening in late type stars. In Chapter 6 we found
\[ \frac{3}{2} \frac{N r^3}{q} \sin^2 i = (1 - 10^{-0.4\Delta m}) \]
where $q$ is the mass ratio, mass secondary/mass primary
\[ i \text{ is the angle of inclination} \]
\[ N \text{ is the ratio of the photometric to geometric ellipticity} \]
\[ r \text{ is the radius of the secondary in units of } a \text{ (the separation of the components)} \]
\[ \Delta m \text{ is the amplitude of the variation in magnitudes.} \]

From our interpretation above we have \( q = 1.4 \) and \( i = 69^\circ \). Warner (1976) gives
\[
\begin{align*}
r &= 0.38 + 0.2 \log q \text{ for } q > 0.5.
\end{align*}
\]

In theory we can therefore calculate \( N_{1.2} \) and \( N_{2.2} \). In practice before \( N \) can be accurately determined the \( J \) and \( K \) light curves must be observed on a larger telescope, over several cycles to smooth out variations from cycle to cycle, so that \( \Delta m \) can be found precisely. However from our observations we can find first estimates of \( N_{1.2} \) and \( N_{2.2} \). Our light curves give values of \( \Delta m_J = 0^m.22 \) and \( \Delta m_K = 0^m.2 \) and thus we find approximate values of \( N_{1.2} = 2.87 \) and \( N_{2.2} = 2.63 \).

A paper on our interpretation of EM Cyg has been written. A copy is included in Appendix 1.

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**Footnote to p224**

REFERENCES

Ahnert, P. (1944), Kleinere Veröff, Berlin-Babelsberg 24, 71.
INTRODUCTION

TT Arietis (BD + 14°341, BV150 Ari) is a nova-like variable with a period of about 3 hr 12 minutes. In spite of being one of the brightest cataclysmic variables, $M_V = 10.2 - 11.8$, few observations have been made of this system. TT Ari was first recognised as a variable star by Strohmeier et al. (1957). Their photographic observations and those of Huth (1960) indicated light variations of irregular character. Herbig (1965) was the first to suggest that TT Ari was a cataclysmic variable. On the basis of photometric and spectroscopic observations by J. Smak and himself, he described the star as "SS Cygni-like".

PREVIOUS WORK

Light Curve

Few observations of the binary light curve of TT Ari have been published. Smak and Stepien (1969) suggest that the light variations of TT Ari can be resolved into three, apparently independent, components. The first is a periodic variation with a period of $P = 0^d.1329$ (i.e. about 3 hr 12 min). The shape of this variation is approximately that of a sine-wave. They assume that the orbital period is twice this (i.e. $P = 0^d.2658$), giving a double sine-wave light curve with two nearly equal minima and two only slightly different maxima per orbit. However they admit that the observed differences in the maxima and minima may not be real, just being due to variations in the light curve from cycle to cycle. In this case the orbital period would be $P = 0^d.1329$. 
The amplitude of the variation is about $0^m.15$.

The second component of the light curves consists of quasi periodic fluctuations with periods between 14 and 20 minutes. Their amplitude can be as large as $0^m.2$. Williams (1966) made a statistical analysis of one of the photometric runs of Smak and Stepie and concludes that this quasi periodicity is a transient phenomena. He found that two predominant periodicities were present of about 14 and 18 minutes. This quasi periodic component comes and goes without any obvious regularity and usually lasts no longer than about 3 hours. The amplitude is largest in the UV and smallest at V.

The third component observed in the light curves is an irregular flickering with an amplitude of about $0^m.1$ and a time scale of the order of 1 minute. Such flickering is observed to a greater or lesser degree in all cataclysmic variables.

Further photometric observations were obtained by Mardirossian et al., in November 1978. These were first described by Mardirossian et al. (1979) and were later published in more detail (Mardirossian et al., 1980). They report strong flickering (up to 0.1 mag) superimposed on the regular sinusoidal light variations of amplitude $0^m.2$, associated with the orbital period (taken as the spectroscopic period $P = 0.137551$ of Cowley et al., 1975). No eclipses were observed in the light curves. They suggest that the almost sinusoidal light variation can be attributed to the phase dependent appearance of the bright spot observed in many cataclysmic variables.

Power spectral analysis of their orbital light curves revealed that no stable periodic brightness variations exist. However they found short lived ($\sim 25$ min) oscillations in some runs. The period of those oscillations changes erratically between 32 and 43 seconds. These oscillations have a duration at least one order of magnitude less than
the coherent oscillations found in many other cataclysmic variables, and
the period of around 40 seconds is longer than in most other systems.
Quasi periodic oscillations with similar periods have been observed
from six cataclysmic variables (see Chapter 2) but their lifetimes are
typically only 3 - 5 cycles.

Sztajno (1979) also obtained photometric observations of TT Ari
in November, 1978. The first three nights of his observations were
simultaneous with those of Mardirossian et al. A comparison of the
two sets of data shows that the star was more active at B (Sztajno)
than in white light (Mardirossian et al.). Sztajno found an orbital
period for TT Ari of $0^d.1326 \pm 0^d.0002$. The amplitude of the variation
in blue light is $0^m.2$. In addition to the orbital period variations, he
found a quasi periodic component of amplitude about $0^m.2$, with a period
of 13.6, 13.1, 14.4 and 13.5 minutes for the four nights respectively,
and a second periodicity of around $0^m.1$ and a period of about 40 sec.

From the various observations it appears confirmed that three
components are seen in the light curves of TT Ari.
1) An orbital period of about 3 hr 12 min.
2) A quasi periodic oscillation of period 13 - 20 minutes.
3) A quasi periodic oscillation of period 32 - 43 seconds.

Spectrum

The first spectra of TT Ari were those of Herbig (see Smak and
Stepien, 1969). He found that the spectrum was essentially featureless
with very weak and diffuse emission lines of the Balmer series.
Williams (1966) reports similar observations.

Recent spectra of Cowley et al. (1975) show more features. The
spectrum is characterised by weak hydrogen emission lines, seen down
to about H12, on broad shallow absorption lines. Broad weak emission
is seen at $\lambda 4686$ (HeII) and near $\lambda 4647$ (a blend of CIII and NIII). An even weaker emission blend of CIII near $\lambda 4069$ and probably the SiIV lines at $\lambda 4088$ and $\lambda 4116$ can also be seen. Faint HeI absorption principally at $\lambda 4471$ and $\lambda 4026$ is sometimes present. The hydrogen emission shows variable structure, even at the rather low ($\sim 80$ Å mm$^{-1}$) dispersion of these observations. The emission peak and centre of the line are not always coincident. The spectrum also shows a very shallow Balmer decrement. The $H\beta$ line is wider and stronger than would be expected from the widths and the decrement of the higher Balmer lines. Cowley et al. (1975) suggest that these observations are explained if the $H$ emission (especially $H\beta$) consists of at least two components, which are never completely resolved and which arise in regions of different physical conditions. Radial velocity measurements support this interpretation. The amplitude of $H\beta$ is smaller than that of the higher lines by about a factor of two.

Cowley et al. (1975) also measured the velocity of the HeII $\lambda 4686$ line. The line is very weak and broad so all measurements are somewhat uncertain. They find that the velocity amplitude of HeII is larger than that of the Balmer lines and shows a phase shift with respect to the hydrogen lines. They interpret this in terms of a non uniform rotating ring about the primary. If the HeII line is formed in a limited region (bright spot) close to the star, then rotation and orbital motion will both contribute to the observed radial velocity, whereas, if the hydrogen lines are emitted around the whole star, their velocity will refer to the motion of the star. The velocity curve for a limited bright spot will differ from the mean motion of the star depending on the relative values of the rotational stream and orbital velocities, but the amplitude should be larger and the maximum is expected to be reached later for the bright spot. This is in agreement with their observations.
Orbital Period

All the lines observed in the spectrum of TT Ari are faint and thus measurements of these lines are subject to error. However, except for Hβ, radial velocities derived from the hydrogen emission lines show similar variations. If the emission lines are interpreted as coming from a ring or disc of material close to the hot star, as with other cataclysmic variables, the measured radial velocity variations can be used to derive the orbital parameters of the system.

The spectroscopic observations of Cowley et al. (1975) extend to four years of observations, 1970-1974. The 1970 data is best fitted by a period of $0^d.13749$ while the best period for the 1973 data is $0^d.1372$. The short period makes it difficult to use data separated by several years to determine the period, since so many cycles intervene, allowing several very nearly equal periods to fit the data. However, they find a best fit period for all their data combined, of $P = 0^d.13755$.

Observed photometric periods differ significantly from the spectroscopic periods. Smak and Stepien (1975) report a photometric period, $P = 0^d.1329 \pm 0.00005$ from observations in 1961-62 and a period, $P = 0^d.1327$ from observations in 1966. Sztajno (1979) found a period, $P = 0.1326$ from his photometric observations in 1978. It appears that these large differences are real and Sztajno suggests that the system has two different periods associated with its photometric and spectroscopic activity.

Cowley et al. (1975) also find that spectroscopic and photometric observations do not agree. They report photometric observations by Nather, Warner and their co-workers in Texas in 1971 and 1972. From photometric observations in 1971, only 1 week from some of their spectroscopic data, they find that light maximum occurs very near velocity maximum of the emission lines. However, adopting their
spectroscopically determined period, the subsequent photometric runs
do not fit this picture. Combining the Texas photometric data and
their spectroscopic data, Cowley et al. (1975) find a best fit period
\[ P = 0^{d}.13735 \pm 0^{d}.0002, \]
but this does not fit the spectroscopic data
as well as their earlier result \( (P = 0^{d}.13755) \). The standard deviation
of the fit of the observations to the orbital elements is increased by
about 20%.

At present therefore we must consider the period only approximately
known. Combined spectroscopic and photometric observations over several
weeks are clearly needed to establish the period accurately. It may be
that maximum light and maximum velocity do not always occur simultaneously
if the extent or position of the bright spot varies.

Masses and Orbital Inclination

From their radial velocity measurements Cowley et al. (1975) have
attempted to estimate the masses of the components and the orbital
inclination of the system. There is evidence in the spectrum that the
emission lines from the disc are contaminated by emission from the bright
spot. The Balmer emission is observed to vary in intensity by a factor
of about two with orbital phase. In addition the HeII and CIII
emission lines are observed to be slightly stronger at the phase of
the enhanced hydrogen lines. From a comparison of their spectroscopic
data and Texas photometric data, Cowley et al. found that maximum
intensity of the emission lines and light maximum both occur near the
same phase (when the hot star is receding). Taking the usual model of
cataclysmic variables, this suggests that a considerable contribution
to both the line emission and the continuum radiation comes from the
bright spot. Therefore, measured radial velocities will not represent
the motion of the central body (white dwarf) without a correction being
applied. Before such a correction can be made accurately a knowledge of the geometry of the system (extent and position of the hot spot, inclination of the orbit, size of the disc, etc.) is required.

The geometry of the system in TT Ari is unknown but some correction must be made to the observed radial velocities before they can be used to estimate the parameters of the system. Cowley et al. (1975) adopt a correction to the observed maximum $K_1$ of the H emission lines of 25%. Their value is based on the observed behaviour of the HeII emission which varies little with phase and is thought (see above) to be emitted primarily by the bright spot, and on the observed line widths. From their observations they then obtain a value of $K_1 = 60$ km s$^{-1}$ with an estimated error of 20%. This leads them to a mass function

$$\frac{PK_1^3}{2 G} = \frac{(M_2 \sin i)^3}{(M_1 + M_2)^2} = 0.0031 \pm 60\%$$

where $M_1$ is the mass of the primary
$M_2$ is the mass of the secondary
$i$ is the orbital inclination.

Cowley et al. (1975) tabulate possible values of $i$, $M_1$ and $M_2$. They find that $M_1$ must be at least twice as massive as $M_2$ for reasonable masses of both stars. Assuming that $M_1 \sim 1 M_\odot$ and $q \sim 0.4$ (from Warner's (1973) period-mass ratio relation) they find $M_2 \sim 0.4 M_\odot$. This agrees well with the estimate of the secondary mass from the mass-period relation of Warner (1976) which gives $M_2 \sim 0.37 M_\odot$. These values lead them to conclude that the orbital inclination of the system is between $30^\circ$ and $40^\circ$. In view of the fact that (a) no eclipses are observed, (b) the emission lines do not show double peaks, as in the edge-on systems and (c) the velocity amplitude is not large, this estimate of the inclination seems reasonable. However in view of the
errors associated with measuring faint emission lines and the uncertainty of the correction for the effect of the bright spot on the radial velocities, it should be considered with caution. Indeed, any value of i that does not cause eclipses would seem possible.

Colours

Szkody (1977) has measured the U, B, V, J, H, K, L colours of TT Ari. Her observations show that from B to K the colours of TT Ari are those of a black body of $T_e \sim 10,000$ K. The L colour shows a small infrared excess which she attributes to a cool shell (black body $T \sim 1000$ K) around the system.

OUR OBSERVATIONS

Our observations of TT Ari were made at Tenerife in August 1979. On 1979 Aug 21/22 the system was observed for just over one complete period simultaneously at K and V. On 1979 Aug 22/23 just over one period was observed simultaneously at J and V, and on 1979 Aug 23/24 B, V, J, K observations were made for about three and a half hours. The resulting light curves are shown in Figs. 9.1, 9.2, 9.3 and 9.4. The readings are plotted in magnitudes calibrated against the standard star BS 718 which has the magnitudes

$$B = 4.23, \ V = 4.29, \ J = 4.41 \text{ and } K = 4.43 \ (Johnson \ et \ al., \ 1966).$$

All readings have been corrected for atmospheric extinction. In Figs. 9.1 and 9.2 each point is the difference between a 20 sec integration performed in each channel while in Figs. 9.3 and 9.4 each point is the average of 10 such readings. The errors shown are estimated from similar observations of a non-varying star of approximately the same magnitude. In view of the uncertainty in the epoch and period the observations are plotted against Julian date rather than phase. Attempts to plot the
Fig 9.1 Simultaneous $K$ and $V$ light curves of TT Arietis. The error bars are derived from observations of a non-variable star of similar magnitude and show that the flickering is definitely real.
Fig 9.2 Simultaneous J and V light curves of TT Arietis. The error bars are derived from observations of a non-variable star of similar magnitude.
Fig. 9.3  B and V light curves of TT Ari. 1979 Aug 23/24
(Errors on the points less than ±0.001 mag)
Fig. 9.4 J and K light curves of TT Ari. 1979 Aug 23/24
observations against the ephemerides of Cowley et al. (1975) failed to produce realistic plots.

Figs. 9.1 - 9.4 show that the system brightened steadily during the three nights of observation. The V magnitudes for the three nights are

1979 Aug 21/22 V $\sim 11.4$
1979 Aug 22/23 V $\sim 10.9$
1979 Aug 23/24 V $\sim 10.75$.

Thus for the majority of the observations the system was below its normal V magnitude V $\sim 10.8$. The V magnitude of the system is known to vary from V = 10.2 - 11.8.

On the first night of observation a very large flickering was observed on the curves. This flickering is so large (particularly at V) that it is difficult to distinguish variations due to the orbital cycle. Observations of other stars of similar magnitude on the same night showed that this flickering is undoubtedly real, not instrumental. At V the instrumental noise is a negligible fraction of the flicker and at K the instrumental noise is about 50% of the amplitude of the flicker. Thus we must conclude that the observed flicker is real since the instrumental noise and a smaller flicker would not be expected to add coherently to produce the observed variation. On the second night of observation, when the system was brighter, the flickering was still present but with a much reduced amplitude. The average flicker on each curve is

1979 Aug 21/22 V flicker $0^m.42$ or 32% total light
1979 Aug 21/22 K flicker $0^m.14$ or 11.5% total light
1979 Aug 22/23 V flicker $0^m.06$ or 5.7% total light
1979 Aug 22/23 J flicker $0^m.08$ or 7% total light.

So that the form of the light curve can be seen more clearly
Fig. 9.5 shows the observations from 1979 Aug 21/22 binned such that each point is the mean of nine readings from Fig. 9.1. A smooth curve has been drawn through the resulting points. Fig. 9.6 shows the second night's data treated in the same manner as a comparison. Error bars are shown on each point.

Since our observations only cover just over one orbital period on each of the three nights they cannot be used to determine an accurate orbital period. Neither can we search for the ~40 sec quasi periodicity, since the time resolution of our observations is only ~35 secs. However, we can look for the 14-20 minute quasi periodicity observed by Williams (1966) and Sztajno (1979). Certainly the humps between JD 2444108.66 and 2444108.68 in Fig. 9.2 suggest that such a periodicity may be present.

Each of the four light curves from the first two nights was tested separately for the presence of a quasi periodic oscillation. The variations due to the orbital cycle were first removed from the data by subtracting a greatly smoothed curve (by method described in Chapter 3) from the original readings. The curves were then tested for periods between 6 and 25 minutes using the method of Bopp et al. (1970). Since a periodicity appeared to be present in the latter halves of the J and V curves from the second night, a separate analysis was also done on each half of these two curves.

The results were inconclusive. The only light curve that showed reasonable evidence for a periodicity was the V curve on Aug 21/22. Periods of 14.11 and 16.88 minutes were identified. No periods were found in the simultaneous K data for this night nor in the analysis of the complete J and V curves from the following night. When the data from the second half of the observations on Aug 22/23 (where the light curves appear to show an oscillation) were analysed no period
Fig 9.5 The K and V observations from Fig 9.1 binned to reduce the intrinsic flickering and instrumental noise. The errors on the V points are less than ± 0.001 mag.
Fig 9.6 The J and V observations from Fig 9.2, binned for comparison with Fig 9.5.
The errors on the V points are less than ± 0.001 mag.
was found in the V curve but some evidence for a periodicity of 18.55 minutes was found in the J curve.

Whether these periodicities really exist is difficult to establish. It certainly seems that if present their lifetimes are only of the order of 5 - 7 cycles. The results of the Bopp analysis are shown in Fig. 9.7. If a periodicity exists a sharp minimum should be observed at that period. The reader may judge for himself the significance of our results.

Interpretation

Our light curves, particularly those of Aug 22/23, closely resemble the light curves of several other cataclysmic variables. A prominent hump is seen per orbital cycle but no eclipses are evident. As in VW Hyi it appears that the orbital variations are due solely to the changing aspect of the bright spot. There is also evidence for a secondary maximum in some curves. This again resembles VW Hyi where a secondary hump in the light curves is sometimes present.

The prominent hump in the curves lasts $\sim 0.35 - 0.4$ of the orbital period. Our observations show that although the V magnitude of the system brightened by $\sim 0.5$ between Aug 21/22 and Aug 22/23, the amplitude of the hump in intensity units remained virtually constant, decreasing only 5% between the two nights. This is in agreement with the observed behaviour of the bright spot hump in other systems (Warner, 1976). The bright spot contributes a considerable fraction of the light of the system at V. The size of the hump gives a lower limit (since the bright spot will make some contribution to the luminosity throughout the orbital cycle) to the bright spot contribution. The hump was 40% of the maximum V flux on Aug 21/22 and 28% on Aug 22/23 and Aug 23/24. This can be compared with VW Hyi where the bright spot contributes about
Fig. 9.7 Bopp analysis curves
50% of the V flux.

At first sight it therefore appears that our light curves show variations due to a typical cataclysmic variable bright spot. From our simultaneous J and V observations on Aug 22/23 1979 we can measure the V-J colour of both the flat part of the curve and the hump. We find

\((V-J)_{\text{hump}} = -0.246\) and \((V-J)_{\text{flat}} = -0.131\). These colours imply blackbody temperatures for the hump (i.e. bright spot) and flat part of the curve (i.e. disc) of 13800 K and 12050 K respectively. On the same night the V flux in the hump was 40% of the V flux of the flat curve.

\[
\frac{A_s}{A_d} \frac{B_v(T_s)}{B_v(T_d)} = 0.4
\]

where \(A_d\) is the observed area of the disc

\(A_s\) is the observed area of the spot

\(T_d\) is the black body temperature representing the disc

\(T_s\) is the black body temperature of the spot.

Substituting the temperatures found from our colours in this equation gives \(A_s = 0.29 A_d\). This is rather large for a typical bright spot. If the secondary contributes to the J flux from the system (but not to the V flux) calculations show that the area of the spot is a larger fraction of the area of the disc as the contribution of the secondary increases.

TT Ari shows another unusual feature in that although the binary period is not known exactly, the spectroscopic period definitely appears longer than the photometric period by \(\sim 6.5\) minutes (Cowley et al., 1975; Sztajno, 1979). It seems likely that the unusual bright spot and the discrepancy in the spectroscopic and photometric periods are connected. The spectroscopic period is probably the true binary period, while the shorter photometric period may possibly be explained as a mass transfer period, the period being less due to the precession of the secondary star.
Colours

From our results we can study both the colours of TT Ari and variations in the colours with changes in the brightness of the system at V. The observed colours are listed below. They are tabulated for both the flat part of the curve (subscript f) and the hump (subscript h) for the nights of Aug 21/22 and 22/23. The V-K colour on Aug 22/23 results from a point measurement simultaneously at V and K. Colours are listed for two points on the light curves of Aug 23/24 where the behaviour of the curve was similar at all wavelengths.

<table>
<thead>
<tr>
<th></th>
<th>Aug 21/22</th>
<th>Aug 22/23</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>V_f = 11.48</td>
<td>V_f = 10.95</td>
</tr>
<tr>
<td></td>
<td>V_h = 11.05</td>
<td>V_h = 10.70</td>
</tr>
<tr>
<td>(V-K)_f</td>
<td>0.49</td>
<td>(V-J)_f = -0.13</td>
</tr>
<tr>
<td>(V-K)_h</td>
<td>0.21</td>
<td>(V-J)_h = -0.25</td>
</tr>
</tbody>
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<table>
<thead>
<tr>
<th></th>
<th>Aug 23/24</th>
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<tbody>
<tr>
<td>JD 2444108.58</td>
<td>JD 244108.68</td>
</tr>
<tr>
<td>V</td>
<td>10.74</td>
</tr>
<tr>
<td>B-V</td>
<td>-0.31</td>
</tr>
<tr>
<td>V-J</td>
<td>-0.27</td>
</tr>
<tr>
<td>V-K</td>
<td>-0.17</td>
</tr>
</tbody>
</table>

Our colours can be compared with those observed by Smak and Stepien (1969) and Szkody (1977).
We can see from the results of Aug 21/22 and Aug 22/23 that the system became bluer as it brightened to close to its normal V magnitude (V = 10.8). Also both nights show that the hump is bluer than the rest of the system. This is in agreement with the results from other cataclysmic variables which are also seen to be bluer on the hump than during the rest of the orbital cycle.

On the third night when the star was at its normal brightness our V, J, K colours imply black-body emission with Te $\sim$ 10,600 - 14,000 K. Our B colour appears bluer although it should be remembered that the B filter is slightly non standard (see Chapter 3), allowing more shorter wavelength radiation through than is normal. When our observed B flux is corrected for the effect of the non standard filter the B-V colour also gives a black-body temperature Te $\sim$ 11,300 K. Our results agree well with the B-V colour of Smak and Stepień (1968) which implies a black-body temperature Te $\sim$ 11,000 K, and the B, V, J, K colours of Szkody which give a black-body temperature, Te $\sim$ 9,500 - 10,600 K. The U colours of both these authors are bluer.

A picture therefore arises for TT Ari at normal brightness of emission with a black-body temperature, Te $\sim$ 11,000 K from the disc and bright spot dominating the spectrum from B to K. At U and sometimes possibly at B excess short wavelength emission, presumably from the hot inner disc region is seen. The L (3.6 μm) point measured by Szkody
shows a small infrared excess. Szkody attributes this to radiation from a cool shell around the system as we have observed in EX Hya but it could also be due to a contribution from the late type secondary, which would be relatively bright in the infrared. When the system is fainter the colours of the system are redder. If the changes in brightness of the system are attributed to variations in the luminosity of the disc, as with other cataclysmic variables, these redder colours are probably due to the contribution of the secondary becoming noticeable, at long wavelengths (J and K).

**Distance**

Cowley et al. (1975) report that the proper motion of TT Ari has been studied by Dr. Luyten. He finds that the proper motion is less than 0".05 annually. In the direction of TT Ari the solar motion would produce a proper motion larger than 0".05 if the distance is less than ~80 pc. This is the only estimate for the distance of TT Ari that is available. However we can use the observed colours and flickering of the system to estimate the K magnitude of the secondary and hence the distance, if we assume that the secondary is a main sequence star. (The secondaries of other cataclysmic variables appear to be on or close to the main sequence.)

Consider the observations of Aug 21/22 when the flickering on the curve was large and the system was faint. The percentage of the light of the system that the flickering represents on both the flat part of the curve and the hump separately is

\[
\begin{align*}
V_f \text{ flicker} & \quad 30\% \\
v_h & \quad 33.6\% \\
K_f \text{ flicker} & \quad 12\% \\
k_h & \quad 11\%
\end{align*}
\]

Assuming that the dilution of the flicker between V and K represents the contribution of the secondary at K, we obtain the relative
The observed $K$ magnitude on each part of the curve is the sum of these two contributions.

We have therefore

\[ 10^{-0.4 \times 10.95} = 10^{-0.4K_S} + 10^{-0.4K_d} \text{ from flat curve} \]

\[ = 1.6666 \times 10^{-0.4K_s} \]

\[ K_S = 11.50 \]

and

\[ 10^{-0.4 \times 10.8} = 10^{-0.4K_S} + 10^{-0.4K_d} \text{ from hump} \]

\[ = 1.5 \times 10^{-0.4K_s} \]

\[ K_S = 11.24 \]

We can also obtain the apparent $K$ magnitude of the secondary from the observed colours of the system. Our observations and those of Szkody (1977) show that at normal brightness the system emits as a black-body with a temperature $T_e \approx 11,000$ K from B to K. Such a black-body has the colour $V-K = -0.17$ (Johnson, 1966). If we assume that this is emission from the disc and bright spot (which seems reasonable) and that the observed $V$ magnitude on the first night, when the system was faint, represents solely radiation from the disc/bright spot, we can then estimate the $K$ magnitude of the disc on the first night.

Taking the flat part of the curve and the hump separately we have

\[ V_d = 11.4 \quad K_d = 11.57 \text{ from flat curve} \]

\[ V_d = 11.0 \quad K_d = 11.17 \text{ from hump} \]

The observed $K$ magnitude, when the system is faint, represents the sum of the emission from the disc/bright spot and secondary. There-
If we then average the results from the two methods, which are in reasonable agreement considering the approximate nature of our calculations we find

\[
K_s = 11.68 \quad \text{considering flat curve}
\]

\[
K_s = 11.67 \quad \text{considering hump}
\]

The apparent magnitude of the secondary is therefore \( m_K = 11.67 \pm 0.45 \).

From the mass-period relation for the secondary (Warner, 1976) we find that the secondary in TT Ari has a mass \( M_2 = 0.37 M_\odot \). This implies an M2V secondary which has \( M_V = 10.12 \) (Allen, 1973) and

\[
V-K = 4.27 \quad \text{(Johnson, 1966), giving} \quad m_K = 5.85.
\]

\[
\frac{m_K - M_K}{K} = 5 \log_{10} Dpc - 5
\]

This distance appears reasonable and is in good agreement with the distances found for other cataclysmic variables. However the spectral type of the secondary in TT Ari given by Warner's mass-period relation is earlier than the observed spectral type of the secondary in U Gem (M4.5; Wade, 1979) which has a longer orbital period. This suggests that the spectral type of the secondary may be later than given above. The resulting distance to the system would then be less.

We can check our distance estimate to see if it leads to a reasonable disc radius. Assuming, as before, that all the V luminosity of the system originates from the disc/hot spot region, we have, when the system is at normal brightness,
\[ \frac{\pi r_d^2 \cos i F_\lambda(T)}{4 \pi D^2} = 3.92 \times 10^{-12} \times 10^{-0.4} \times 10^{0.8} \]

where \( r_d \) is the radius of the disc

\[ F_\lambda(T=11,000 \text{ K}) = 7.594 \text{ W m}^{-2} \]

with \( D = 146^{+33}_{-27} \) pc and taking \( i = 35^\circ \) (Cowley et al. (1975) estimate \( 30^\circ < i < 40^\circ \)) we find

\[ r_d = (4.95^{+2.03}_{-0.92}) \times 10^{10} \text{ cm} \]

From Kepler's Law we know that the separation of the two components \( a \) is given by

\[ a = \left( \frac{G(M_1 + M_2)P^2}{4 \pi^2} \right)^{\frac{1}{3}} \]

Taking estimates for the masses of

\[ M_1 = 1 \text{ M}_\odot \]
\[ M_2 = 0.37 \text{ M}_\odot \text{ (from Warner's mass-period relation)} \]

we have

\[ a = 8.468 \times 10^{10} \text{ cm} \]

Our disc radius is therefore \( r_d = (0.58^{+0.13}_{-0.1})a \). This appears to be rather large. From Roche geometry we can estimate the size of the Roche lobe of the primary for our chosen mass ratio.

\[ \frac{R_L}{a} = 0.38 + 0.2 \log \left( \frac{1}{q} \right) \text{ where } q = \frac{M_2}{M_1} \text{ (Paczynski, 1971)} \]

\[ R_L = 0.47a \]

From our distance estimate we therefore find a disc radius which is greater than the radius of the Roche lobe of the primary. If we take the lower limit to the radius of the disc, given by the errors in our calculations of the apparent magnitude of the secondary, we find that the disc is virtually the same size as the Roche lobe of the primary. Since tidal effects are expected to truncate the disc at the
size of the primary's Roche lobe (Papaloizou and Pringle, 1977;
Paczynski 1977) our calculated disc radius is obviously too large. The
distance we calculated must therefore be too great since varying the
values of $i$, $M_1$ and $M_2$ will have little effect on the results. In
view of the approximate nature of our calculations it is not surprising
that there is some error.

If we assume that the disc fills the Roche lobe of the primary
we can reverse the above procedure to find the distance of the system
and the spectral type of the secondary. Taking $r_d = 0.47a$ and other
values as before we find $D = 118$ pc. This then implies, if the
apparent magnitude of the secondary is taken as $m_K = 11.67$ (the value
estimated from our considerations of the colour of the system and the
flickering) a secondary with an absolute magnitude at $K$, $M_K = 6.31$.
This in turn leads to a secondary of spectral type $M4V$ ($M_K = 6.37$).
This spectral type is two divisions later than predicted by the mass
period relation but still earlier than the observed spectral type of
the secondary in U Gem. Considering the errors in our estimate of the
apparent $K$ magnitude of the secondary we find that the spectral class
of the secondary lies in the range $M2V - M5V$.

From our considerations of the flickering and colour of the
system and accepting that the disc fits within the Roche lobe of the
primary we find a distance to TT Ari of 118 pc and a spectral type for
the secondary of $M4V$. If we force the disc to be smaller than the Roche
lobe of the primary the distance becomes less and the spectral type of
the secondary later. A lower limit to the distance of 80 pc has been
set by Luyten's proper motion results. Taking the apparent magnitude,
$m_K = 11.67^{+0.45}$, the minimum distance $D = 80$ pc implies a secondary of
spectral type $M5V - M6V$ and a disc radius 70% of the radius of the
Roche lobe of the primary ($r_L$).
We can estimate the radius of the disc on the first night of observation, when the system was faint, from the observed $V$ magnitude, $V = 11.5$. Taking the minimum distance $D = 80$ pc we find $r_d$ (radius of disc) = 49% $r_L$ (radius of the Roche lobe of the primary) while if we take $D = 120$ pc (maximum distance) we find $r_d = 74\% r_L$.

We conclude that the distance to TT Ari $D = 100 \pm 20$ pc and the spectral type of the secondary lies in the range M2V - M6V. The calculations suggest that at normal brightness ($V = 10.8$), the disc in TT Ari is large ($> 70\% r_L$). Since a $\nu$ disc spectrum is not observed at $V$, $J$ and $K$ the disc must be hot.
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Z CHAMAELONIS

Z Chamaeleontis is a southern dwarf nova with a mean $V$ magnitude, $m_V = 15.2$ at quiescence. It was discovered to be an eclipsing binary with a period of 107 minutes by Mumford (1969a,b; 1971). It is a confirmed member of the SU UMa subgroup showing both normal outbursts and supermaxima. Although it is fairly faint at quiescence it has been well studied because for a long time it was the only dwarf nova in which the white dwarf was known to be eclipsed by the companion star. It therefore provided a unique opportunity for the study of the accretion processes in dwarf nova systems and the changes which take place during outburst. Recently the dwarf nova OY Carinae has also been found to show the eclipse of the white dwarf.

The New Zealand Variable Star Observers have made extensive observations of the outburst light curve of Z Chamaeleontis (Bateson, 1978). They find a mean interval between successive maxima of $93.35^d$ with the system reaching a maximum brightness of $M_V = 12.4$ during normal outbursts and $M_V = 11.8$ during supermaxima.

PREVIOUS WORK

Spectrum

At quiescence the spectrum of Z Cha shows strong doubled emission lines of H and HeI ($\lambda 4471$, $\lambda 5876$). A study of spectra taken around the 107 minute binary orbit, (Whelan et al., 1979) shows that the Balmer emission line flux varies little as a function of orbital phase but is slightly increased when the bright spot is visible. In contrast the
HeI lines are noticeably stronger at phases when the bright spot is visible.

During eclipse the continuum flux decreases and becomes much redder. However some line emission remains visible. The eclipse data show that the effective size of the Balmer emitting region is nearly the same as that part of the red star along the line of sight. An investigation of the Hα line profile during eclipse shows that the disc rotates progradely as found for DQ Her, by Greenstein and Kraft (1959) and Kraft (1959) and also that the inner disc rotates faster than the outer part.

The spectrum of Z Cha during a supermaximum has been observed by Vogt (1979). He identifies HeII and CIII in emission and the K line in absorption. In the majority of his spectra the Balmer lines show three components. A blue and a red emission component which are mainly present in Hβ and Hγ and one absorption component which is confined to the higher members of the Balmer series. All three Balmer components show roughly parallel variations with a semi-amplitude of about 120 km s$^{-1}$ which proves that they all originate from the blue component of the binary system.

The two emission components can be attributed to the outer part of the disc. Their separation of about 1200 km s$^{-1}$ and small resulting system velocity near 0 km s$^{-1}$ are typical values for cataclysmic binaries of high orbital inclination. However the absorption lines show a mean velocity of +260 km s$^{-1}$ which differs significantly from the system velocity. The velocity of the absorption line also appears to vary from night to night. The parallel velocity variations of absorption and emission with orbital phase suggests that the absorption lines are caused in the central part of the disc or in the white dwarf's atmosphere. This is supported by the disappearance of the absorption
lines during the eclipse. However this does not explain the large mean velocity of the absorption system.

**Binary light curves**

Z Cha was discovered to be an eclipsing binary by Mumford (1969a,b; 1971). His observations comprise the only published U, B, V light curves of the system, the other photometric observations being in white light. His three colour observations indicate that the system gets bluer as expected during the rise to maximum pre eclipse brightness. He found the primary minimum to be $2^m0$ deep. This suggested a high orbital inclination, perhaps sufficient to ensure eclipses of the primary during outburst and so prompted Warner (1974) to study Z Cha.

Both Warner (1974) and Bailey (1979) have obtained high speed photometric observations in white light of Z Cha. At quiescence Warner's (1974) light curves show a hump lasting approximately half the orbital period. The hump shows the same increase in flickering activity at its peak as is observed in other systems (e.g. U Gem). The primary minimum shows a sudden onset followed by an extremely rapid drop in brightness. At about 62% of the way down to minimum there is a pause lasting about 20s, after which the decline to minimum is relatively slower. Eclipse minimum shows a gently rounded or flat bottom. There is a very rapid rise in the first stage of egress during which the increase of intensity is closely equal to the initial drop at ingress. The final stages of egress show a more gradual recovery of brightness. The width of the eclipse at half depth is 340s. No secondary eclipse is observed.

Bailey's (1979) light curves show a similar form. However during the six eclipses he observed the standstill on the decline lasted about 80s compared with the 20s standstill observed by Warner. In some of
Bailey's light curves it is also clear that the rise occurs in two stages, separated by a much longer standstill. A typical light curve of Z Cha in white light and a magnified view of three eclipses observed by Bailey (1979) are shown in Fig. 10.1.

Both authors explain the observed eclipse behaviour by assuming that there are two eclipsed objects, A and B. The initial sharp drop is caused by object A going into eclipse. Following the standstill object B goes into eclipse and the slower fall indicates that it is larger than A. The initial rise is clearly the emergence of object A as it closely matches the initial fall. After a longer standstill object B emerges from eclipse. The eclipse of object A shows no significant variation in duration or binary phase. On the other hand the eclipse of object B is variable in phase and the brightness of object B varies both in the long term and during each eclipse.

In terms of the standard model of cataclysmic variables it is natural to interpret object A as the white dwarf and object B as the bright spot. The observed duration of the ingress and egress of object A is 40s. With the typical separation of a short period binary system this indicates a radius of order $10^9 \text{ cm}$ - just that expected for a white dwarf. It is not clear whether the radiation actually comes from the white dwarf or from the central parts of the disc which can have a brightness distribution highly concentrated towards the centre (Bath et al., 1974).

For a long time, until the recent observation of the eclipse of the white dwarf in OY Car, Z Cha was the only dwarf nova in which the eclipse of the white dwarf was observed. Thus observations of this system during outburst are important for testing outburst models. Warner (1974) observed Z Cha during a supermaximum and found a deep primary minimum still present in the light curves. At maximum the
Fig. 10.1(a) Light curve of Z Cha obtained on 1977 December 9/10.
(after Bailey, 1979)

Fig. 10.1(b) Eclipse light curves of Z Cha observed on (a) 1977 Nov.15/16 and (b,c) 1977 Dec. 9/10. (after Bailey, 1979)
primary eclipse is symmetrical except for a slow recovery during the last stages of egress. During one of his observing runs Z Cha was about 13 times brighter than at normal light indicating that the outbursting region was contributing at least 92% of the light from the system. The presence of deep eclipses shows that the outbursting region was being largely obscured and the rounded bottom to the observed eclipse suggests a partial or annular eclipse. The fact that the eclipses during outburst occur at the times predicted from primary minima observed at normal light establishes that the same star is eclipsed at minimum and maximum light and therefore that the white dwarf/inner disc is the seat of the outbursts.

Warner (1974) found a change in the shape of primary minimum between maximum and minimum light. At maximum the eclipse has a width at half depth of 350s (i.e. essentially identical to that seen at minimum light) but its width from first contact to last contact is \( \sim 825 \)s (against \( \sim 400 \)s at minimum). The similarity of eclipse width at half depth shows that the eclipsing body has a constant diameter while the increase in total width implies an increase in the radius of the white dwarf/inner disc from \( \sim 10^9 \) cm to \( \sim 1.3 \times 10^{10} \) cm.

Coherent Oscillations

Warner and Brickhill (1978) found coherent oscillations with a period of 27.7 seconds in observations during a supermaximum. Computations of the phases of these oscillations during eclipse show a systematic phase shift although the low amplitude of the oscillations and the rapidity of the eclipse means the results are not clear cut as in DQ Her and UX UMa.
X-ray emission

Cordova et al. (1980) observed Z Cha during a supermaximum at 'soft' (0.18 - 0.43 keV) X-ray wavelengths with the HEAO-A2 experiment. No soft X-rays were detected.

Parameters of the System

The secondary in dwarf nova systems is normally assumed to fill its Roche lobe. In this case the observed duration of the eclipse of the white dwarf in Z Cha defines a unique relation between the mass ratio \(q' \equiv M_1/M_2\) and the inclination of the system \(i\). Bailey (1979) and Fabian et al. (1979) both use only the eclipse observations of Bailey (1979) (and exclude those of Warner (1974)) to derive values of:

\[
\begin{array}{c|c}
q' \equiv M_1/M_2 & i \\
0.5 & 66.84^\circ \\
1.0 & 71.00^\circ \\
1.5 & 73.38^\circ \\
2.0 & 75.04^\circ \\
5.0 & 80.13^\circ \\
\end{array}
\]

Smak (1979) has analysed the eclipses using both the observations of Bailey (1979) and Warner (1974). He suggests, as do other authors, that the variations in the shape of the eclipse are due to changes in the dimensions of the disc. Fabian et al. (1979) give evidence that the variations in disc size are related to the outbursts and that the disc is larger immediately after outburst as would be expected. Analysing Warner's and Bailey's observations separately, Smak (1979) finds almost identical values for the inclination \(i\) of the system for a given fractional mass of the secondary \(M_2/(M_1 + M_2)\) but different values for the radius of the white dwarf. The relation he derives between \(i\) and \(\mu=M_2/(M_1 + M_2)\) differs slightly from that obtained by
Bailey (1979) and Fabian et al. (1979), mostly due to the combined treatment of Warner's and Bailey's data. Smak (1979) concludes that the fractional mass of the secondary component, \( \mu \), must be within \( 0.2 > \mu > 0.1 \) and that the differences between Bailey's and Warner's light curves result from differences in the radius of the disc and in the dimensions of the white dwarf and of the hot spot.

Taking the new orbital elements derived by Bailey (1979), Smak (1979) reanalyses Warner's (1974) eclipses measured during supermaximum and finds a systematic shift in the eclipse minimum. He suggests that the bright body which is eclipsed during the outburst is located somewhat asymmetrically with respect to the centre of the white dwarf and has an asymmetric distribution to the surface brightness. Such an asymmetry of the white dwarf, or of the inner parts of the disc, could be associated with an inclined magnetic axis of the white dwarf. Vogt (1979) proposes just such a magnetic rotator in Z Cha to explain the large mean velocities of the hydrogen absorption lines seen in spectra of Z Cha, taken during supermaximum. The width of the eclipses is smaller than predicted from the outer dimensions of the disc but larger than the width of the white dwarf eclipse. Thus the main source of light at the outburst is smaller than the disc but larger than the central star. Smak (1979) suggests that it is possible that we are seeing radiation from an accretion column scattered in the central parts of the disc. Vogt (1979) proposes that the hydrogen absorption lines originate from this accretion column.

Ritter (1980) has analysed spectroscopic and photometric data on Z Cha to derive the physical parameters of the system. The parameters he obtains are listed in Table 10.1. For his calculations Ritter uses Bailey's photometric data and spectroscopic observations obtained by Vogt. Since photometric observations of Z Cha show a strong bright spot
Table 10.1

Physical Parameters of Z Cha (Ritter, 1980)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>mass of white dwarf</td>
<td>$M_1 = (0.34 \pm 0.06)M_\odot$</td>
</tr>
<tr>
<td>mass of secondary</td>
<td>$M_2 = (0.10 \pm 0.02)M_\odot$</td>
</tr>
<tr>
<td>radius of white dwarf</td>
<td>$R_1 = (1.8 \pm 0.2) \times 10^{-2}R_\odot$</td>
</tr>
<tr>
<td>radius of secondary</td>
<td>$R_2 = (0.16 \pm 0.01)R_\odot$</td>
</tr>
<tr>
<td>orbital inclination</td>
<td>$i = 77^\circ \pm 1^\circ$</td>
</tr>
</tbody>
</table>

Contribution radial velocity measurements used for Ritter's calculations will be subject to error and should be treated with caution. In the analysis Ritter did not assume the secondary to be a main sequence star. His calculations give a secondary which has slightly above the theoretical mass-radius relation of low mass main sequence stars (Grossmann et al., 1974). The derived values for the primary fit the theoretical mass-radius relation for white dwarfs. Ritter's calculations give us estimates of the orbital parameters but are probably not as accurate as his quoted errors would lead one to believe. Firstly blending of a bright spot component in the emission lines with the disc lines will lead to errors in calculating the radial velocities. Secondly he assumes that the observed value of $v \sin i$ for the disc is the Keplerian rotation velocity at the hot spot's distance from the centre of the disc. It is not known whether this is the true case or not.

Our observations of Z Cha were made at the Anglo Australian Telescope with the common user infrared spectrophotometer. This does not have the capability of making simultaneous optical measurements. Poor weather prevented us obtaining both J and K light curves during
the same observing trip. The J curve was observed on January 31 1980 and the K curve on April 25 1980. These light curves are shown in Fig. 10.2. The observations were calibrated against the standard star BS2803 on January 31 which has the magnitudes

\[ V = 3.98, J = 2.75, K = 2.34 \] (Glass, 1974)

and against BS3871 which has the magnitudes on April 25

\[ V = 4.78, J = 3.74, K = 3.27 \] (Allen, private communication).

The results are shown plotted by phase using the ephemeris

\[ \text{HJD 2440264.68155 + 0.0744992705 (Bailey, 1979)}. \]

Error bars are shown marked on the light curves. The K curve shows relatively large errors because on April 25 the infrared spectro-photometer was operating without the focal plane chopper. In addition the data shows that the weather conditions were less than ideal at the beginning of the run and this shows up as an increased scatter in the data points. The estimated errors on the data from the start to around phase 0.7 are twice the marked error bars.

The Light Curves

At optical wavelengths the light curves of Z Cha show a deep primary minimum. No secondary minimum is observed. Primary minimum is on average \( 1^m.9 \) deep (Mumford, 1971) and is very narrow. It shows two definite stages which are attributed to the eclipse of the bright spot and of the white dwarf.

Our infrared curves show two distinct minima. At J primary minimum is still \( \sim 0^m.2 \) deeper than secondary minimum and is wider than at V. The hot spot hump prior to primary minimum is still present, the light curve showing unequal maxima. Primary minimum is asymmetrical with a steeper decline and a slower recovery. It is unfortunate that the K curve is of lower quality since this makes it difficult to measure
Fig 10.2 The J and K light curves of Z Chamaeleontis. The error bars are derived from observations of non-variable stars of similar magnitude. Due to poor weather conditions the errors on the K curve from the start to ~ phase 0.3 are about twice the marked error bars.
the depths of the minima. However it can be seen that the two minima are of roughly equal depths. The maxima are still uneven, the maximum prior to primary minimum being the brighter showing that there is still a noticeable contribution from the bright spot at K.

Colours measured on both the nights that the system was observed showed that Z Cha was $\sim 0.3$ brighter in the infrared on April 25 than it had been on January 31.

**Interpretation**

The shapes of the infrared light curves suggest that the secondary dominates the light from the system in the infrared and that much of the observed variations are due to ellipsoidal variations of this red secondary. Examination of the J curve suggests that most or all of secondary minimum and the widening of the ingress and egress of primary minimum is due to ellipsoidal variations. The eclipse of the primary still shows up clearly but its depth ($\sim 0.5$) is very much less than at optical wavelengths. This indicates that the residual radiation at mid eclipse is redder than the system as a whole in agreement with the results from photometry by Mumford (1971) and the spectrophotometry of Whelan et al. (1979). We know from optical studies (Warner, 1974; Bailey, 1979) that at mid eclipse the white dwarf, bright spot and central parts of the disc are all eclipsed. In terms of the standard disc model this leaves two possible sources for the uneclipsed radiation: the secondary star which is probably late M type and the outer cooler parts of the disc, both of which will be relatively red.

We can test our hypothesis of ellipsoidal variations simply since we know that ellipsoidal variations will produce, to a good approximation, a sine wave shape curve. If we therefore fit a sine
wave (by eye) to our J curve, fitting the height of the maximum at phase 0.25 rather than at phase 0.75 where there is additional flux due to the bright spot, and then subtract this sine wave from our J curve, to approximately remove the effect of the ellipsoidal variations, we would expect the remaining curve to bear close resemblance to the optical curves.

Fig. 10.3 shows the sine wave fitted to the J curve and the resulting curve, when this sine wave variation has been subtracted from the J curve. It can be seen that the remaining curve closely resembles the optical curve which is to be expected as we are now seeing the light of the white dwarf and bright spot which dominate in the optical. The main difference is a residual dip at phase 0.5 which can be explained as the eclipse of the secondary by the disc. This indicates that at J secondary minimum is mainly due to ellipsoidal variations with in addition a small contribution ($\sim 0^m.1$) from the eclipse of the secondary.

Unfortunately at K secondary minimum is not well defined due to the poor quality of the data and almost any sine wave would fit the curve equally well. We cannot therefore independently estimate the size of the ellipsoidal variations at K. Our observations of U Gem and EM Cyg have shown that the amplitude of the ellipsoidal variations at J is $0^m.03$ greater in U Gem and $\sim 0^m.02$ greater in EM Cyg than at K. This is to be expected since the effects of limb darkening and gravity darkening become less at longer wavelengths. Since the amplitude of the ellipsoidal variations at J for Z Cha measured from our sine wave is $0^m.23$ we would expect the amplitude of the variations at K to be $\sim 0^m.2$. As can be seen from Fig. 10.2 this would leave us with residual eclipses at both primary and secondary minimum of $\sim 0^m.22$.

The light variations of Z Cha in the infrared can thus largely be attributed to ellipsoidal variations of the late type secondary.
Fig 10.3 The upper curve shows the $J$ data on Z Cha plotted in intensity units with a sine wave fitted. The lower curve shows this same data with the variations due to this sine wave removed.
Eclipses of both the primary and secondary are seen both at J and K. Z Cha is therefore a good candidate for the study of ellipsoidal variations in late type stars but our data is not of sufficient quality to warrant a detailed investigation. Before such a study is made good quality light curves at J, H and K, repeating over many cycles to smooth out changes from cycle to cycle, are needed.

Following the method described in Chapter 6 we can calculate approximate values for N, the ratio of the photometric ellipticity to the geometrical ellipticity, at 1.2 μm and 2.2 μm from our light curves. In Chapter 6 we showed that, to a first approximation

\[
\frac{3}{2} \frac{N r^3 \sin^2 \frac{i}{2}}{q} = (1 - 10^{-0.4 \Delta m})
\]

where \(q\) is the mass ratio, \(M_2/M_1\)

\(i\) is the angle of inclination

\(N\) is the ratio of the photometric to geometric ellipticity

\(r\) is the radius of the secondary in units of \(a\) (the separation of the components)

\(\Delta m\) is the amplitude of the variation in magnitudes.

Ritter (1980) estimates \(i = 77^\circ\) and \(q = 0.294\) while Bailey (private communication) finds \(q = 0.4\) which, from his mass ratio-inclination relation discussed earlier implies \(i = 76^\circ\). Warner (1976) gives

\[
r = 0.462 \left( \frac{q}{1+q} \right)^{\frac{1}{2}} \text{ for } q < 0.5
\]

and estimating \(\Delta m\) at 1.2 μm from our sine wave we find \(\Delta m_J = 0^m.23\). As we discussed earlier this leads us to estimate \(\Delta m_K = 0^m.2\). We therefore find

\[
N_{1.2} = 1.77 \text{ and } N_{2.2} = 1.56 \text{ taking Ritter's values}
\]

and

\[
N_{1.2} = 1.9 \text{ and } N_{2.2} = 1.68 \text{ taking Bailey's values.}
\]
These are only approximate estimates since we simply fitted out a sine wave by eye. Further light curves will allow these values to be determined more accurately.

With the present light curves we can find out little more about the system. It is interesting to note however that an estimate of the temperature of the primary (i.e. disc plus bright spot plus white dwarf) from the depth of primary minimum at $J$ gives us a reasonable value. If we assume that primary minimum is total and therefore that the $J$ magnitude at minimum represents solely the light from the secondary, the $J$ magnitude of the primary is given by

$$J_p = -2.5 \log(10^{-0.4M_{\text{max}}} - 10^{-0.4M_{\text{min}}})$$

where $M_{\text{max}}$ is the maximum magnitude at $J$ of the system and $M_{\text{min}}$ is the $J$ magnitude at minimum. From our light curve we find $M_{\text{max}} = 14.23$ and $M_{\text{min}} = 14.84$ and therefore $J_p = 15.15$. At $V$ the primary contributes all of the flux (no secondary minimum is seen) and so the average $V$ magnitude of the system, $V = 15.2$ represents the $V$ magnitude of the primary. This gives a colour for the primary $V-J = 0.05$ which implies an effective temperature for the primary (Johnson, 1966) of $\sim 9600 \text{ K}$. Since we expect temperatures of around $10^4 \text{ K}$ for the primary our estimate seems reasonable although it should not be regarded as a determination of the primary's temperature.

Our estimate that the secondary contributes all of the $J$ flux at primary minimum appears to be a reasonable approximation. Smak (1979) estimates the total brightness of the disc (eclipsed and uneclipsed parts) to be $\sim 1.2$ times the eclipse minimum level. Mumford (1971) finds that the $B$ magnitude of the system at mid eclipse is $\sim 17^m.0$. The $B$ magnitude of the disc is thus $\sim 16^m.8$. If the disc has the $4^1$ spectrum expected for a steady state accretion disc out to $J$ the
corresponding J magnitude is 16.2, which is 27% of the observed mid
eclipse flux. However the disc contribution at J will be less than
this. The disc spectrum tends to a Rayleigh-Jeans law at long
wavelengths. If this turn down in the disc spectrum occurs at a
wavelength < 1.2 μm in Z Cha the total J flux from the disc will be
lower than our estimate. Also a substantial fraction of the disc
radiation will be eclipsed. Hence the disc probably accounts for no
more than about 10% of the observed J flux at mid eclipse.

Clearly further observations of this system will be of considerable
interest. We know that the continuum spectrum of a dwarf nova must be
composed of a number of components arising from the secondary, the
white dwarf, the accretion disc and the bright spot but the separation
of these components is usually a difficult problem. Z Cha however
offers an excellent opportunity to separate out the individual contribu­
tions. White light curves obtained by Warner (1974) and Bailey (1979)
allow us to estimate the relative contributions of the white dwarf,
bright spot and disc, but unfortunately these curves are uncalibrated.
Similar quality UBV curves would allow us to find the fluxes from the
white dwarf, bright spot and disc at these wavelengths. Infrared
curves, ideally observed simultaneously with the optical curves, of
the quality of our J curve, would enable us to find the J flux from
the white dwarf and bright spot and analysis of the ellipsoidal
variations at J and K would give us the infrared fluxes from the
secondary. It should then be possible to find the contribution of each
component to the observed fluxes at all wavelengths.

This system is interesting because it is the first ultrashort
period cataclysmic binary in which the secondary has been directly
observed. Unfortunately the J-K colour index is virtually independent
of the spectral type of the star in the range K7-M8 and so we cannot
obtain the spectral type of the secondary from our infrared observations. However our infrared observations have shown that the secondary emits most of the 1.2 μm and 2.2 μm flux from the system. This suggests that spectrophotometric observations in the 6000 - 10000 Å range as in U Gem will be of interest. Since the secondary is the major contributor of the 1.2 μm flux it should also contribute a fair proportion of the flux at 8000 Å. (A rough estimate suggests 35 - 40%.) Therefore observation around this wavelength offers the possibility of detecting the absorption features in the secondary's spectrum and thus determining its spectral type. Also a determination of the radial velocity amplitude of the secondary would be of great value in constructing a detailed model of the Z Cha system. The best spectral feature to use for this purpose would be the NaI absorption lines at 8183 and 8194 Å.

Z Cha is the first ultrashort period cataclysmic binary in which the secondary has been directly observed and so offers the opportunity to determine for the first time the spectral type of the secondary in such a short period system. The faintness of Z Cha will make such observations difficult but the other ultrashort period systems are as faint or fainter (except EX Hya and VW Hyi which show disc spectra in the infrared) and so a better opportunity to investigate the secondary in an ultrashort period system is unlikely to occur.
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CHAPTER ELEVEN

CONCLUSIONS

We have learnt a great deal from our infrared observations of cataclysmic variables and the study of the few systems described here has given us insight into the form future observations should take and what we might hope to learn from these observations.

We were able to learn little from our light curves of EX Hya and VW Hyi but our infrared colours of EX Hya (and probably VW Hyi) combined with optical and UV observations (Bath et al., 1980) showed that on occasion the accretion disc can be observed out to 2.2 μm. This showed that for systems such as these where the accretion disc is large and emits most (or all) of the 1.2 μm and 2.2 μm radiation from the system, the near infrared is a powerful tool for studying the extent and outer temperature of the disc. Once further similar systems have been identified a comprehensive study of accretion discs will be possible and the models produced will be relevant to other stars such as X-ray binaries. The best results will be obtained by combining infrared observations with simultaneous optical and UV observations. However arranging time (and finding clear weather!) on two telescopes and IUE simultaneously will prove difficult. Systems such as VW Hyi, which show frequent outbursts and undergo supermaxima whose occurrences can be predicted to fair accuracy, offer an excellent opportunity for studying changes in the accretion disc over the course of an outburst. Simultaneous optical, infrared and, if possible, UV observations, will place constraints on outburst models.

Our recent observations of EX Hya discovered the presence of a
dust cloud around the system. The only other indication of material
around a dwarf nova is Robinson's (1973) observations of Z Cam.
Infrared observations extending out to 3.6 \( \mu m \), and if possible in
the future 5 \( \mu m \) and 10 \( \mu m \), of other systems would certainly be of
interest. More sensitive detectors are needed if the survey is to be
extended out to 5 \( \mu m \) and 10 \( \mu m \) and even at 2.2 \( \mu m \) and 3.6 \( \mu m \) our sample
will be limited with present detectors. CVF spectra, as for EX Hya,
of those systems which indicate an excess at 3.6 \( \mu m \) would clearly show
the turn up in the spectrum and allow us to fit a temperature to the
dust. Again there will be a problem with sensitivity for systems
fainter at 2.2 \( \mu m \) than EX Hya (i.e. \( K > 12.2 \)). Szkody (1976, 1977)
has obtained infrared colours out to L (3.6 \( \mu m \)) of about a dozen
cataclysmic variables including Z Cam. In this sample the only system
which shows evidence for a cool 'shell' is TT Ari which has K-L \( \sim 0^{\circ} .85 \).
(However the errors on the L measurement are large, \( \pm 0^{\circ} .4 \)). The
secondary star in this system (P \( \sim 3 \) hr 12 min) will not be later than
M5-M6 which implies K-L = \( 0^{\circ} .37 - 0^{\circ} .45 \) (Johnson, 1966). Clearly
further observations of this system are indicated. Evidence for a dust
cloud around TT Ari would, if nova-like variables are accepted to be
dwarf novae in extended standstills rather than old novae, indicate
that loss of material from dwarf nova is continuous rather than outburst
related as in classical novae.

Systems which show well defined primary eclipses in the optical
and infrared like UX UMa and RW Tri (Frank and King, 1980) are
interesting. Simultaneous observations of the light curves at optical
and infrared wavelengths allow us to model such systems by considering
the eclipse of a disc of standard brightness distribution by a late type
star. The good fit of the curves predicted by the model to the
observations is support for current disc theories.
The systems which have produced the least results from our observations so far, are those systems in which the infrared light curves are dominated by ellipsoidal variations of the secondary, i.e. U Gem, EM Cyg and Z Cha, to date. In principle, observations of such systems provide an excellent opportunity for the study of ellipsoidal variations in late type stars. In practice, numerous hours of observations on large telescopes, following the systems for many orbital periods at each wavelength to smooth out changes in the light curves from cycle to cycle, are necessary before accurate calculations of the ellipsoidal variations are attempted.

In earlier chapters we have estimated $N$, the ratio of the photometric ellipticity to the geometric ellipticity, at 1.2 \( \mu \)m and 2.2 \( \mu \)m from our light curves for each of the three systems which show ellipsoidal variations. We can now compare these estimates with values calculated theoretically. Assuming a grey body atmosphere, Russell (1945) gives expressions for the gravity darkening coefficient $y$ and the limb darkening coefficient $x$.

\[
y = \frac{1}{4} \left( \frac{hc/\lambda kT_e}{-hc/\lambda kT} \right) \left( 1 - e^{-hc/\lambda kT} \right)
\]

\[
x = \frac{3y}{2 + 3y}
\]

where $T_e$ is the effective temperature of the star,

and $N = \frac{15 + x}{15 - 5x}$ (Binnendijk (1974)).

However Russell's equations apply only to radiative stars and we would expect our secondaries (K2, M4.5 and M6-M8) to have convective envelopes.

Lucy (1967) working on W UMa systems showed that stars with convective envelopes have a gravity darkening which is considerably
smaller than that in radiative stars. Radiative stars obey the gravity
darkening law
\[ T_e = g^{0.25} \]
which gives the variation of the effective temperature \( T_e \) with the local
gravity \( g \) over the surface of a distorted star. For stars with
convective envelopes Lucy (1967) found that the gravity darkening law
took the form
\[ T_e = g^{0.08} \]
This was confirmed by Rucinski (1969) for a typical Algol secondary
component. Calculating \( x \) and \( y \) as before our expression for \( N \) when
applied to stars with convective envelopes becomes
\[ N = \frac{15 + x}{15 - 5x} (1 + 0.32y) \]
However Kopal (1968) found that observations of gravity darkening
in the components of W UMa systems with convective envelopes showed
that the gravity darkening coefficient was considerably larger than
the coefficient calculated for radiative stars not smaller as expected
from theory. He offers no explanation for the discrepancy. Observations
of the gravity darkening of the secondary component of Algol by Budding
and Kopal (1970) confirmed this result. They found that gravity
darkening for the subgiant secondary is not smaller than predicted
for radiative stars, as expected for a star with a convective envelope, but larger.

Clearly much work needs to be done before an accurate theory is
formulated and the reasons for the discrepancy between observations
and theory for convective stars is understood. Observations of
cataclysmic variables providing information about gravity darkening and
limb darkening in low mass stars with convective envelopes at infrared
wavelengths will provide an interesting test for any new theories.
Table 11.1 shows our observed values of $N_{1.2}$ and $N_{2.2}$ compared with the values calculated for radiative stars (Russell) and stars with convective envelopes (Lucy). These values are also shown in Fig. 11.1 plotted against the spectral type of the secondary. For the Z Cha values, the marked error bars on the calculated points represent possible variations caused by the uncertainty in the spectral type of the secondary. The values of $N_{\text{observed}}$ using both Ritter's and Bailey's estimates of $q$ and $i$ are shown and the uncertainty in the spectral type still applies. Errors in the measurement of the size of the ellipsoidal variations from our light curves are not shown on any of the points.

The calculated values for $N$ for both radiative stars and convective stars show the same trend with spectral class but the levels of the curves differ. The observed values of $N_{1.2}$ and $N_{2.2}$ show the same increase in $N$ as the spectral class of the secondary becomes later between EM Cyg and U Gem as predicted by theory, although the values of $N$ are considerably higher in agreement with Kopal's results for W UMa stars. However, the values of both $N_{1.2}$ and $N_{2.2}$ derived from our light curves show a turn down to Z Cha. Theory predicts that $N$ should continue to show an increase in this range. In fact, the values of $N$ predicted by theory for stars with a convective envelope and the values of $N$ found from our observations for Z Cha are in excellent agreement. In view of the complete failure of the theory to predict the correct values for EM Cyg and U Gem this is probably just a coincidence.

At 1.2 $\mu$m the observed turn down in the trend of $N$ with spectral class would remain even if the whole of the secondary minimum at J in the Z Cha curve is attributed to ellipsoidal variations rather than accounting for part of the minimum as an eclipse of the secondary as at present. If we take the whole of secondary minimum at J to be
<table>
<thead>
<tr>
<th>N. 2.2</th>
<th>Radiative</th>
<th>Convective</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.72</td>
<td>1.48</td>
</tr>
<tr>
<td></td>
<td>2.63</td>
<td>2.75</td>
</tr>
<tr>
<td>2.87</td>
<td>1.50</td>
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</tr>
<tr>
<td>2.06</td>
<td>1.50</td>
<td>2.40</td>
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### Table 11.1

<table>
<thead>
<tr>
<th></th>
<th>Radiative</th>
<th>Convective</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.77-1.9</td>
<td>2.71</td>
</tr>
</tbody>
</table>

- EM Cyg: $T_e = 4960K$
- KZV: $T_e = 3150K$
- U Gem: $T_e = 2850K$
- Z Cha: $T_e = 1.77-1.9$
Fig. 11.1 The observed and calculated values of N1.2 and N2.2 as a function of the spectral class of the secondary.
ellipsoidal variations we find $N_{1.2} = 2.38$ and $2.60$ taking Ritter's and Bailey's values for $q$ and $i$ respectively.

At K we cannot be so specific. If we attribute the whole of secondary minimum at K to the ellipsoidal variations we find $N_{2.2} = 2.9$ and $3.16$ taking Ritter's and Bailey's values for $q$ and $i$ respectively. In this case the amplitude of the ellipsoidal variations would be considerably greater at $2.2 \, \mu m$ than at $1.2 \, \mu m$, which is contrary to expectations since the effects of gravity darkening and limb darkening should be less at longer wavelengths. It would also be in contrast to our results on EM Cyg and U Gem which show the variations to be greater at $1.2 \, \mu m$. Secondly if we take $N_{2.2} \approx 3.0$ then the variation of $N$ with spectral class found from our observations would show a turn down between M4.5 and M6 - M8 at $1.2 \, \mu m$ but a steepening rise at $2.2 \, \mu m$. Logically this seems improbable.

It is unlikely that this turn down will disappear when more accurate observations of all three systems are available although a drop in the values of $N$ for U Gem would mean that $N$ decreased with spectral type from K2 - M7 with the decrease steepening between U Gem and Z Cha. The observed results would then show the opposite trend to that predicted by theory. It is interesting to note that the break in the trend of $N_{1.2}$ and $N_{2.2}$ with spectral class occurs between the values found for U Gem ($P = 4 \, hr \, 10 \, min$) and Z Cha ($P = 1 \, hr \, 47 \, min$) which lie either side of the gap between 2 hrs and 3 hrs in the observed binary periods of cataclysmic variables. We cannot draw any conclusions from our present observations but clearly further observations to examine the variation of $N_{1.2}$ and $N_{2.2}$ with spectral type and to investigate the possibility of a connection between the period discontinuity and the break in the trend of $N_{1.2}$ and $N_{2.2}$ with spectral type (and therefore period) will be of great interest.
For the majority of the systems we have observed it has been possible to estimate one further piece of information, the distance. To do this it is generally necessary to assume that the secondary is a main sequence star which fills its Roche lobe. This assumption is often made about the secondaries in cataclysmic variables although there is no conclusive proof to support it. In most cases the errors in our results allow quite a range of distances for each system. All our estimates to date lie between 70 and 350 pc which is in agreement with the expected distances of cataclysmic variables.

Just as at optical wavelengths we have found that there is no relation between the binary period of a system and which component(s) dominates our infrared observations. Our observations have produced some interesting results but at the end of this study we are no nearer to finding an answer to our initial question than we were at the start:- Why is such a range of behaviour seen in systems whose components are so similar?
APPENDIX 1
The UV spectrum of AE Aqr

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Summary. Ultraviolet spectra of the cataclysmic variable AE Aquarii obtained by the IUE satellite are reported. They show strong emission lines (La, He ii and various collisionally excited alkali-like resonance transitions) on a weak continuum. We show that while Mg ii, Ca ii and some La emission probably arise in optically thin regions of the accretion disc, the higher ionization species (N v, Si iv, C iv, He ii) must be radiatively produced outside the disc to explain the observations. The parameters required of the ionizing radiation suggest that it comes from the hot inner part of the disc. This picture is used to discuss the time variation of the system and the origin of the unusually strong line emission.

1 Introduction

AE Aqr is probably best described as a very unusual dwarf nova. The time-scale of its flare activity is very short, about 1 hr, compared to more normal dwarf novae that flare about every 30–100 day. The magnitude of its flares is also small, about 0.3 mag but can occasionally be as great as 2 mag (Zinner 1938).

The optical spectrum of AE Aqr is dominated in the red region by the continuum spectrum of the red dwarf together with H α emission. In the blue region the continuum is very weak and the spectrum is dominated by the emission lines of hydrogen and the Ca ii lines (see Joy 1954; Crawford & Kraft 1956).

Walker (1965) has found that the usual small flares are due to an increased intensity in the emission lines with the continuum remaining constant. The larger flares, however, correspond to an increase in the continuum. AE Aqr is not an eclipsing binary but attempts have been made to measure the radial velocity curve. Joy (1940) finds a period of 17 hr whereas Walker (1965) finds 10 hr. Either way the period is long for a dwarf nova which is consistent with a large red star.

AE Aqr was chosen for observation with the IUE satellite partly because the system is consistently quite bright (12 mag) and thus readily found, but mainly with a view to correlating the optical variations with variations in the UV spectrum in the short observation times, 8 hr, available. IUE is equipped with an optical channel (the Fine Error Sensor) for
maximizing the star signal in the spectrograph slit; this can be used to provide crude optical photometry.

2 Observations

Six spectra of AE Aqr were obtained with IUE, four low dispersion short-wavelength and two low dispersion long-wavelength spectra. Short-wavelength spectra cover the range 1000–2000 Å and the long-wavelength covers 1700–3400 Å, the resolution in both cases is better than 6 Å. The first spectrum (short-wavelength) was observed on 1978 September 13 and was rather underexposed. The remainder were observed on September 15 and were well exposed although the Mg II line is saturated on the first long-wavelength spectrum. Before each exposure the optical brightness was measured (see above).

Figure 1. The spectrum of AE Aqr from 1200 to 2000 Å and 2350 to 3100 Å. The regions 1000–1200 Å, 2000–2350 Å and 3100–3400 Å are not shown but have no obvious lines. x’s denote reseaux; these do not seriously distort any of the important lines. The ordinate measures ‘equivalent A 2536 photons per pixel’ and must be multiplied by the IUE calibration to convert to true fluxes.
Examples of both long- and short-wavelength spectra with the line identifications are shown in Fig. 1. It should be noted that the spectrum clearly shows intrinsic Lyman-α emission; the effect of the geocoronal Lyman-α background has been subtracted.

3 Analysis of the spectra: the ionization structure
We shall discuss the spectra on terms of the usual model for a cataclysmic variable, in which a white dwarf accretes from a late-type companion (here a K2V star: Warner 1976, and references therein) via Roche lobe overflow. We may expect the line emission to originate in regions in or near the accretion disc around the white dwarf. Our procedure is to try to understand what physical processes can give rise to the ionization and excitation conditions which must hold to give the observed line strengths (Table 1) and then to investigate possible sites for the emission-line region. As usual for dwarf novae (e.g. Bath, Pringle & Whelan 1980) interstellar extinction (except possibly for Lα — see Table 1) may safely be neglected in discussing the spectra.

For the kind of optically thin emission-line region required by the observations, it is easy to show that the dominant recombination processes entering the ionization balance equations must be radiative rather than collisional if hydrogen is appreciably ionized, as suggested by the presence of N v, He II, Si IV etc. For three-body recombination to be important for hydrogen-line ions, electron densities $N_e$ at least of order $10^{16}$—$10^{17}$ cm$^{-3}$ are required. At such densities, and conceivable electron temperatures $T < 10^6$K), the emission-line region would become optically thick to free-free absorption in the observed UV wavelength range over length-scales short compared to the scale height in the system's orbital plane (i.e. in or near the accretion disc); there being similar difficulties with electron scattering. Hence the two allowable possibilities for determining the ionization balance of species such as H, He I, N v, Si IV, C IV, Mg II (which produce most of the strongest observed lines) are:

(a) collisional ionization balanced by radiative and dielectronic recombination;
(b) photo-ionization balanced by radiative and dielectronic recombination.

<table>
<thead>
<tr>
<th>Line</th>
<th>Luminosity (erg s$^{-1}$)</th>
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<tbody>
<tr>
<td>Lα λ 1216</td>
<td>$1.4 \times 10^{31}$</td>
</tr>
<tr>
<td>He II λ 1640</td>
<td>$1.4 \times 10^{29}$</td>
</tr>
<tr>
<td>N V λ 1238</td>
<td>$6.1 \times 10^{24}$</td>
</tr>
<tr>
<td>Si IV λ 1400</td>
<td>$7.6 \times 10^{19}$</td>
</tr>
<tr>
<td>C IV λ 1549</td>
<td>$1.0 \times 10^{19}$</td>
</tr>
<tr>
<td>Mg II λ 2795</td>
<td>$&gt; 7.5 \times 10^{19}$ (saturated)</td>
</tr>
</tbody>
</table>

Notes:
1. The fluxes have been converted to luminosities assuming a distance of 100 pc.
2. Possible interstellar absorption of Lα has not been taken into account. The chief uncertainties in estimating its effect are due to the lack of good values for the interstellar neutral hydrogen density $n_H$ and the true width of the line at emission. Using the optical depth $\tau(\Delta \lambda) = 12.78 n_H D_{100}^2 (\Delta \lambda)^2$ for a natural damping profile (e.g. Bohlin 1975), where $D_{100}$ is the distance in units of 100 pc, the discrepancy is estimated to be less than a factor of 2.
In possibility (a), the excitation of the lines is of necessity primarily collisional. In view of the fairly low densities required, this situation resembles the case of the solar corona, and the ionization calculations of Jordan (1969), and Cox & Tucker (1969) are relevant. In possibility (b), line emission can be produced via either recombination or collisional excitation. This possibility resembles the ionization balance of H ii regions or planetary nebulae, although the dominant loss processes in these systems involve forbidden line emission, rather than permitted lines, as here. (The semi-forbidden intersystem lines of O iii (λ 1660), N iii, N iv and Si iv are present but considerably weaker than for example λα, N v or Si v.) In the following it will become clear that to attempt to reconcile possibility (a) with the observed spectrum requires temperatures $T \sim 10^5$ K, and that the line ratios are still not satisfactorily fitted in this case.

We consider now the ratio of N v λ 1238 to λα λ 1216, which is observed to be 0.44. The N v line is the $2p^5 3P - 2s^3 1S$ resonance doublet, and if we try to impose possibility (a) conditions, it must be produced by collisional excitation from the ground $2s^3 1S$ term. The data given by Osterbrock (1974) imply a collisional de-excitation rate coefficient $q_{ps} = 1 \times 10^{-7} T_4^{1/2}$ cm$^3$ s$^{-1}$, where $T_4$ is $T$ in units of $10^4$ K, as opposed to the Einstein coefficient $A_{ps} = 3.4 \times 10^{15}$ cm$^{-3}$ s$^{-1}$ for the radiative decay. Thus for $N_4 < A_{ps}/q_{ps} = 3.4 \times 10^{15} T_4^{1/2}$ cm$^{-3}$ collisional excitations to $2p^5 3P$ will be followed by radiative decays, with emission of λ 1238. (For higher densities, which are unlikely here because of the considerations given above, we would get just the LTE emission rate.) By detailed balancing we find the collisional excitation rate coefficient for populating $2p^5 3P$ from $2s^3 1S$ to be

$$q_{sp} = 3 \times 10^{-7} T_4^{1/2} \exp(-11.59/T_4) \text{ cm}^3 \text{s}^{-1}.$$ 

In the low-density regime ($N_4 < 3.4 \times 10^{15} T_4^{1/2}$ cm$^{-3}$) the emissivity of λ 1238 is

$$N_n q_{sp} h \nu_{1238},$$

where $h \nu_{1238}$ is the photon energy and $N_n$ the number density of N v ions in the ground $2s^3 1S$ term, will be very close to $N_{Nv}$, the number density of N v ions itself. This is because statistical equilibrium implies $N_p/N_n = N_n q_{sp}/A_{ps} < 1$ (by assumption) for the relative populations of the $2p^5 3P$ and $2s^3 1S$ terms, with similar results for higher terms. If $V_{Nv}$ is the volume containing $N_{Nv}$, $A_N = 9 \times 10^{-5}$ the relative abundance of N, and $f_V$ the fraction of N in the form of N v, the total emission in λ 1238 is given by

$$L(\lambda 1238) = f_V A_N V_{Nv} N_n N_H q_{sp} h \nu_{1238} \text{ erg s}^{-1},$$

where $N_H$ is the hydrogen (neutral or ionized) number density. The λα emission is

$$L(\lambda 1216) = V_H N_H N_{H} (j(\lambda\alpha)/N_n N_H) \text{ erg s}^{-1},$$

with $V_H$ the volume of emitting hydrogen, and $j(\lambda\alpha)$ the λα emission cm$^{-3}$. The value of $j(\lambda\alpha)/N_n N_H$ depends on the ionization state of H; as the graphs of Cox & Tucker (1969) show, this can be as high as $10^{-22}$ erg s$^{-1}$ cm$^{-3}$ if most of the H is neutral and λα collisionally excited. This happens at temperatures near $10^5$ K, but for higher temperatures H is fully ionized and recombination emission dominates. If one λα photon is produced per recombination we have

$$j(\lambda\alpha)/N_n N_H \sim 1.65 \times 10^{-11} \alpha(T),$$

where $\alpha(T)$ is a suitable recombination rate coefficient. This is a lower limit to the λα recombination emission; the maximum would result from converting all the recombination energy into λα, increasing the emission by a factor $\eta$. Using all the above considerations, we find

$$L(\lambda 1238) = \frac{4.3 \times 10^{-22} f_V T_4^{1/2} \exp(-11.59/T_4)}{V_N} V_{Nv},$$

$$L(\lambda 1216) = \frac{j(\lambda\alpha)/N_n N_H}{V_H} V_H$$
If $\lambda \alpha$ is collisionally excited with $T_\alpha \sim 1$ we find under possibility (a) conditions

$$\frac{L(\lambda 1238)}{L(\lambda 1216)} = 4f_\nu T_\alpha^{\nu^2} \exp \left( -11.59/T_\alpha \right) \cdot \frac{V_{\nu V}}{V_H}$$

while if $\lambda \alpha$ is due to recombination and $N\nu$ obeys possibility (a) conditions

$$\frac{L(\lambda 1238)}{L(\lambda 1216)} = 127f_\nu \exp \left( -11.59/T_\alpha \right) \phi^{-1} \cdot \frac{V_{\nu V}}{V_H}$$

where we have used the tables of Spitzer (1978) for $\alpha(T)$; $\phi$ is a slowly varying function of $T$ which is of order one for all temperatures of interest. We must now try to find conditions under which $L(\lambda 1238)/L(\lambda 1216)$ can be made to equal the observed value of 0.44. Clearly $V_{\nu V} \leq V_H$ and $f_\nu < 1$. For the first form of the ratio to be applicable, $T_\alpha \sim 1$; but Jordan’s (1969) ionization structure calculations show that $f_\nu$ is less than about $10^{-4}$ unless $T_\alpha \sim 10$, so we cannot attain the observed value of the ratio this way.* A value $T_\alpha = 10$ is required to make the second form (equation 1) of the ratio of order the observed value, since Jordan’s tables give $f_\nu \sim 10^{-2}$ (we assume $V_{\nu V} \sim V_H$). Thus temperatures of order $10^5 \text{ K}$ or more are needed for the observed ratio of $\lambda 1238$ to $\lambda \alpha$ to be achieved under possibility (a) conditions. Such a high temperature is rather uncomfortable, but also necessary to get the observed $\text{SiIV} \lambda 1400$ and $\text{HeII} \lambda 1640$ emission. Under possibility (a) conditions, Jordan’s (1969) calculations show that at $T_\alpha = 2.5$ less than $10^{-3}$ of Si is in the form of SiIV; this reaches $10^{-1}$ only near $T_\alpha = 10$. $\lambda 1640$ is the HeII, HeI-like transition, so electron energies of $\sim 48 \text{ eV}$ are required to excite the $n = 3$ level collisionally, again leading to temperatures of order $10^5 \text{ K}$. However, at such temperatures the predicted ratio of $\text{CIV} \lambda 1549 : N\nu \lambda 1238$ is too large by a factor $\sim 25$: $\lambda 1549$ is again a $2p^2 P \rightarrow 2s^2 S$ resonance doublet, so using Osterbrock’s (1974) collision strength for the excitation and comparing abundances we find

$$\frac{L(\lambda 1549)}{L(\lambda 1238)} = 4.0 \frac{f_{\nu V_{\nu IV}}}{f_\nu V_{\nu IV}} \exp \left( -2.3/T_\alpha \right).$$

From Cox & Tucker (1969) and Jordan (1969) one sees that the ionizations of CIV, N\nu under possibility (a) conditions are virtually identical functions of temperature; indeed $f_{\nu V}$ for C is slightly larger than $f_\nu$ for N where they are not both negligible. Thus for possibility (a), $f_{\nu V_{\nu IV}} \approx f_\nu V_{\nu IV}$, so

$$\frac{L(\lambda 1549)}{L(\lambda 1238)} = 4 \exp \left( -2.3/T_\alpha \right).$$

For $T_\alpha = 10$ this ratio is 4, as opposed to an observed ratio of 0.16. In order to get the observed value one needs $T \sim 7000 \text{ K}$, which is totally unrealistic, since huge volumes would be needed to give the observed line strengths because of the negligible abundances of CIV, N\nu at such temperatures. Indeed this difficulty would remain even if one did not require $T \sim 10^5 \text{ K}$ to explain the $\lambda 1238/\lambda \alpha$ ratio. It is readily checked that values of $N\alpha$ large enough to produce LTE emissivities cannot give the correct line ratios, even if one could overcome the optical depth problem discussed at the beginning of the section.

*Of course one could get the possibility (a) form of the ratio to equal the observed value by assuming a suitable temperature gradient; namely $T_\alpha \sim 20$ in the region where $\lambda 1238$ is formed, with $T_\alpha \sim 1$ where $\lambda \alpha$ is formed. However, this assumption still would not enable one to get the ratio of $\text{CIV} \lambda 1549$ to $\text{N\nu} \lambda 1238$ right because the ionizations of CIV, N\nu under possibility (a) conditions are almost identical functions of temperature – see the discussion of this ratio in the text.
We must therefore conclude that in AE Aqr an ionization structure for the emission line region determined by collisional versus radiative processes does not provide a satisfactory fit to the observed line strengths. The reasons may be summarized as follows:

1. The general level of ionization, and the ratio $\lambda 1238/\lambda 1216$ in particular, demand temperatures $T \approx 10^5 K$ under possibility (a) conditions.

2. Under these conditions, the ratio $\lambda 1549/\lambda 1238$ does not approach the observed value unless $T \approx 7 \times 10^4 K$, which would demand inadmissibly large volumes to get the observed line strengths. At $T \approx 10^5 K$ the ratio is 25 times too large.

It is clear that these problems cannot be overcome by the assumption of some convenient temperature gradient or inhomogeneity. This is because under possibility (a) the ionization balance and the collisionally excited line strengths are determined locally and simultaneously. This contrasts with possibility (b), where the ionization structure depends on some non-local ionizing radiation field: in particular the relative abundance of two species such as C iv, N v can vary from point to point depending on how much of the radiation producing each species is present, in a way that cannot occur in possibility (a).

4 Photo-ionization equilibrium

In discussing possibility (b), we must now use the observed line strengths to determine as far as possible the ionizing continuum producing the observed species. This turns out to be quite tightly constrained, but fortunately still compatible with the likely accretion rate for the system. The ratio of $N v/\lambda 1238$ to $L a/\lambda 1216$ immediately provides a good indication of the conditions required of the emitting gas under possibility (b) conditions: we can show that $\lambda 1238$ must be collisionally excited, as its interpretation as a recombination line leads to far too low a value compared to $L a$. An upper limit to the $\lambda 1238$ recombination luminosity is given by supposing that all the recombination energy ($\approx 97.89$ eV per recombination from $N v i$) is degraded into the resonant $\lambda 1238$. The recombination rate coefficients of Aldrovandi & Pequignot (1973) then yield a maximum emissivity of

$$2.1 \times 10^{-25} N_e N_H f_v T_4^{-0.35} \text{erg s}^{-1} \text{cm}^{-3}.$$ 

Forming the ratio in the same way as equation (1) we get

$$\frac{L(\lambda 1238)}{L(\lambda 1216)} = 6.2 \times 10^{-2} f_v T_4^{-0.35} \frac{V_{N v}}{\phi V_H}.$$

Thus even with the best assumptions $f_v = 1$, $V_{N v} = V_H$ the ratio can never approach the observed 0.44. If $\lambda 1238$ is instead assumed collisionally produced we get a ratio of the same form as equation (1), but where $f_v$ must now be interpreted as radiatively determined. Photo-ionization equilibrium tends to produce $f'$s near unity in some region and small elsewhere, with quite sharp transitions between different regions (see e.g. Osterbrock 1974). Thus $f_v$ can be taken = 1 throughout $V_{N v}$: the relative size of $V_{N v}$ and $V_H$ will be determined by the ionizing continuum. Using $f_v = 1$ and $V_{N v} \leq V_H$ it is immediate that equation (1) cannot yield a $\lambda 1238/\lambda 1216$ ratio of the correct order of magnitude unless $T_a > 2$. If $T_a = 2$, $V_{N v} = V_H$, while if $T_a = 3$, $V_{N v} = 0.1 V_H$, and so on. If $V_{N v}/V_H$ is much smaller than unity most of the nitrogen in the emitting gas must either be in lower or higher ionization states. N iv are only weakly present in the optical and UV so the first alternative seems implausible, while the presence of N vi demands substantial emission at $> 0.1$ keV, and so requires (soft) X-ray production within the system.
The UV spectrum of AE Aqr

One can also show very quickly that the other resonance 2P–2S doublets from alkali-like ions, i.e. Si iv λ1400, C iv λ1549 and Mg ii λ2795, are all collisionally excited like N v λ1238. In each case the most optimistic estimates of recombination emission are manifestly insufficient to explain their strength relative to La. We can compare the observed line ratios N v : Si iv : C iv : Mg ii = 1 : 1.2 : 0.16 : > 1.2 (saturated) to the collisionally excited line emissivities which vary from 1 : 3.4 : 39.7 : 239 at 10^4 K, through 1 : 1.7 : 12.6 : 9.3 at 2 x 10^4 K, to 1 : 0.85 : 4 : 0.36 in the limit of large temperatures (T ≥ 10^5 K). Clearly N v and Si iv emission are produced in regions of comparable emission measure V N^2 while the C iv emission measure must be much smaller than that of N v, which is of course the reason for the difficulty with the λ1549/λ1238 ratio under possibility (a) conditions. The steep temperature dependence of the Mg ii emission does not allow any conclusion to be safely drawn, although we shall see later that there is a good candidate for the site of this emission.

Before discussing the alkali-like ions further we turn to La and He ii λ1640. These may both be straightforwardly interpreted as recombination lines; the presence of strong La emission suggests that all the hydrogen in the emission-line region is ionized, so case A conditions are likely. This conclusion is supported by the lack of significant time variation in La (see Section 6). The time variation of He ii λ1640 suggests that the He iii zone is ionization bounded, with case B conditions holding. From La we find an emission measure V He iii N^2 = 10^5 D^2_100 cm^2 for the He ii zone, assuming temperatures 2 ≤ T ≤ 10. Here D_100 is the system's distance in units of 100 pc; we expect D_100 ~ 1. We note that emission measures of just this order are typically inferred for Balmer emission from cataclysmic variables (e.g. Warner 1976). λ1640 is the He ii Hβ transition, so using Osterbrock's (1974) tables for the case B recombination emission with the relation

\[ i_{nn}(H β, T) = 8 i_{nn}(H, T/4) \]

between emission coefficients, we find an emission measure V He iii N e N He iii for the He iii zone of order 4 x 10^5 D^2_100 cm^3. With cosmic abundances we may take N He iii = 0.085 N e in this zone, yielding an equivalent emission measure V He iii N^2 = 5 x 10^4 D^2_100 cm^3. As this is a factor ~ 2 smaller than V H ii N^2, and H will be ionized throughout the He iii zone, we may conclude either that the He iii zone is physically smaller than the emission-line region, or that some collisionally ionized region contributes half the La. We can now use these emission measures to get some insight into the nature of the ionizing radiation producing them.

If the spectral luminosity of the ionizing continuum is L_ν erg s^-1 Hz^-1 the maximum possible ionizing flux producing ions of threshold frequency ν_T is

\[ \int_ν ν_i \frac{L_ν}{ν} dν \]

by the usual Strömgren sphere argument. The only plausible candidate for ionizing radiation in a system like AE Aqr is the Wien tail of self-absorbed thermal radiation from either the hot central regions of the accretion disc, or the 'hot spot' if the system has one. (Such self-absorbed radiation is clearly necessary to explain the observed continuum luminosity, which near 2700 Å is of order 10^17 D^2_100 erg s^-1 Hz^-1; free–free radiation from the emission measure V N^2 = 10^5 D^2_100 falls short of this by more than an order of magnitude.) Hence taking L_ν = 2πAhνe^(-hν/kT*) exp(-hν/kT*), where A is the effective emitting area, the above integral is approximately equal to L_ν/kT* hν_T, provided hν_T > kT*. If the continuum is just capable of producing the He iii emission measure inferred from λ1640 this quantity, evaluated at the He iii threshold hν_T = 5.44 eV, must equal the total (case B) recombination rate V He iii N e N He iii A_B on to He ii. Using our previously derived value for the emission measure...
and recombination coefficients from Osterbrock (1974) this rate is \( \sim 3 \times 10^{41} D_{100}^2 \text{ s}^{-1} \), leading to \( L_\nu T_\nu \sim 10^{39} \text{ erg s}^{-1} \text{ Hz}^{-1} \text{ K} \) at \( h\nu = 54.4 \text{ eV} \). A similar calculation, assuming \( L_\nu \) can just produce the hydrogen emission measure, gives \( L_\nu T_\nu \) at \( h\nu = 13.6 \text{ eV} \), although this is almost certainly a lower limit. These two values now imply a blackbody temperature \( T_\nu = 7.5 \times 10^5 \text{ K} \), with an effective area \( A = 7.3 \times 10^{17} \text{ cm}^2 \). If it is assumed that \( L_\nu \) actually produces much more than the necessary ionizing flux at 13.6 eV, so that the H II zone is 'density-bounded', as seems likely, \( T_\nu \) is reduced and \( A \) increased. However, \( T_\nu \) cannot be reduced below a value which will account for the ionization of N, which is inferred to be predominantly N V or higher ionization states. Hence a lower limit to \( T_\nu \) and an upper limit to \( A \) are provided by demanding that \( L_\nu \) should be capable of keeping most of the nitrogen in the emitting region at least in the form of N V. The ionizing flux required can be worked out from the H emission measure plus the recombination coefficients of Gould (1978) or Aldrovandi & Pequignot (1973). The result is \( T_\nu = 5.4 \times 10^4 \text{ K}, A = 2.6 \times 10^{19} \text{ cm}^2 \); we shall see that these limits can probably be tightened further.

An apparent problem emerges from the limits on \( L_\nu \); all of the allowed \( L_\nu \) 's would leave Si, C and Mg in higher ionization states than are observed (Si V, C V, Mg IV). It is obvious that this result does not depend on the Wien form assumed for \( L_\nu \); only a very contrived form of \( L_\nu \), with a drop of more than five orders of magnitude (!) between 13.6 and 15 eV, could account for the coexistence of H II, Mg II; with similar unlikely requirements for Si, C. This 'problem' is, however, a result of assuming that all of the emission-line region is equally exposed to the ionizing radiation. In the highly non-spherically symmetrical geometry of the primary = white dwarf + accretion disc (+ hot spot?) this is extremely unlikely, some regions will be sheltered from the ionizing flux, and we shall investigate how this can happen in the next section. We conclude this section by noting that because of the much greater efficiency of collisional excitation versus recombination in producing line radiation, such sheltered regions can be fairly small compared to the emission-line region as a whole.

5 The site of the emission-line region

In the two previous sections we have reached various conclusions about the emission line region, arguing solely from the observed line strengths, without any preconceived model for this region. The more important conclusions were as follows:

1. The ionization structure of H, He, N, Si and C must be determined by photo-ionization–radiative recombination processes, while that of Mg II can be determined by collisional–radiative balance.

2. Emission lines of H, He are produced by recombination but those of N, Si, C and Mg by collisional excitation.

3. The ionizing radiation required to produce the species observed can be characterized by a blackbody temperature \( T_\nu \) in the range \( 7.5 \times 10^4 \text{ K} > T_\nu > 5.4 \times 10^4 \text{ K} \), with corresponding effective emitting areas \( 7.3 \times 10^{17} \text{ cm}^2 \) and \( 2.6 \times 10^{19} \text{ cm}^2 \) respectively.

4. Parts of the emission-line region producing Si IV, C IV and Mg II line radiation must be to some extent sheltered from this ionizing radiation.

We can now use these observationally determined constraints to investigate possible sites for the emission-line region. Since the accretion disc in cataclysmic variables is now known to possess optically thin regions (G. T. Bath, private communication) especially at low accretion rates, economy of means suggests such a region as a first candidate. For collisionally ionized species, such as Mg II may be, this is an attractive hypothesis; but for photo-ionized species such as He II–III, Si IV, C IV, N V it is difficult to sustain. First, the
The UV spectrum of AE Aqr

'sheltering' required under 4 above is difficult to arrange: if the outer radius of the optically thin region is $R$, its volume is $V \sim 2\pi R^2 h$, where $h$ is the average scale height of the thin disc. The emission measure $N_e^2 \sim 10^{55}$ cm$^{-6}$ required of the region then translates into the requirement $h r_{es}^2 \sim 10^6$ cm, where $r_{es}$ is the electron-scattering optical depth along the disc. At reasonable temperatures $h$ will be $\gtrsim 10^2$ cm, giving $r_{es} \lesssim 1$. Since the continuum near 15 eV is at least $10^5$ times what is needed to ionize all the Mg$II$ to Mg$III$, much more effective shielding than this is required. It is readily checked that other absorbing or scattering processes do not help. Even if this difficulty could somehow be overcome a second serious problem remains. If a thin region of the disc is the emission-line region, the ionizing continuum can come only from that part of the disc (or hot-spot) luminosity emitted in directions intercepting the plane of the disc. This subtends such a small solid angle that unless the ionizing radiation is somehow 'beamed' with very high efficiency, which seems most implausible, the total luminosity in the continuum will be much larger than that required for ionization. This obviously leads to high continuum luminosities, in conflict with observation. Thus optically thin regions of the disc probably cannot account for any of the strong emission lines except (at least partly) La, Mg$II$ and Ca$II$ (optical). Thus N$V$, C$IV$, Si$IV$ and He$II$ emission must arise in some other region: the He$II$-zone emission measure implies that this other region supplies at least about half the observed La.

A candidate for the higher-excitation emission line region is not hard to find. As pointed out by many authors (e.g. Warner 1976; Paczyński 1978) there is ample material for an emission-line region in the upper parts of the disc atmosphere (i.e. that part of the accreting matter more than one scale height from the central plane of the disc). Ionizing radiation for such a 'chromosphere' is provided by the hot, optically thick central parts of the disc near the white dwarf, which itself contributes to the ionization. Some ionization might be caused by a hot spot, but this should be less important as most of the accretion energy is liberated near the white dwarf. The 'sheltering' required under conclusion 4 above is now quite naturally provided by absorption and scattering of radiation emitted near the disc plane, plus an aspect (cosine) effect for such radiation from the inner parts of the disc. The parameters derived before for the ionizing continuum fit very well the kind of spectrum and luminosity expected from the inner regions of the disc; if the continuation to longer wavelengths is the typical flattish ($\nu^{-2}$) disc spectrum below the blackbody peak of the hottest part of the disc (see e.g. Bath et al. 1980) we should probably choose temperatures fairly near the upper limit $T_e = 7.5 \times 10^4$ K ($A = 7.3 \times 10^{17}$ cm$^{-2}$) in order to avoid conflicting with the observed continuum in the UV*. The total luminosity $\int L_\nu d\nu$ from the hot inner part of the disc is therefore of order $10^{32}$ ergs$^{-1}$: this we may expect to be of order one-quarter of the total accretion luminosity (one factor of $\frac{1}{2}$ from the two sides of the disc, another because about one-half the accretion luminosity is released in the central parts of the disc). There is then excellent agreement with the luminosity expected at accretion rates of order $10^{16}$ ergs$^{-1}$ typical for cataclysmic variables at quiescence. The area $A \sim 10^{18}$ cm$^2$ implies that the ionizing flux comes from parts of the disc very close to the white dwarf, as is also demanded by the temperature, and for consistency of the model.

6 Time behaviour

The picture suggested above can be used to predict the temporal behaviour of the system. As mentioned in the Introduction, the optical light from the system is characterized by

* In AE Aqr it is not so much the case that the UV continuum is weak (it is of the same order as that observed by Bath et al. (1980) in EX Hya) but rather that the emission lines are unusually strong. Thus the values of $T_e$ and $A$ inferred here are perfectly compatible with the observed continuum.
Figure 2. The time variability of the optical and emission line intensities of Mg II \( \lambda 2795 \) and He II \( \lambda 1640 \). The earliest He II point is anomalous but could be explained by a small flare, as suggested by the dotted line section of the optical variation. The variation of NV \( \lambda 1238 \) closely follows that of He II \( \lambda 1640 \), including the earliest point.

almost continuous variability, the smaller variations being due chiefly to changes in the strengths of the Ca II emission lines. The optical 'bright' states must actually correspond to low states in the accretion rate (which means in turn short-term drops in the brightness of the inner disc) since Ca II emission will be increased if the accretion rate is reduced. Since Ca II emission only comes from a comparatively small region near the outer edge of the disc, quite small fluctuations in the continuum will manifest themselves in this way, accounting for the continuous variability. Moreover, we expect Mg II emission from the same region, so that Mg II \( \lambda 2795 \) should go up and down with the optical, as observed. The changes in the other line strengths are explained by the change in ionizing radiation. He II \( \lambda 1640 \) should vary directly with the ionizing continuum since it arises in an ionization-bounded zone. Thus the strength of \( \lambda 1640 \) is anticorrelated with the optical count rate. Fig. 2 shows the variability of \( \lambda 1640, 2795 \) compared with optical counts. NV \( \lambda 1238 \) behaves like \( \lambda 1640 \), as it is probably produced in regions nearer the ionizing source and the maximum continuum is only slightly more than that required to ionize it all. Si IV \( \lambda 1400 \) also displays such an anticorrelation, presumably because less Si III ionizing radiation penetrates to the outer parts of the chromosphere; no extra Si IV appears in the central regions because the continuum flux is always easily sufficient to keep it ionized. C IV \( \lambda 1549 \) behaves similarly. Finally, as expected, there is no significant variation in Lα, since at least one-half of it comes from a density-bounded photo-ionization zone.

7 Conclusion
Our analysis of the UV spectrum of AE Aqr has led to a picture in which lines of lower ionization states (Mg II, Ca II and some Lα) arise from collisional–radiative processes in
optically thin regions of the accretion disc. At least one-half of the observed \( \text{La} \) and all the lines from higher ionization states (\( \text{He} \, \text{II}, \text{N} \, \text{V}, \text{C} \, \text{IV}, \text{Si} \, \text{IV} \)) are produced in a 'chromospheric' region photo-ionized by radiation from the hot central parts of the accretion disc; \( \text{La}, \text{He} \, \text{II} \, \lambda 1640 \) are recombination lines, but all the others are collisionally excited. The need for two regions arises because although the thin disc regions must be present, they cannot account for the higher ionization species; we stress that this conclusion follows from the observed line strengths, not from model-dependent considerations. In the thin disc regions, all of the locally released accretion energy must be radiated as line emission, chiefly \( \text{La}, \text{Mg} \, \text{II} \). The cooling curves of Cox & Tucker (1969) show that this is eminently possible for quite plausible temperatures and densities in such regions if the accretion rate is of the order \( (10^{16} \text{gs}^{-1}) \) we have inferred to produce the requisite ionizing continuum.

The picture presented here gives a natural explanation for the great strength of the emission lines compared to the continuum in AE Aqr: the 9.88 hr binary period implies a fairly wide system by the standards of cataclysmic variables. The relatively modest accretion rate \( (10^{16} \text{gs}^{-1}) \) which we have inferred means that the accretion disc, which will be large because of the large separation, contains extensive optically thin regions near its edge (G. T. Bath, private communication). These will produce strong \( \text{La}, \text{Mg} \, \text{II} \) and \( \text{Ca} \, \text{II} \) emission. The enhanced \( \text{N} \, \text{V}, \text{Si} \, \text{IV} \), etc, emission probably arises because more material is available out of the plane of the disc to be photo-ionized; this occurs because the angle subtended at the centre of the disc by a scale height at its edge goes as \( \frac{R_d}{T} \), where \( R_d \) is the disc radius and \( T \) the temperature near the edge. For AE Aqr, as explained, \( R_d \) is large, while \( \frac{R_d}{T} \) is likely also to be greater than it would be in an optically thick part of the disc as it must increase to make emission-line cooling efficient. By comparison, in systems with shorter periods and higher accretion rates the equivalent widths of the lines will be reduced by the inverses of the above effects together with the greater strength of the continuum. These conclusions are supported by the observations of Bath et al. (1980).

Acknowledgments

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References

Infrared observations of the black-hole candidate V861 Sco

V861 Sco was found to be an eclipsing binary by Cousins and Lagerwey\(^1\) and its radial velocity curve has been determined by Walker\(^2\). The primary is a BO\(_1\) star, and taking suitable values for its mass the radial velocity curve suggests the unidentified secondary has a mass in the range 5–12 \(M_\odot\). Recently Polidan et al.\(^3\) showed that the system may be an X-ray source; it is therefore a black-hole candidate. We therefore thought that observations at other wavelengths would be of interest and we report here IR observations from 1.2 to 3.6 \(\mu\)m.

V861 Sco was observed from 25 July to 17 August 1978 at the Cabezon observatory, Tenerife, with the 1.5 m IR flux collector. The observations were made with the Leicester University and Royal Edinburgh Observatory IR photometers, both of which are of conventional design, use InSb detectors, and have identical interference filters. Each observation is the average of a number of 20 integrations. The error bars for our data shown in Fig. 1 are the standard error of the mean found from these integrations. V861 Sco is very low on the southern horizon from Tenerife, and can therefore only be observed once each night.

The standard used was SAO 227504 which is less than 0.5\(^\circ\) from V861 Sco. This standard was in turn calibrated against \(\alpha\) Cyg, which was just rising at the time of observation of V861 Sco, and subsequent observations of \(\alpha\) Cyg allows a correction for atmospheric extinction to be made. This procedure gives rise to a light curve of very reliable shape but whose absolute calibration has errors of \(\pm 0.1\) magnitudes.

The ephemeris used is calculated from the data of Cousins and Lagerwey\(^1\) and gives the primary minimum a phase of zero.

\[ \phi = (JD - 2440493.236) \times 0.127418 - 0.123 \]

We have not used the ephemeris quoted by Cousins and Lagerwey\(^1\) as this uses an epoch of JD = 2430000 which exaggerates any errors in the period. As can be seen from our data and the error in the period, this ephemeris is quite adequate at present and does not need clarifying as suggested by Polidan et al.\(^3\). Furthermore, this ephemeris places Polidan’s possible X-ray eclipse at about primary minimum, when the secondary is in front of the BO\(_1\)a primary, which is not very satisfactory.

Figure 1 shows our 1.2 and 2.2-\(\mu\)m light curves and also includes the IR data of Tazni et al.\(^4\). Their data agrees well with ours at 2.2 \(\mu\)m but is about 0.1 mag fainter at 1.2 \(\mu\)m; this is probably due to our error in absolute calibration due to the large air-masses. Neither our data nor that of Tazni et al.\(^4\) is of sufficient quality to draw a useful 3.6-\(\mu\)m light curve.

The main interest of these observations is the shallow IR secondary minimum. Table 1 shows our best estimate of the IR eclipse depths together with the optical data taken from Cousins and Lagerwey\(^5\). The ratio of secondary to primary surface brightness, \(B_2/B_1\), is calculated from these depths. We have also calculated \(A_2/A_1\), the eclipsed area at either primary or secondary eclipse divided by the area of the primary, assuming the eclipse is total. If the eclipse is not total this column is a lower limit for \(A_2/A_1\).

The rapid decrease of the surface brightness of the secondary from the optical to the IR clearly shows that this is a non-stellar object. For example, if we take –0.79 for the \(V-K\) colour of the BO\(_1\)a primary, we can show the \(V-K\) colour of the secondary is –1.71 which doesn’t correspond to any known star.

The non-secondary surface is probably a compact object surrounded by an accretion disk. In the IR the cool outer regions of the disk are optically thick to free–free radiation and a low surface brightness is observed. In the visible region of the spectrum, however, the outer regions of the disk would be optically thin, allowing the hotter central region to be observed.

The presence of an optically thin accretion disk is also supported by the emission lines seen by Walker\(^2\) and Polidan et al.\(^3\).

It may be argued that we have taken the eclipse depths at face value and not made any allowance for gravity darkening, ellipticity or heating effects on the near side of the primary. These effects can be removed by ‘rectifying’ the light curve and this has been done by Walker\(^2\) for the optical data. If the main distortion to the light curve is the ellipticity of the primary this effect should be the same in both the visible and near IR. Thus we might apply Walker’s rectification to the IR light curves but, as this has an amplitude of 0.15 mag, it would more than remove the secondary minimum. Walker’s rectification may therefore be excessive.

Any rectification applied to the IR light curves will only make the ratio \(B_2/B_1\) smaller still, so our conclusion that the secondary is non-stellar remains. The shallow IR secondary eclipse also means that the area of the primary seen at phase 0.25 cannot be more than 10% greater than the area seen at phase 0.5. This small ellipticity of the primary implies that it does not fill its Roche lobe. If the primary were to fill its Roche lobe a difference of \(1\%\) would be needed; this requirement is almost independent of the assumed mass ratio. Thus the photosphere does not apparently fill its Roche lobe; however, the likely extended atmosphere of the primary could give a substantial mass transfer through the inner Lagrangian point. Alternatively, if we regard the mass transfer as being due to a stellar wind then the secondary must contain a compact object, which would have to be a black hole. This conclusion is independent of any assumption about the possible X-rays.

It should also be noted that if, following Walker\(^2\), we take \(A_1=1.47\) the whole system has a \(K\) excess of 0.4 mag. This cannot, of course, be due to the eclipse radiation from the secondary. If the eclipses are partial, and the secondary is effectively larger at IR wavelengths this would give the IR excess. Alternatively the whole system may be surrounded by free–free emitting material.

We conclude that these observations support the idea that the secondary of V861 Sco contains a black hole. However, a more convincing identification of the X-ray source with V861 Sco is needed. Even if V861 Sco does not turn out to be an X-ray star it would still seem to be an interesting system. Either way the IR data should assist with any future models of the system.

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The Infrared Variability of SS433

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We report here the results of a year long monitoring programme of SS433 at infrared and visual wavelengths. The most striking feature of these observations is the near constancy of the infrared colours while the source's flux varies over a range of $\sim$1.2 magnitudes. There is no evidence for the 13.1 day period first reported in radial-velocity measurements by Crampton et al.\textsuperscript{1} However it seems possible that an 11.8 day period is present.

SS433 remains an object of great interest because of the presence of enormously Doppler-shifted emission lines swinging back and forth across its spectrum.\textsuperscript{3,4,5} Suggested models include those of Rees and Fabian\textsuperscript{6} and Abell and Margon,\textsuperscript{7} and comprehensive reviews of the spectroscopic data can be found in Murdin et al.\textsuperscript{8} and Margon et al.\textsuperscript{9} The work reported here is not directly connected with the emission-line phenomena but provides additional information about the nature of the underlying binary system. The variability of the source has been studied at several wavelengths\textsuperscript{2,10,11,12,13,14} and the radial velocity period of 13.1 days first reported by Crampton et al.\textsuperscript{1} has now also been detected in the $\text{H}$ line-to-continuum ratios by Margon et al.\textsuperscript{15} and by Liller et al.\textsuperscript{16} and Noyes et al.\textsuperscript{17}

We have observed SS433 between April and November 1979 with a variety of instruments, mostly from the Cabezon Observatory, Tenerife, using the 1.5 m Infrared Flux Collector. At Tenerife most of the data were obtained at VJHK with the Leicester photometer or Hatfield polarimeter/photometer, which use the same InSb dewar and photon counting systems. Additional V points were obtained at Tenerife with the RGO travelling optical polarimeter/photometer. Further JHK data were obtained at the AAT in Australia and at UKIRT in Hawaii. This collection of data has been supplemented with the published data of Impey\textsuperscript{18} and that of Wynn-Williams and Becklin.\textsuperscript{19}
All these data are presented in Tables 1, 2 and 3 but the rest of this paper is confined mainly to a discussion of the more abundant data in the first of these tables. The JHK measurements have been combined to produce Fig. 1 which shows the remarkable constancy of the infrared colours. This is just as expected for free-free emission, as suggested by Giles et al.\textsuperscript{20} and Allen\textsuperscript{21} and supported by Wynn-Williams and Becklin.\textsuperscript{19}

The J data in Table 1 have been folded at trial periods in the range 0.1 - 50 days using the technique described by Bopp et al.\textsuperscript{22} to find the most likely period. This method was chosen as it is appropriate to a small sample of data containing large and irregular gaps in temporal coverage and the result is shown in Fig. 2. The curve shows no indication of a 13.1 day period and this may readily be confirmed by folding the data at this period for which no reasonable light curve results.

Originally Giles\textsuperscript{23} reported smooth JHK light curves for a period of $11.8 \pm 0.05$ days, possessing two minima, the broader one being used to define the ephemeris

$$1979 \text{ Aug } 14.26(\pm 0.5) \text{ UT } + 11.8E.$$  
This ephemeris was used to predict the occurrence of the possible narrow 'eclipse' feature\textsuperscript{23} which was then apparently confirmed by several subsequent observations at UKIRT in Hawaii. Further points obtained at the AAT in early 1980 also apparently confirm this feature, in phase, and width, although the depth is undefined. The dip around 11.8 days from the Bopp analysis in Fig. 2 naturally produces a reasonable light curve when the data is folded at this period. Fig. 3 shows the resulting J light curve. The apparent smoothness of this curve is somewhat less than that evident for the first attempt\textsuperscript{23} now that additional points have been added. It may well be that SS433 has some variability over long time scales in addition to that caused by any binary period modulation.
We note that the photometry by Glass\textsuperscript{24} agrees with our range of intensity and colour variation but is not entirely consistent with our possible period. Such differences may prove important when a much larger data base is available if they can be related to the 164 day period. It is clearly very important that the existence or otherwise of this 11.8 day period should be demonstrated over the coming summer. This will best be achieved by \( \sim 3 \) weeks of complete coverage rather than by folding irregularly spaced short data sets. The limited optical data we have obtained shows no periodicity.

Given the unprecedented nature of SS433 it seems not inconceivable that the source should have two periods, only one or even neither of which is a true orbital period. SS433 will clearly repay further detailed photometric study. Observations of any modulation in the X-ray flux or low-energy cutoff would be of especial interest.

\textbf{Acknowledgements}

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References

Table 1

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Table 2
V Photometry of SS433

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Table 3

B, I Photometry of SS433

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Figure Captions

Fig. 1. J-K and J-H colours vs J magnitude for SS433.

Fig. 2. An analysis of the J data for periodicities (Bopp et al.\textsuperscript{22}). Sharp dips indicate periods of interest and the vertical scale is logarithmic ($S = \Sigma \Delta M$).

Fig. 3. J light curves for the data folded at 11.8 days.
FIG. 1

\[ \Delta M \]

J-K

J-H

MAG (J)

8.8
8.6
8.4
8.2
9.0
9.2
9.4
9.6
9.8
10.0
Summary. We report the results of a sensitive search for 'hard' (≥ 2 keV) X-ray emission from 47 dwarf novae, based on Ariel V Sky Survey Instrument (SSI) observations, using the Point Summation Technique (PST). X-ray emission is detected from the region of two dwarf novae: SS Cygni and EX Hydrae. The refined SSI error box for the previously catalogued source, 2A 1251-290, is consistent with the position of EX Hya, and the variability indicated by the X-ray light curve implies that the cluster originally suggested is no longer a reasonable identification. These results are discussed in terms of the model described by Fabian et al. for X-ray emission from a system containing an accreting white dwarf.

1 Introduction
Several dwarf novae are already established as X-ray sources in the soft X-ray energy range (≤ 2 keV) but, to date only SS Cyg has been shown to emit 'hard' X-rays (≥ 2 keV) (Ricketts, King & Raine 1978 and references therein), although the related cataclysmic AM Her is a hard X-ray emitter (e.g. Cooke et al. 1978). We present here the results of a systematic search for 'hard' X-ray emission (~ 2–18 keV) from dwarf nova systems, based on the extensive observations made by the Ariel V Sky Survey Instrument (SSI— for details see Villa et al. 1976 and Cooke et al. 1978) made over the last 3½ yr. One dwarf nova, EX Hydrae, is clearly detected in this survey and we present details of both the SSI error box and light curve for the associated X-ray source. We conclude by discussing these results in terms of the proposed X-ray emission mechanism for dwarf nova systems.

2 Observations and analysis
2.1 PST survey results
The survey was performed on a list of 47 dwarf novae taken from a compilation by Glasby (1970). The list, given in Table 1, includes 29 'U Gem' and 18 'Z Cam' systems and although
Table 1.

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<th>(4)</th>
<th>(5)</th>
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<td><strong>Name</strong></td>
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<td><strong>Dec.</strong></td>
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<td><strong>$m_{\text{min}}$</strong></td>
<td><strong>$T_{\text{out}}$</strong></td>
<td><strong>$P_{\text{orb}}$</strong></td>
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<td>52</td>
<td>6.63</td>
<td>1.20 + 0.12</td>
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<td>16.0</td>
<td>34</td>
<td>–</td>
<td>&lt;0.30</td>
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</tbody>
</table>

* AE Aqr is listed by Warner (1976) as a nova-like variable.

Notes:

Column (1): name of dwarf nova. 'Z Cam' systems are marked with an asterisk.

Columns (2) & (3): celestial position in degrees (1950.0).

Columns (4) & (5): outburst and quiescent apparent magnitudes taken from Glassby (1970). Magnitudes are mainly photographic or visual.

Column (6): mean recurrence period in days between outbursts, taken from Warner (1976) or Glassby (1970).

Column (7): orbital period in hours (where known), taken from Warner (1976).

Column (8): flux obtained by PST analysis in SSI count/s. For fluxes $<2\sigma$ a flux +3$\sigma$ upper limit is given, for fluxes $>2\sigma$ actual flux and $1\sigma$ error is given.
Plate 1. The optical field near EX Hya (marked) showing the 2A, 4U and 2AR error boxes (see text and Table 2). The cross marked 'Cl' is the approximate centre of the cluster (see text), and the circle marks the cluster extent corresponding to distance class 3. The faint vertical line arises from the joining of the two Palomar Observatory Sky Survey red plates (© National Geographic Society) used for this plate.
not complete, forms a reasonably representative sample. The 'UGem' systems considered are those with outburst magnitudes brighter than 12.1 mag; all the 'Z Cam' systems listed by Glasby were included (the faintest 'Z Cam' system has outburst magnitude ~ 14.0 mag).

X-ray emission was searched for at the position of each dwarf nova by coherently summing all the scans made by the SSI at this point employing the Point Summation Technique (PST, Cooke et al. 1978). In this context a 'scan' refers to a set of observations by the SSI with nominally the same spacecraft attitude, which can therefore be coherently summed. This method has been successfully used in surveys of X-ray emission from QSOs (White & Ricketts 1977), Seyfert galaxies (Elvis et al. 1978) and clusters of galaxies (Ricketts 1978).

The present results are given in Table 1 together with some of the more important optical characteristics of the dwarf novae.

The PST yields a significant increase in sensitivity when compared with that obtained from any single SSI scan across an object (the typical 5σ sensitivity, which is that established as the significance threshold in PST analysis, is ~ 0.7 SSI count/s = 1.9 Uhuru count/s = 3.5 × 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}), but it is seriously affected by the presence of nearby sources. In the PST analysis, scans affected by nearby catalogued sources are routinely rejected, but in regions of high source density, particularly in the galactic plane, the technique becomes useless owing to the rejection of the majority of the data. These cases are flagged 'confused' in Table 1. However, we have examined the individual scans made of these objects, and indeed of all the dwarf novae which gave a signal in excess of 2σ, in order to determine whether these showed significant signals. In no case did this examination reveal compelling evidence for an X-ray source at the location of the dwarf nova.

Only two dwarf nova systems studied gave a significant signal (> 5σ) in this survey: SSCyg and SXHya. For the others the upper limits obtained lie mainly in the range 0.2–1 SSI count/s. For a typical dwarf nova distance of 100 pc this corresponds to a limiting 2–18 keV luminosity in the range (1–6) × 10^{31} \text{ erg/s}. We stress that these upper limits necessarily refer to an average over all the SSI observations, which typically total only 30 day for any object over the 3%-yr observation period. Because of the possibility of large variability in the X-ray emission from dwarf nova systems, which is clearly demonstrated by the SSI observations of SSCyg (Ricketts et al. 1978) and of SXHya (this paper), one must be very cautious in interpreting these upper limits.

2.2 EX HYDRAE

The dwarf nova EXHya was previously suggested as the identification of the Uhuru source 2U 1253-28 on the basis of positional coincidence alone (Warner 1972, 1973). In the later 2A and 4U catalogues, the sources 2A 1251-290 and 4U 1249-28 (which are almost certainly identical, Cooke et al. 1978; Forman et al. 1978) are tentatively identified with a distance class 3, richness class 3 cluster of galaxies (SC 1251-28, see Bahcall 1977). In an attempt to resolve this ambiguity, and of course encouraged by the probable PST detection of EX Hya, a revised error box was obtained for this X-ray source by combining all the significant lines of position (LOP) which overlap in this region, in a manner very similar to that employed by Cooke et al. The large reduction in the error box size (see Plate 1) results partly from the use of additional observations made since the 2A catalogue was compiled, but the major improvement derives from the greater positional accuracy of each LOP made possible by using sightings of accurately positioned catalogued sources to refine the spacecraft attitude. The revised error box for the X-ray source, now 2AR 1249-289, is shown in Plate 1 together with the 2A and 4U error boxes, and the position and extent of the cluster as given by Bahcall (1977); the coordinates are given in Table 2. EX Hya lies within 3 arcmin of the centre of the revised error box thus, on positional grounds alone, must be regarded as a good candidate.
We note, however, that the cluster, which is a cD type on the Rood–Sastry classification scheme, would be expected to be an X-ray emitter at something like the luminosity previously inferred by McHardy (1978). Also OSO-8 satellite observations have revealed evidence for iron line emission, often associated with X-ray emitting clusters, from this region with an equivalent width of $0.53^{+0.3}_{-0.4}$ keV (Mushotzky et al. 1978). However, the recent discovery of iron line emission from SSCyg (Swank 1978, private communication) makes it quite likely that the emission feature may be associated with EX Hya, rather than the cluster as previously assumed.

We have also examined the variability of 2AR 1249-289 using the SSI observations. The X-ray light curve, shown in Fig. 1, is based on all the reliable observations, unconfused by nearby sources, made by the SSI from 1974 October until 1977 April (the source has not been scanned since). Each data point represents, typically, a 3-day summation with the spacecraft attitude approximately steady. These observations yield a reduced $\chi^2$ value of 2.28 (for 25 degrees of freedom) when tested against the hypothesis that the source is constant. The formal probability of obtaining this $\chi^2$ from a steady source is less than 0.1

![Figure 1](image.png)

**Figure 1.** The SSI X-ray light curve of 2AR 1249-289. The time axis is marked in MJD ($= JD - 2400000.5$), and calendar years are indicated at the top. Each point represents a summation over several days (actual duration given by length of horizontal bar) and is plotted with $\pm 1\sigma$ error bars. The dashed line indicates the weighted mean flux.
per cent giving us confidence that it is indeed variable. This variability adds further weight to the association of this source with EX Hya, rather than the cluster SC 1251-28, since cluster X-ray emission is widely believed to originate in the hot intracluster gas having dimensions of the order Mpc.

There remains the possibility that the X-ray source is associated with another object in or near the error box. We cannot totally exclude this possibility without an extensive optical study, but we note that there are no catalogued objects in the error box region of the type known to be associated with variable X-ray emission (such as Seyferts or active galaxies). The cluster may contribute some small, steady fraction of the X-ray flux, but EX Hya remains a strong candidate for the identification of 2AR 1249-289.

EX Hya is known to be an eclipsing binary with a period of 98 min (Warner 1976). This is unfortunately very close to the nominal time-resolution of the SSI (~ 100 min), making a search for any binary modulation in the X-ray data impractical. The dwarf nova outbursts in EX Hya have a mean recurrence period of 465 day, with a large scatter, but last typically for only 4 day (Bateson, Jones & Menzies 1970). We have compared the optical light curve of EX Hya over the last 4 yr (kindly compiled by F. M. Bateson from the work of the RASNZ Variable Star Section) with the X-ray observations shown in Fig. 1. Not surprisingly, with the small duty-cycle of both optical outbursts and X-ray observations, no obvious correlation exists. Indeed the last reliably monitored outburst occurred around JD 2442758 (= MJD 42757.5) during a long gap in the X-ray coverage so we are unable to comment on the possibility of correlated X-ray/optical activity in EX Hya, such as is displayed by SS Cyg (Ricketts et al. 1978).

3 Discussion

The established model for dwarf nova systems involves a close binary with period < 1 day consisting of a white dwarf and late-type main sequence star. Mass loss from the main sequence star via Roche-lobe overflow leads to accretion on to the white dwarf from the accretion disc which is formed around it. The accretion disc, and hot-spot where the flow meets the disc, are presumed to be responsible for most of the unusual optical properties of such systems (e.g. Bath 1976). 'Hard' X-ray emission above ~ 2 keV cannot be produced in dwarf novae unless rather special conditions apply. In the model by Fabian, Pringle & Rees (1976), shock-heating of the radially infalling matter on to a magnetized white dwarf can lead to hard X-ray emission from near its poles by the optically thin bremsstrahlung process. A significant hard X-ray flux escapes, however, only if the accretion rate and magnetic field lie within narrow ranges, thereby avoiding the effects of photoelectric absorption and inelastic electron scattering, or the possibility of dominant emission via optical cyclotron radiation. These constraints are more fully discussed by Ricketts et al. (1978) with reference to the detailed X-ray/optical behaviour of SS Cyg.

The PST results suggest that only a small percentage of a reasonably uniform sample of 47 dwarf novae are 'hard' X-ray emitters at luminosities ≥ 10^{31} erg/s, which may reflect the rarity in dwarf novae of the optimum conditions discussed above. The two objects detected are, however, the second and fifth ranked according to quiescent magnitude, and it may be that many more dwarf novae are hard X-ray emitters at luminosities slightly below the limit of this survey. From both an observational and theoretical point of view, the X-ray emission from dwarf novae is expected to be highly variable and may only be detectable at particular outburst or quiescent phases (cf. SS Cyg; Ricketts et al. 1978). This highlights the need for more extensive observations in the future. To achieve a detailed understanding of the X-ray emission from dwarf novae, it would be useful to observe them with higher time resolution in order to study any modulation with the binary period.
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References

Infrared and optical light curves of EX Hydrae and VW Hydri

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Summary. Optical and infrared light curves of EX Hya (V and K) and VW Hyi (J and K) are presented. The infrared colours imply very large discs for these systems. It is also found for EX Hya that the structure of the light curves is non-repeatable.

Introduction

During the last 18 months we have observed the infrared light curves of a number of dwarf novae. We present here the light curves of EX Hya and VW Hyi at 1.2 and 2.2 μm, since both these systems have very short periods and we believe secondary stars which are virtually invisible at longer wavelengths. The only previous infrared observations of dwarf novae are those of Szkody (1977) who did not observe the binary light curves.

Observations

EX Hydrae was first observed at 2.2 μm on 1978 April 6 with the 1.5 m IR Flux Collector at the Cabezon Observatory, Tenerife. Our infrared photometer with an InSb detector has since been modified to include an optical channel which allows simultaneous optical and infrared observations. Two further cycles were measured at V and K on 1979 April 22. All this data together with the appropriate error bars derived from observations of non-variable stars of similar magnitude are shown in Fig. 1. The standard star used was BS 4757 and this was observed before and after each light curve. Heliocentric corrections have been applied to all phases. Attempts to measure the 1.2 μm light curve were frustrated by cloud but a \( V - J = 0.7 \) was measured at phase \( ~0.3 \) on 1979 April 24. All the above observations were made at quiescence, \( V \sim 13.2 \).

VW Hydri was observed at 2.2 and 1.2 μm on 1978 December 5 and 6 using the SAAO 1.9 m telescope and IR photometer. This does not have the capability of simultaneous optical photometry. This data together with error bars is shown in Fig. 2. VW Hydri was observed in a quiescent state just before an outburst (see below).
Figure 1. Light curves of EX Hydrae. The top four curves are the $K$ and simultaneous $V$ light curves observed in 1979. The bottom $K$ curve was observed in 1978.
Light curves of EX Hydrae and VW Hydrai

Discussion of EX Hydrae

This discussion is best divided into three sections, the colours, the time variability and a possible 67 min periodic modulation.

COLOUR

The mean colours of the system are $V-J = 0.7$ and $V-K = 1.5$. These colours fit very well a $\nu^{1/3}$ spectrum as shown in Fig. 3. This is to be expected for an accretion disc (Lynden-Bell 1969). Before accepting this conclusion we must consider two other possibilities, namely that the secondary star contributes to the red colour or that there is a large region around the system of hot free–free emitting material. Warner (1976) derives relations between the orbital period and the mass and absolute magnitude of the secondary, assuming it is a main sequence star filling its Roche lobe. Using these equations and the period of 99 min we find $M_2$ (secondary) = 14.78 and $M_2 \sim 0.19 M_\odot$. This mass implies a spectral type of M5.5V Allen (1973), leading to $V-J = 4.45$ and $V-K = 5.40$ Johnson (1966). Thus, using the likely distance of ~100 pc, the apparent magnitudes of the secondary are $J = 15.3$ and $K = 14.4$.

The $K$ magnitude of the system is 11.8 so the secondary is only contributing 9 per cent of the $\nu^{1/3}$ flux. Even allowing for some deviation of the secondary from the main-sequence assumptions it seems unlikely that it provides more than a small fraction of this flux. The flux from the secondary could be increased by a strong reflection effect but if this were significant it would be apparent from the light curves.

If the whole system is losing mass out of the orbital plane, this material, heated by the UV and X-ray flux, from the system will give optically thin free–free radiation. Such a spectrum is of course flat, but could conceivably alter the $K$ magnitude to give an apparent $\nu^{1/3}$ spectrum. It is difficult to see how such a contribution could be reconciled with the observed variation. Also such ionized gas is inconsistent with the Balmer line intensities. Thus we conclude the red colour of the system is due to the disc.

If we ascribe the $\nu^{1/3}$ continuum to an optically thick steady-state accretion disc we may put limits on the disc size. As explained by Bath, Pringle & Whelan (1980), the temperature
at radius $R$ in such a disc is

$$T(R) = T^*_e \left( \frac{R}{R^*_e} \right)^{-3/4} \left[ 1 - \left( \frac{R^*_e}{R} \right)^{1/2} \right]^{1/4}$$  \hspace{1cm} (1)$$

where $R^*_e$ is the inner radius of the disc, and $T^*_e$ is a parameter related to the accretion rate. For EX Hya in quiescence, $T^*_e$ is already determined from Bath et al. UV observations to be $(7.0 \pm 1.4) \times 10^4$ K. The spectrum of the disc is

$$f_\nu = \int_{R^*_e}^{R_{out}} B_\nu(T(R)) \frac{2\pi R dR}{\nu^3}$$

with $B_\nu(T)$ the Planck function and $R_{out}$ the outer radius of the disc: thus

$$f_\nu \propto \frac{X_{out}}{X_{in}} \frac{X^{5/3}}{\exp(X) - 1}$$

where $X_{in} = h\nu/kT(R^*_e)$ etc. Hence the $\nu^{1/3}$ law holds for frequencies $\nu$ with $kT_{out} < h\nu < kT_{in}$ (i.e. $X_{in} \approx 0$, $X_{out} \approx \infty$), giving way to a Wien distribution for $h\nu > kT_{in}$ and a Rayleigh–Jeans tail for $h\nu < kT_{out}$.

Fig. 3 shows the UV, optical, and IR data fitted with disc spectra having $T^*_e = 7 \times 10^4$ K and three values of $T_{out}$: $T_{out} = 0, 2170$ and $3000$ K (the fit of these values of $T_{out}$ is not affected by different values of $T^*_e$ within the range $(7.0 \pm 1.4) \times 10^4$ K). As can be seen, the K point is in fact well fitted with $kT_{out} < h\nu K$ (formally $T_{out} = 0$); a value $T_{out} = 2170$ K is just acceptable if the $K$ flux has been measured 20 per cent too high; while values of $T_{out}$ greater than this, e.g. $T_{out} = 3000$ K, are definitely excluded. If the errors on the $K$ point are tightened to $\pm 10$ per cent the largest acceptable $T_{out}$ is only 1450 K.

From equation (1), which is $T = T^*_e (R/R^*_e)^{-3/4}$ for $R > R^*_e$, we immediately see that the disc is rather large: with $T^*_e = 7 \times 10^4$ K, $T_{out} = 2170$ K, we find $R_{out} = 103 R^*_e$, which is larger even than the binary separation $a = 5 \times 10^{16}$ cm unless $R^*_e < 5 \times 10^{16}$ cm, corresponding to the radius of a white dwarf of mass $1 M_\odot$ or higher. While it is perfectly possible for an accretion disc to be as large or larger than the binary separation, and indeed still exhibit a.

![Figure 3](image-url)
\( p^{1/3} \) spectrum since this depends on purely local considerations, it is rather unlikely that a smooth \( p^{1/3} \) spectrum from 1225\( \lambda \) out to 2.2\( \mu \)m would result. This is because tidal effects are expected to truncate the disc near the primary's Roche lobe (Papaloizou & Pringle 1977; see also Paczyński 1977). The spectrum of any material further out would then probably not fit on to the disc's \( p^{1/3} \) spectrum, even if this itself had the \( p^{1/3} \) form.

The average radius \( R_L \) of the Roche lobe of the primary is given by Paczyński (1971) as a function of the primary mass \( M_p \) (in solar units) and the ratio \( q \) of secondary to primary mass. If we assume \( R_{out} = R_L(M_p, q) \) (as suggested by the considerations of the previous paragraph), and that \( R_{out} \) is given by the radius of a white dwarf of mass \( M_1 \) (e.g. Chandrasekhar 1967), a value of \( T_{out} \) implies a relation between \( M_1 \) and \( q \); i.e.

\[
R_{out} = \left( \frac{T_\odot}{T_{out}} \right)^{1/3} R_{in}(M_1) = R_L(M_1, q).
\]

Putting in the errors on \( T_\odot \) we get a band of allowed values in the \( M_1, q \) plane for each value of \( T_{out} \), as shown in Fig. 4, where \( T_{out} = 2170 \) K is assumed. Also shown is the curve on which the secondary mass \( qM_1M_2 \) has the minimum value 0.085\( M_2 \) for a hydrogen-burning star (Graboske & Grossman 1971); for a main sequence secondary to be possible the system must lie to the right of this curve. If instead of \( T_{out} = 2170 \) K we take \( T_{out} = 1450 \) K, corresponding to a 10 per cent error in the measurement of the \( K \) flux, the upper limit to \( M_1 \) given by the upper curve labelled '\( T_{out} = 2170 \) K' becomes instead a lower limit; the corresponding upper limit is greater than the Chandrasekhar mass. Obviously if we demand that \( R_{out} \) is actually smaller than \( R_L \), the corresponding lower limits on \( M_1 \) and upper limits on \( q \) become still tighter.

Fig. 4 implies a fairly high white dwarf mass \( M_1M_2 \) (> 1.1\( M_2 \)) for \( T_{out} = 2170 \) K, > 1.3\( M_2 \) for \( T_{out} = 1450 \) K) unless an extreme mass ratio \( q < 0.01 \) is adopted. This is in agreement with the observational estimates \( M_1 > 1.07, q < 0.15 \) (Warner 1976, and references therein). Clearly, an accurate measurement of the \( L \) flux in quiescence would considerably tighten the limits on \( T_{out} \) and hence \( R_{out} \) and \( M_1, q \).

![Figure 4](image-url)

Figure 4. The relation between the white dwarf mass \( M_1 \) (solar masses) and ratio \( q \) of secondary to primary masses in EX Hya, assuming the radius \( R_{out} \) of the disc is equal to the average Roche lobe size. If minimum 20 per cent errors in the \( K \) photometry are assumed the system must have \( M_1, q \) lying between the curves labelled '\( T_{out} = 2170 \) K'. If the errors at \( K \) are only 10 per cent, the system must lie between the upper curve and the Chandrasekhar limit. Also shown is the region of the \( M_1, q \) plane where a main sequence secondary is impossible.
Finally, it should be noted that all the above estimates of \( M_f \) lead to reasonable values for the distance \( D \) to the system. Bath et al. (1980) derive the relation

\[
D = 650 \left( \frac{R_{eq}}{10^8} \right) (\cos i)^{1/2} \text{pc}
\]

(where \( i \) is the orbital inclination) by comparing the deduced accretion rate with the apparent bolometric luminosity. For \( M_f \) in the range 1.1 < \( M_f \) < 1.38 we have 5 \( \times 10^8 > R_{eq} > 2 \times 10^8 \), so with \( i > 70^\circ \), which is probably required to get the \( V \) band primary eclipse, we have 76 < \( D < 190 \) pc. (If \( i \) turned out to be somewhat greater than 70° we would need to adopt one of the larger values of \( R_{eq} \) in order to prevent \( D \) becoming so small that the system's parallax would be measurable.)

### Variability

Careful examination of both the \( V \) and \( K \) light curves shows that primary minimum at zero phase is always present. In addition there are numerous other significant features but none of these repeat from cycle to cycle.

That many features of the \( K \) light curve do not repeat is readily understandable; if, as is strongly suggested by our estimates of its size, the disc fills the Roche lobe of the primary, its outer regions are expected to be prey to all manner of disruption. Clearly tidal effects will be important (Papaloizou & Pringle 1977), as will the impact of the gas stream from the secondary. The time-scale of variability in the \( K \) curve, as implied by the mean time between local minima, is of order (5 ± 2) min (considerably longer than the average interval between points). It is suggestive that this is close to the dynamical time-scale \( (R^2_{out}/GM_f)^{1/2} \) for material near the edge of the disc; for acceptable values of \( M_f \) this is \( \approx 6.6 \) min unless extreme values of \( q \) are adopted, in which case it becomes of order 15 min (= 1/2π × binary period).

### The 67 min periodicity

In a remarkable paper, Vogt, Krzeminski & Sterken have analysed \( V \)-band photometry of EX Hya taken during the period 1962—76 and find in addition to the 99 min binary period a modulation of the light curve with a period of 67 min, which has remained coherent over the 14 yr of observation. The very accurate ephemeris derived for this modulation by these authors has enabled us to test our data for its presence. Fig. 4 shows the \( K \) and \( V \) photometry folded on the 67 min period, phase 1.0 corresponding to the occurrence of the maximum amplitude of modulation. As can be seen, there is some evidence for the 67 min period in the \( V \) data but very little in the \( K \) data. This is consistent with the modulation being caused by radiation from a region rather hotter than the outer parts of the disc.

The ratio of the period of the modulation to the orbital period is just 2.2 per cent greater than 2:3. This fact might suggest an interpretation in terms of a density enhancement produced by resonant tidal torques from the secondary and rotating with 2/3 of the system's orbital period. This explanation of course requires the Roche lobe of the primary to enclose the orbit of the perturbation, at radius \((2/3)^2 a \approx 0.76 a\). This is only possible for mass ratios \( q \) of order 3 per cent or less, so that in this case the secondary clearly could not be a main sequence star.

### Discussion of VW Hya

Bateson (1979, private communication), has collected visual magnitudes obtained by the RAS NZ variable star observers for the dates when we observed the system at \( J \) and \( K \).
Light curves of EX Hydrae and VW Hydri

Figure 5. K and V photometry of EX Hydrae folded on the ephemeris of the 67 min periodic modulation of the light curve (Vogt et al. 1979), with maximum at phase 1.0.
Using this data we find $V - J = 1.1$ and $V - K = 1.85$ and thus $J - K = 0.75$; note that there is a small variation in $V$ between the nights. If we ignore this we find $J - K = 0.90$, from our observations alone. Clearly we cannot rely too heavily on colour indices involving $V, J - K = 0.90$ gives the $\nu^{1/3}$ expected for a disc. The period of VW Hyi is 107 min, almost identical to that of EX Hya, so using the same arguments we conclude that the colour is due to the disc.

The hump in the light becomes progressively weaker at $J$ and $K$. There is also some additional structure which, if the system is like EX Hya, is probably non-repeatable.

The near-absence of the hump in the IR light curves is at first sight surprising in view of its great strength at $V$, where it contributes about half the flux (Warner 1976). Evidence for a hot spot does not show up in the spectrophotometry of Bath et al. (1980), since this was obtained on the decline from outburst, when the disc dominates the system's luminosity (Vogt 1974). However, if the hump is due to the anisotropic part of the radiation from an optically thick hot spot this is quite reasonable, since the ratio of fluxes from the hot spot and disc will go as $\nu^2/\mu^{13} = \nu^{13}$. Thus if the anisotropic part of the hot spot light is comparable to that of the disc at 5500 Å, it will produce only one-quarter of the disc's light at 1.25 μm and one-tenth at 2.2 μm. The maximum amplitudes of the hump at the two wavelengths should then be ~0.25 and 0.1 mag respectively, consistent with observation. Obviously the hot spot must be much smaller in area than the parts of the disc contributing appreciably to the flux at any given wavelength.

Since the UV and optical spectrophotometry of Bath et al. (1980) was performed while the system was still declining from an outburst we cannot compare their results directly with the infrared data, which were obtained at quiescence. In particular, we cannot carry over their estimate of $T_\star > 1.6 \times 10^5$ K as this depends directly on the accretion rate, which was presumably lower at the time of the infrared measurements. On the other hand, the general similarity in period and infrared light curves, together with the excellent agreement of the $J - K$ colour with that expected for an optically thick accretion disc, strongly suggests that in VW Hyi also the disc is large. Indeed, we note that Bath et al. estimate $R_{\text{out}}/R_{\text{in}} > 90$, using only data out to 7500 Å, already puts $R_{\text{out}}$ (near outburst) close to the Roche lobe even for the smallest values of $R_{\text{in}}$. It will be especially interesting to obtain the infrared colours of VW Hyi at or near outburst, as these presumably must begin to show some deviation from the $\nu^{1/3}$ law. If on the contrary the colours implied a $\nu^{1/3}$ spectrum to high accuracy out to 2.2 μm, the estimate $T_\star > 1.6 \times 10^5$ K of Bath et al. (1980) would lead (with $T_{\text{out}} < 2170$ K) to a disc size definitely larger than the orbital separation. As mentioned above, we expect instead the disc to be tidally truncated near the Roche lobe, with some kind of gap between it and material orbiting outside the lobe.

Conclusions

The infrared photometry of EX Hya and VW Hyi reported here clearly shows the $\nu^{1/3}$ continuum expected from an optically thick steady-state accretion disc. When taken in conjunction with Bath et al. (1980) spectrophotometry from 1250 to 7500 Å the data show that the discs are likely to fill the primary's Roche lobe. Further observations, especially an L point for EX Hya and infrared colours of VW Hyi at or near outburst, may well constrain the disc radii to be quite close to the orbital separation, implying very low mass (non-main sequence) secondaries. In this case a natural interpretation of the 67 min periodic modulation of EX Hya's optical light curve is available in terms of tidal resonances in a large accretion disc.
As we have seen, it is only possible to fit the disc into the primary's Roche lobe when its inner radius corresponds to that of a high-mass white dwarf. This makes it rather unlikely that the white dwarf in EX Hya can possess a significant magnetosphere, as this would probably increase the size of the disc too much. Hence models of X-ray production involving accretion on to the poles of a magnetized white dwarf seem to be excluded for EX Hya; this is indirect evidence in favour of hard X-rays being emitted from the boundary layer where the disc meets the white dwarf surface, as proposed by Pringle & Savonije (1979).

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References

The Infrared Spectrum of the Dwarf Nova EX Hydrae.


Sept 1980

Summary

Infrared photometry and spectrophotometry of the dwarf nova EX Hydrae shows that its flux increases for wavelengths $> 2\mu m$. This is interpreted in terms of a circumstellar dust cloud resulting from mass loss during the accretion process. We comment on the variability of the near-infrared spectrum, and report the detection of the $B\gamma$ line of hydrogen.
Introduction

Previous work on the dwarf nova EX Hyrae (Bath et al., 1980) has demonstrated the presence of a UV/optical continuum of the form \( F_\nu \propto \nu^{1/2} \) expected for a steady-state, optically thick accretion disc (Lynden-Bell, 1969). Sherrington et al. (1980) found that the \( \nu^{1/2} \) law appeared to extend out at least to about 2.2\( \mu \)m, tightening Bath et al.'s limit of \( T_{out} \leq 3700 \) K on the temperature of the outer edge of the optically thick region of the disc to \( T_{out} < 3000 \) K. Both estimates are considerably lower than the theoretical limit \( T_{out} \geq 6000 \) K obtained by Williams (1980) from LTE calculations of the opacity in the outer regions of a model accretion disc, although this result is somewhat dependent on binary geometry and accretion rate. An attempt to measure the infrared spectrum in more detail and, if possible, also at longer wavelengths, was felt to be worthwhile in order to learn more about the outer parts of the accretion disc. (As explained by Bath et al., 1980, and Sherrington et al., 1980, the contribution of the secondary star may be safely neglected at all wavelengths.)

Since the continuum spectrum of an optically thick accretion disc must show a Rayleigh-Jeans turnover at frequencies \( \nu \ll kT_{out}/h \), one would expect the flux at wavelengths greater than \( \sim 2.2\mu \)m to decline. However HKL photometry obtained at UKIRT on 1980 April 21/22 showed an L (3.6\( \mu \)m) flux well above the expected level. This trend was confirmed by higher resolution continuously variable filter (CVF) spectrophotometry obtained at the AAT three nights later. We suggest that these results indicate the presence of dust grains at a temperature in the range 500 - 900 K around the system, contributing up to 30% of the observed K(2.2\( \mu \)m) flux. Because the K flux measured during the previous observations (Sherrington et al., 1980) was rather higher than that reported here the assumption of a similar amount of dust emission does not affect the conclusions of that paper. We comment on the night-to-night variability...
of the JHK photometry, and report the detection of the hydrogen Brackett \( \gamma \) line.

2. Observations

Infrared photometry of EX Hydrae was performed with the common user InSb photometers at the U.K. Infrared Telescope, Mauna Kea, Hawaii, and the Anglo - Australian Telescope. Details of these measurements are given in Table 1. For reference the 1978 and 1979 observations of Sherrington et al. (1980) have been added to this table. Additionally, 2\( \mu \)m CVF spectrophotometry was performed at the AAT on 1980 April 21/25. The standard star BS 5163 was measured immediately after EX Hydrae to calibrate the CVF data. All these data are shown in Fig. 1.

3. Results

(a) An obvious feature of the CVF spectrophotometry shown in Fig. 1 is the presence of B\( \gamma \) \( \lambda 2.17\mu m \) in emission, at a level better than 3\( \sigma \). Graphical estimates of the flux in this line and in H\( \beta \) from the observations of Bath et al. (1980) yield an approximate B\( \gamma \)/H\( \beta \) line ratio of 0.03. The two observations were of course non - simultaneous, but it is interesting to note that Case B recombination theory (Osterbrock, 1974) predicts values for this ratio in the range 0.033 to 0.028 for electron temperatures in the range 5000 - 10000 K. The LTE line ratio is 0.012 to 0.023 for temperatures in the range 5000 - 5\times10^4 K.

(b) As is clear from the photometry of Sherrington et al. (1980), EX Hya is variable by up to a few tenths of a magnitude at infrared wavelengths on timescales of minutes. Since the JHK photometry reported in the first three lines of Table 1 represents isolated measurements (\~\~2 mins integration) it is not surprising that there is some small variation from one night to the next, or between the K flux measured on 1980 April 21/25 and the 2.2\( \mu \)m CVF flux measured the same night. The latter observation essentially gives mean fluxes over \~3 hr, and implies a mean K\~12.1 for this epoch. This is clearly lower than the mean K\~11.8 measured by
Sherrington et al. (1980) in 1978 and 1979 April. Similarly all the 'spot' J and K fluxes from 1980 April are less than or equal to those measured in 1978 and 1979. EX Hya was at quiescence (V ≈ 13.2) for all of these epochs (Bateson, 1979 and 1980), so we conclude that the infrared fluxes of the system can drop below the values measured by Sherrington et al. (1980) with little or no change in the optical fluxes. Such changes are entirely compatible with the idea that the optical thickness of the outer parts of the accretion disc can vary erratically, perhaps in response to small changes in the accretion rate. In terms of the parameters of a standard accretion disc, this would mean that \( T_{\text{out}} \) can increase above previously inferred limits \( (T_{\text{out}} \leq 3700 \text{ K}, T_{\text{out}} < 3000 \text{ K}) \) by factors of two or so, with similar changes in the radius \( R_{\text{out}} \) of the optically thick disc region. Some caution is however in order here, as it is not clear whether the quasi steady-state assumptions involved in a standard disc model are valid for the description of such changes.

(c) Perhaps the most interesting of the results reported here is the shape of the infrared continuum spectrum implied by Fig. 1. While the JHK fluxes show a decrease with wavelength as would be expected for a disc, the CVF points reverse this trend, and lead back to the L point at 3.6\( \mu \text{m} \). In the absence of nonthermal emission, which has not so far been suspected in cataclysmic variables, this rise in flux towards longer wavelengths must indicate the presence of material at a temperature \( \leq 1000 \text{ K} \). This is far too low to be the secondary star, which is thus presumably undetectable at all wavelengths, being swamped by the disc (+ bright spot) at short (UV, optical, near IR) wavelengths, and by this low temperature component at wavelengths \( \geq 2\mu \text{m} \). A circumbinary disc could conceivably supply the low-temperature component, but a more plausible candidate is circumstellar dust, presumably originating in mass-loss accompanying the accretion process.

To gain some idea of the nature of the low-temperature material,
we have tried to fit its spectrum to a black-body distribution. The fit is of course affected by 'contamination' at shorter wavelengths from the disc spectrum, about which we have rather little information (mainly in J, H). Accordingly we used a trial function of the form

\[ F_\nu = \alpha B_\nu (T_b) + \beta B_\nu (T_d) \]  

(1)

where \( B_\nu \) is the Planck function, \( T_b \) represents the low-temperature component and \( \alpha \) and \( \beta \) are constants. \( T_d \) is thus some temperature roughly characterizing the disc; the main importance of the second term in (1) is to allow a reasonable fit of the low-temperature component \( (T_b) \).

Since Fig. 1 scarcely constrains the short wavelength spectrum of EX Hya the use of a full disc spectrum (involving more free parameters) in (1) would not be justified.

We have performed various error-weighted least-squares fits to the data of Fig. 1, excluding the three points belonging to B\( \nu \), using trial functions of the form (1). If only the CVF points are included the best fit is \( T_b = 870 \, K \), \( T_d = 6600 \, K \), \( \alpha = 1.6 \times 10^{-18} \) sterad, with the low-temperature component contributing about 40\% of the K flux. If the J and H points measured the same night as the CVF observations, in addition to the L point, are included as well, the best fit is \( T_b = 560 \, K \), \( T_d = 6600 \, K \), \( \alpha = 3.6 \times 10^{-17} \) sterad, with the low-temperature component contributing 12\% of the K flux. This fit, represented by the curve labelled 'a' in Fig. 1, has the following 90\% confidence limits based on the standard \( \chi^2 \) test:

\( 430 \leq T_b \leq 1200 \, K \) and \( 5700 \leq T_d \leq 8000 \, K \). Finally to take account of the likely variation of the J and H fluxes discussed in (b) above, we artificially increased the errors on these points by a factor of ten. The resulting best fit, giving curve 'b' in Fig. 1, has \( T_b = 730 \, K \), \( T_d = 13000 \, K \), \( \alpha = 5.4 \times 10^{-18} \) sterad, with the low-temperature component contributing 30\% of the K flux. The 90\% confidence limits for this fit are as follows:

\( 540 \leq T_b \leq 1750 \, K \), \( T_d \geq 4350 \, K \).
L. Discussion

Adopting the view suggested above, that the low-temperature component in the continuum spectrum of EX Hya results from blackbody emission by circumstellar dust, the typical size $R$ of the dust cloud is given by

$$\frac{R}{1 \text{AU}} \sim \left( \frac{L_{\text{bol}}}{L_\odot} \right)^{\frac{1}{2}} \left( \frac{T_{\text{rad}}}{390 \text{ K}} \right)^{-2}$$

where $L_{\text{bol}}$ = bolometric luminosity $\approx L_\odot$ for EX Hya (Bath et al., 1980), and $T_{\text{rad}}$ is the radiation temperature. For equilibrium we require

$T_b \sim T_{\text{rad}}$. Thus curves 'a' and 'b' of Fig 1 imply typical sizes

$$R \simeq 7 \times 10^{12} \text{ cm} \quad \text{(a)}$$

$$R \simeq 4 \times 10^{12} \text{ cm} \quad \text{(b)}$$

much larger than the binary separation $a \approx 5 \times 10^{10} \text{ cm}$.

We may check the circumstellar extinction resulting from these distributions. If the cloud consists of $N_g$ dust grains, each of surface area $\sigma_g$ and all radiating at the temperature $T_b$, equating fluxes at each wavelength implies

$$N_g \sigma_g \pi B_\nu(T) \simeq \propto B_\nu(T) \pi D^2$$

where $D$ is the distance to the system. If the cloud has effective thickness $l$ along the line of sight and effective radius $R_\perp$ orthogonal to it the extinction $A_v$ due to these grains alone is (Spitzer, 1978, eq 7.1)

$$A_v \simeq n_g \sigma_g \pi \frac{l \propto D^2}{\pi R_\perp^2} \quad \text{(mag)}$$

where $n_g$ is the number density of grains. From the measurements of Bath et al. (1980), $A_v \leq 0.12$ so $R_\perp \geq 1.0 \times 10^{21} D_{100}^{\frac{1}{2}} \text{ cm}$, where $D_{100} = D/100 \text{ pc}$. For cases 'a' and 'b' above we find

$$R_\perp \geq 6 \times 10^{12} D_{100} \text{ cm} \quad \text{(a)}$$

$$R_\perp \geq 2 \times 10^{12} D_{100} \text{ cm} \quad \text{(b)}$$

Thus for $D_{100} \sim 1$ (as expected), $R_\perp \sim R$ in both cases. Hence a spherical dust cloud of typical size $\sim 1 \text{AU}$ and a temperature in the range
550 -750 K is consistent with all observations. We conclude that this is the most likely explanation for the infrared excess at wavelengths $\geq 2\mu m$. The dust presumably originates via mass loss from the binary during the accretion process; simple assumptions about the grains lead to masses $\lesssim 10^{21} \text{ g}$ for the dust cloud, which could easily be supplied in plausible timescales by mass - loss rates very small compared to the accretion rate $\sim 10^{16} \text{ g s}^{-1}$.

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Notes:

(*) Light curves.

(1) Same right as CVP.
References


Figure Caption

**Fig. 1**  The infrared observations of EX Hya, with fluxes in units of $10^{-26}$ erg/s/Hz/cm$^2$. Curves 'a' and 'b' represent error-weighted least-square fits to the data by the superposition of two blackbody distributions (see eq. (1) of text). Curve 'a' is a fit to all the points with errors as marked; for curve 'b' the errors on the J and H measurements were formally increased by factors of ten to take account of the variability at these wavelengths. For fit 'a' the blackbody temperatures are $T_b = 560$ K, $T_d = 6600$ K; for fit 'b' $T_b = 730$ K, $T_d = 13000$ K.
Summary

We present infrared and optical light curves of the cataclysmic variables UX UMa and U Gem. The curves for UX UMa can be well fitted by the eclipse of an optically thick steady-state accretion disc. In U Gem the infrared curves are dominated by ellipsoidal variations of the secondary star.
Introduction

This paper presents J and K light curves with simultaneous V curves of the cataclysmic variables UX UMa and U Gem. We have made numerous observations of cataclysmic variables but we present these two systems together, since although they have similar period (≈ 4 hr) their properties are in sharp contrast. We show that the light curves of UX UMa provide strong evidence for the presence of an accretion disc of standard type, while the infrared light curves of U Gem are dominated by the ellipsoidal variations of the secondary star.

1. The Observations

These were made with the 1.5 m infrared telescope at the Cabezon observatory, Tenerife. A standard IR photometer with an InSb detector operating at 63°K was used. This photometer incorporates an offset guider and a UBV photometer operating behind a dichroic mirror which reflects the IR but transmits visible radiation.

The light curves could not be completed in one night and were made at the following times in 1979:— U Gem at 2.2 μm on the 25/26th and 29/30th April and at 1.2 μm on the 26/27th and 30/1st April/May; UX UMa at 2.2 μm on the 28/29th April and 2/3rd May and at 1.2 μm on the 1/2nd and 3/4th May. The breaks where a change of night occurred in the observations can be seen clearly by gaps in the light curves shown in Figures 1 and 4. In each case the eclipses were completed on one night and the magnitudes of the systems at all wavelengths were consistent from night to night. The standard stars used were BS 3249 (J = 1.09, K = 0.16) for U Gem and BS 4983 (J = 3.24, K = 2.90) for UX UMa (Johnson et al., 1966). Each observation is the difference between a 20 sec. integration performed in each channel. The errors are estimated from similar observations of a non-varying star of similar magnitude and are shown in Figures 1 and 4. Heliocentric and atmospheric extinction corrections have been applied. Because the standard was measured only at the
beginning and end of each run, drifts of up to ± 0".1 in the absolute photometry are not ruled out.

The data are plotted by phase using the following ephemerides:

U Gem:  J.D.2437638.82645 + 0.176906N (Arnold et al., 1976)
UX UMa: J.D.2420238.24245 + 0.1966713N (Kukarkin, 1977)

The light curves are shown in Figures 1a, 1b, 5a and 5b for UX UMa and U Gem respectively.

2. Discussion of UX UMa

UX UMa has been extensively studied at optical wavelengths (Warner and Nather, 1972 and references therein), and at 8000 Å (Krzeminski and Walker, 1963). The white light curves of Nather and Robinson (1974) show the characteristic deep and slightly asymmetrical eclipse also seen in our V curves. Nather and Robinson (1974) attributed the asymmetry, and the small hump preceding ingress, to the presence of a 'bright spot', possibly where the gas stream from the secondary star strikes the accretion disc surrounding the white dwarf. Following Nather and Robinson's (1974) qualitative model, we see that the contribution of the 'bright spot' may be split into two components; an isotropic component, responsible for about 10% of the primary's optical flux outside eclipse (excluding the hump before ingress), and an anisotropic component, responsible for the pre-eclipse hump, and contributing a flux of about 13% of the steady primary flux in the optical at the hump maximum. The remaining optical flux (i.e. about 90% of the light outside eclipse and hump) must presumably be supplied by the accretion disc, and it is the nature of this disc which we shall try to investigate using our light curves.

Earlier papers (Bath et al., 1980; Sherrington et al., 1980) have shown that the continuum spectrum of a 'standard' optically thick steady-state accretion disc (Shakura and Sunyaev, 1973) provides a good fit to observations of the ultraviolet/optical and probably infrared (out to 2.2 μm) continuum of
3. cataclysmic variables, particularly the dwarf nova EX Hya. The deep, well-defined optical eclipses of UX UMa, together with the simultaneous rather shallow infrared eclipses, offer the possibility of trying to fit the VJK light curves by considering the eclipse of a standard disc by a secondary star. This will then provide a test of whether the surface brightness distribution as well as the continuum spectrum of such a disc is a reasonable approximation to reality. A similar analysis has been carried out for RW Tri (Frank and King, 1980). The wide spread of wavelengths offered by simultaneous V, J and V, K photometry is very useful for this programme; firstly, the VJK colours of cataclysmic variables can be fitted using a combination of disc and secondary spectrum, while more importantly, the predicted surface brightness distributions at these wavelengths differ markedly. By contrast it is well known that model disc atmospheres (see e.g. Mayo et al., 1979, and Herter et al., 1979) do not yet produce good fits to the observed UBV colours of cataclysmic variables, while the closeness of the effective wavelengths in these bands means that the predicted UBV surface brightness distributions are rather similar to each other.

There are two main difficulties in trying to carry out this programme. First, the contribution of the late-type secondary star becomes more important at longer wavelengths (as we shall see for U Gem) and so it must be taken full account of in trying to reproduce simultaneously the VJK colours and light curves. Second, the 'bright spot', to which we have referred above, introduces a certain degree of freedom because its physics is so ill-understood. The eclipse curves and colours provide enough information to separate out the contributions of secondary and primary (given our assumptions, see below), but the bright spot has to be dealt with phenomenologically.

Our VJK light curves on their own do not contain enough detail to pin down all the parameters of the system including the bright spot. In fact
they can roughly be fitted with a disc eclipse plus secondary contributions. This is so because the bright spot is relatively weak. At the top of Fig. 2 the dotted line indicates the best symmetrical fit in the V band obtained without bright spot (see Section 3).

But the bright spot is known to be present, as Nather and Robinson (1974) show very convincingly. Also the nature of the deviations of the observed V light curve from our simple symmetrical model is suggestive. Thus we take bright spot parameters from the semi-quantitative discussion in Section VII of Nather and Robinson (1974) and construct composite eclipse curves by adding a simulated bright spot light curve to our disc eclipses. We assume (arbitrarily) the bright spot contributions to have the same VJIK colours as the uneclipsed accretion disc. Within reasonable limits the predicted infrared light curves are not greatly affected by this assumption and our data cannot rule out moderate variations in shape.

We then compare the composite light curves with our own observations at VJIK (as in Fig. 2), and to check that our simulation of the bright spot is approximately correct we compare our V curve with one of Nather and Robinson's eclipses (as in Fig. 3). Subsequently we adjust the disc and system parameters, generate new disc eclipses, add the bright spot variations as before and compare with the observed VJIK and white light curves. The process is iterated until satisfactory agreement is achieved. In practice a readjustment of disc and system parameters was necessary only once and Figs. 2 and 3 show our adopted fit. If the bright spot contributed a larger fraction of the disc light at all wavelengths the process of convergence to an acceptable fit could presumably involve more iterations.

When comparing our model with the white light curve in Fig. 3 one has to remember that the detailed shape and depth of the observed curve could only be reproduced with an adequate knowledge of the spectral and photometric characteristics of the bright spot and the response function of the detector. Considering the crudeness of our model the agreement in Fig. 3 is excellent.
A number of geometrical and physical parameters had to be fixed to produce the fit shown in Fig. 2, and we check that these and other parameter values deducible from them (using the relations appropriate to a standard disc) are physically reasonable. This should not be regarded as a determination of these parameters, nor in particular should the "error estimates" we give be regarded as fixing these quantities. We merely assert that given our assumptions (see below), parameters in the quoted ranges will reproduce the observations within limits defined in the next section. Happily, it appears that changing the bright-spot variations subject to the constraints imposed by Nather and Robinson's (1974) observations does not have a large effect on our best-fitting parameters.

3. Fitting Procedure for UX UMa

To attempt to synthesise the VJK light curves of UX UMa we now add to the bright spot light variations (see above) model curves produced by occulting a steady-state, optically thick disc. This has a surface temperature distribution (Bath et al., 1980)

\[ T(R) = T_\star \left( \frac{R_{\text{in}}}{R} \right)^{\frac{3}{2}} \left[ 1 - \left( \frac{R_{\text{in}}}{R} \right)^{\frac{3}{2}} \right] \frac{1}{2} K \]  

(1)

at radius \( R \), where \( R_{\text{in}} \) is the inner disc radius and

\[ T_\star = 4.1 \times 10^4 \dot{M}_{16}^{\frac{1}{3}} M_1^{\frac{1}{3}} (R_{\text{in}}/10^9 \text{ cm})^{-\frac{3}{4}} \]  

(2)

Here \( \dot{M}_{16} \) is the accretion rate in units of \( 10^{16} \) g/sec and \( M_1 \) the white dwarf mass in units of \( M_\odot \). The disc spectrum is

\[ f_\nu = \int_{R_{\text{in}}}^{R_{\text{out}}} B_\nu[T(R)] 2\pi R dR \]

with \( B_\nu(T) \) the Planck function and \( R_{\text{out}} \) the outer disc radius. Thus one finds

\[ f_\nu \propto \nu^{1/3} \]
for frequencies \( \nu \) such that \( kT_{\text{out}} < \hbar \nu < kT_{\text{max}} \) (where \( T_{\text{max}} = 0.488 T_\star \) is the maximum value of \( T(R) \)) (Lynden-Bell, 1969). For \( \hbar \nu \gg kT_{\text{max}} \) the spectrum has the Wien form, and for \( \hbar \nu < kT_{\text{out}} \) a Rayleigh-Jeans form. In EX Hya the \( \nu^{1/3} \) law extends all the way from the near UV (Bath et al., 198) out to \( \approx 2.2 \mu\text{m} \) (Sherrington et al., 1980); this enables one to estimate \( T_\star \) and put an upper limit on \( T_{\text{out}} \).

In the case of UX UMa it is clear from the infrared colours outside eclipse that the \( \nu^{1/3} \) law does not extend into the near infrared: we observe V-J = 0.5 and V-K = 0.8, whereas a \( \nu^{1/3} \) disc has V-J = 0.55, V-K = 1.45. The observed colours might suggest a \( \nu^{1/3} \) spectrum extending out to a Rayleigh-Jeans turnover at about J; indeed the colours outside eclipse can be so fitted. However, this cannot be a correct fit, as will emerge later; it is caused by the fact that for binary periods near 4.5 hours, the secondary star has (as in U Gem) a J-K colour rather similar to a \( \nu^{1/3} \) disc, so that a substantial contribution from this star does not spoil the disc-like appearance of the continuum.

For the purpose of generating the light curves, the secondary is taken to be spherical of radius \( R_2 \), moving in a circular orbit of separation (using Kepler's law)

\[
a = 9.9 \times 10^{10} M_1^{1/3} (1+q)^{1/3} \text{ cm},
\]

where \( q = M_2/M_1 \) is the mass ratio (\( M_2 = \) secondary mass in \( M_\odot \)). A spherical secondary has the advantage that one can find its projection on the disc plane (and hence the occulted area) analytically, with a consequent saving in computing time. A full Roche model would have the advantage of automatically enforcing the constraints of Roche geometry, but would be much more expensive to compute. We take \( R_2/a \) to determine \( q \) by assuming \( R_2 \) equal to the average Roche lobe radius (e.g. Warner 1976). We neglect all limb darkening effects for both the disc and secondary star.

To start the fitting procedure we assume a spectral type for the
secondary (but not its absolute magnitude) and fit the colours of the system outside eclipse by adding the disc; the choice of secondary spectrum will be justified later, but it is obviously sensible to begin with a spectral type close to what would be expected from the period-secondary relations (Warner, 1976). This preliminary fit provides estimates of the temperature of the disc edge, $T_{\text{out}}$, and the relative contribution of disc and secondary at all wavelengths. $R_{\text{in}}$, which can be taken as the radius of a white dwarf of mass $M_1 M_0$, is poorly determined by this fit, as it only strongly affects the short-wavelength spectrum of the disc. In the next step of the fitting procedure we compute model light curves simultaneously in V, J and K by evaluating numerically the fluxes lost from the occulted area of the disc as the secondary moves around a circular orbit of radius $a$, varying parameters to optimise the fit to the data. The result of this initial fit in the V band is shown as a dotted line in the top third of Fig. 2. Next we add the bright spot variations and iterate as described in Section 2. The effect of this is to change the inclination $i$ by $0.5^\circ$; all the other geometrical parameters remain unchanged. The best simultaneous fit to all the light curves (Figs. 2 and 3) yields estimates $i = 65^\circ$, $R_2/a = 0.43$, $R_{\text{out}}/a = 0.33$, $T_{\text{out}} = 6500$ K, with best-fit secondary colours being those of a M2V star (Johnson, 1966): $V-J = 3.37$, $V-K = 4.27$ (we restricted ourselves to lower-main-sequence colours for the secondary, implying a relation between $V-J$ and $V-K$; the fit would have been improved by allowing them to vary independently (see below). We also obtain the estimate that the system in the K waveband is $0^m.7$ brighter outside eclipse and hump than the secondary star alone, which enables us to compare the fluxes of the disc and secondary at any wavelength. From the estimate of $i$, $R_2/R_{\text{out}}$, we find a ratio of average surface brightnesses of secondary to disc of 0.26 at K, and much less at J, V. Hence there should be no detectable secondary eclipses, as observed.

To evaluate formal errors for the fit obtained would involve a full multi-parameter fit, and disproportionate amounts of computer time. It is
possible however to gain some idea of the likely errors by considering the results of "unsuccessful" fits. In particular, varying $R_2/a$ or $R_{\text{out}}/a$ by amounts between 5 and 10 percent and adjusting the other parameters accordingly results in clear corruption of the fit, manifest either in departures of more than 0.1 from observed eclipse depths, or in a systematically incorrect eclipse shape. Because $T_{\text{out}}$ affects both the overall colour fit and the eclipse shapes we assert that it cannot be outside the range 5900 - 8200, the fit at 6500 K being clearly better than at these extremes. Finally the acceptable colours of the secondary are such as to confine the spectral type to the range K8V - M6V. Because we have only used the eclipse shapes and average colours, these conclusions are not affected by drifts ($< 0^m.1$) in the absolute (as opposed to relative) photometry.

Fig. 4 shows the relative contributions of secondary star and disc to the overall spectrum for our best fit. It will be noticed that the secondary does contribute significantly to the spectrum at K, although a disc alone could be fitted to the curves outside eclipse as remarked above. However, such a disc would need $T_{\text{out}}$ of order 2700 K, which from (1) implies a large value for $R_{\text{out}}/R_{\text{in}}$, since $T_{\text{out}} = T_* (R_{\text{out}}/R_{\text{in}})^{3/2}$. (A small $T_*$ causes the disc spectrum to begin its Wien turn-down at unacceptably long wavelengths.) As $R_{\text{out}}$ is essentially fixed by the light curves ($R_{\text{out}} = 0.33a$, $a = 9.9 \times 10^{10} (M_1 + M_2)^{1/3}$ cm) this means a very small value for $R_{\text{in}}$. This implies that the dominant optical radiation of the disc comes from a region very small compared to the orbital dimensions (the size of this region scales as $R_{\text{in}}$). The resulting eclipse in V is then systematically much too narrow as compared to observation, even with very large radii assumed for the secondary.

We must now check that the estimates given above are reasonable in the sense that they imply realistic parameters for the system. We emphasize again (see Section 2) that this should not be regarded as a determination of these derived parameters, but rather as a check on the disc model. To proceed we need to introduce the absolute dimensions of the system via (3) which we
\[
\alpha = 9.9 \times 10^{10} M_2^{1/3} (1+q^{-1})^{1/3} \text{ cm}.
\]

Allowing 10\% errors on \(R_2/\alpha\), the condition that the secondary fill its Roche lobe implies

\[0.9 > q^{-1} > 0.4, \text{ or } 1.2 > (1+q^{-1})^{1/3} > 1.1.\]

The value \(R_{\text{out}}/\alpha = 0.33\) means that the disc almost fills the white dwarf's Roche lobe. If the secondary has masses consistent with our estimates of its lower-main-sequence spectral type then \(0.2 < M_2 < 0.5\), implying \(1.0 \times 10^{11} \text{ cm} > a > 0.9 \times 10^{11} \text{ cm}\). (If this restriction on the secondary's mass is dropped and we merely ask that the secondary should be capable of burning hydrogen while the white dwarf does not exceed the Chandrasekhar limit we get \(1.4 \times 10^{11} \text{ cm} > a > 0.5 \times 10^{11} \text{ cm}\).) This estimate, i.e. \(a = 0.95 \times 10^{11} \text{ cm}\), gives \(R_2 = 0.6 R_\odot\), in good agreement with a lower-main-sequence (M2V) assignment. With a value of \(a\) assumed, our estimates of \(i, R_{\text{out}}/\alpha\), and \(T_{\text{out}}\) give the absolute magnitude of the disc at say \(K\) (where \(R_{\text{in}}\) has no effect). The estimate of the flux ratio of disc and secondary then gives the absolute magnitudes \(M_K, M_{K}(2)\) of the system and secondary. With \(a = 0.95 \times 10^{11} \text{ cm}\) we get \(M_K = 4.3, M_{K}(2) = 5.0\), this latter value being also in reasonable agreement with the spectral assignment M2V for this star. The value \(M_K = 4.3\) together with the apparent \(K = 12.0\) would give a distance 340 pc as interstellar reddening is certainly negligible at \(K\). Using (1) (which gives \(T_{\text{out}} = T_\star (R_{\text{out}}/R_{\text{in}})^{-2}\)) and (2) we have

\[
\dot{M}_16 = 48 \left[\frac{T_{\text{out}}}{6500}\right]^4 \left[\frac{1+q}{2}\right] \left[\frac{R_{\text{out}}}{0.33a}\right]^{-3} \tag{4}
\]

With our estimates of \(q\), and allowing 10\% error on the estimates of \(T_{\text{out}}\) and \(R_{\text{out}}/\alpha\) we get

\[180 > \dot{M}_16 > 24,\]

independently of any assumption about \(a\) and hence about absolute masses. Taking
as before $0.2 < M_2 < 0.5$ and $0.4 < q^{-1} < 0.9$ we find $0.1 < M_1 < 0.5$. This would imply a low mass white dwarf with $R_{in} = 10^9$ cm and hence a limit on the interstellar reddening (from the VJK colour fit) $A_V < 0.1$, which is consistent with the distance estimate 340 pc.

For reference the adopted best fit parameters are collected in Table 1. From (4) the total accretion luminosity

$$L_{acc} = 6.5 \times 10^{32} \frac{M_1}{10^9} \left(\frac{R_{in}}{10^9}\right) \text{M}_1 \text{ erg/sec}$$

becomes

$$L_{acc} = 1.3 \times 10^{34} \left(\frac{T_{out}}{6500}\right)^4 \left(\frac{R_{out}}{0.33}\right)^3 \left(\frac{M_1 + M_2}{0.8}\right) \left(\frac{R_{in}}{10^9}\right) \text{ erg/sec}, \quad (5)$$

where the bracketed factors should be of order one for UX UMa. Putting in the errors we get

$$3.0 \times 10^{34} \text{ erg/sec} > L_{acc} > 2.3 \times 10^{33} \text{ erg/sec.}$$

From (5) the total flux at Earth is

$$F_{tot} = \frac{L_{acc} \cos i}{2\pi D^2} = 1.7 \times 10^{-9} \text{ erg cm}^{-2} \text{ s}^{-1}$$

(with the brackets in (5) put equal to one), whereas the total V-band flux observed at Earth is $2.5 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$. Hence only $\sim 1\%$ of the accretion luminosity is radiated in the V-band. The total flux in the region 0.55 $\mu$m - 2.2 $\mu$m is less than 10% of the accretion luminosity. Thus it is impossible to use the observed flux levels to estimate parameters of the system with any degree of accuracy. If it were possible it would lead to an independent estimate of the white dwarf mass; the errors are however such that any reasonable white dwarf mass ($< 1.4 M_\odot$) lies comfortably within them.

4. Discussion of U Gem

U Gem has been extensively studied at optical wavelengths, and its optical light curve in quiescence is known to be dominated by a bright spot, (e.g. Warner and Nather, 1971) presumably where the gas stream from the
secondary strikes the accretion disc. The $V$ curves shown in Fig. 4 agree with previous observations, the system being quiescent at the time of observation with a maximum brightness $V \approx 14.0$ and minimum $V \approx 15.0$. In contrast the infrared curves are roughly sinusoidal with total amplitudes $\Delta J = 0.33, \Delta K = 0.30$. The system showed a large infrared excess with maximum brightnesses $J = 11.8, K = 10.7$. This is readily explicable using the spectrophotometric observations of Wade (1979), who found that the secondary is near the main sequence and of spectral type M4.5; as it is already prominent in the system's spectrum at 0.9 $\mu$m and would have $V-J = 4.0, V-K = 5.0$, we would expect it to dominate at $J$ and $K$ and provide the infrared excess of the system. This conclusion is supported by simple estimates of the possible contribution of the accretion disc and bright spot in the infrared. In the optical, the disc probably cannot be brighter than the residual flux at primary minimum; thus taking $V(\text{disc}) \gtrsim 15.0$ and assuming a $\nu^{1/3}$ disc spectrum between $V$ and $K$ (the best case) we find $J(\text{disc}) \gtrsim 14.1, K(\text{disc}) \gtrsim 13.55$. Similarly, as the bright spot is expected to be optically thick and have roughly Rayleigh-Jeans colours between $V$ and $K$, one finds $J(\text{spot}) \gtrsim 14.0, K(\text{spot}) \gtrsim 14.0$.

Since all other radiation sources than the secondary contribute at most a few percent of the $J$ and $K$ light, eclipses of the bright spot or disc or the spot's anisotropic radiation pattern cannot provide the $0^m.33$ and $0^m.30$ amplitudes in the $J$ and $K$ curves. Indeed, the sinusoidal shapes of these curves, with equal depths at phases 0.0 and 0.5, together with the rough constancy of the $J-K$ colour around the binary cycle, strongly suggest that the curves are due to ellipsoidal variations of the secondary, together with the effects of gravity and limb darkening. Given an accurate orbital solution one might therefore hope to extract considerable information about these effects for late type stars at infrared wavelengths using a Roche model for the secondary. However to carry out this programme requires more accurate
observations using a larger telescope and following several binary periods to smooth out variations from cycle to cycle.

If we assume the secondary is an M4.5V star then its absolute magnitude $M_V$ is given by Allen (1973) as 11.52. Using Johnson's (1966) colours we find $M_K = 6.50$ and hence using the mean value at $K = 10.85$, a distance of 74 pc. Wade (1979) finds that the secondary is not main sequence and indeed our J-K colour is more appropriate to a red giant than a main sequence star. Inevitably, there will be problems comparing a component of a close binary system with individual stars which will introduce uncertain errors into the distance estimate. Despite this, 74 pc agrees very well with Wade's value of 76$^{+36}_{-24}$ pc.

5. Conclusions

The infrared and optical observations of UX UMa and U Gem show that despite the near-identity of their binary periods and their very similar secondaries the two systems exhibit markedly different behaviours. This is almost certainly due to a sharp difference in accretion rates: for UX UMa we have found $\dot{M} > 2.4 \times 10^{17}$ g s$^{-1}$, while in U Gem this rate is probably at least an order of magnitude lower. Thus in U Gem the relative weakness of the accretion disc in the optical means that the bright spot shows up strongly in the light curves, while the secondary dominates the infrared light of the system. UX UMa's high accretion rate causes its accretion disc to be the major contributor to its radiation at all these wavelengths, despite the high orbital inclination. It is interesting to note that our best fit involves a secondary having M2V colours, and that this fit itself implies an absolute magnitude and radius for the secondary in good agreement with this spectral assignment. This supports the view that in UX UMa the secondary lies close to the main sequence. However our best fit is too faint by $0^m.3$ at J (see Fig. 2) and cannot be improved without spoiling the good agreement at V and K,
because J-K is virtually constant throughout main sequence types later than K5V. Earlier spectral types for the secondary are ruled out by both the colour and eclipse fits. Also our fit produces a secondary brighter by 0.7 than quoted values for its type (but well within the scatter on the HR diagram). This suggests that one should be cautious about concluding that the secondary is a main sequence star.

The main gap in our understanding of the light curves of these systems is the lack of any physical model of the 'bright spot'. The fact that its effect is comparatively minor in UX UMa allows us to conclude that a steady-state, optically thick accretion disc does represent fairly accurately the surface brightness distribution of the primary at widely spaced wavelengths. This system and RW Tri (Frank and King, 1980) are the first for which this comparison of theory and observation has been possible. Further observations (particularly in the ultraviolet) will be of great importance in gaining a more complete understanding of the accretion disc in these systems.

Acknowledgements

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### TABLE 1

Parameters for UX UMa from the best fit to the light curves

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inclination</td>
<td>$i$</td>
</tr>
<tr>
<td>Absolute magnitude of secondary</td>
<td>$M_K(2)$</td>
</tr>
<tr>
<td>Adopted colours (M2V; Johnson, 1966)</td>
<td>$V - J = 3.37$ $V - K = 4.27$</td>
</tr>
<tr>
<td>Secondary radius</td>
<td>$R_2/a$ $R_2$</td>
</tr>
<tr>
<td>Disc radius</td>
<td>$R_{out}/a$ $R_{out}$</td>
</tr>
<tr>
<td>Secondary Mass (assumed)</td>
<td>$M_2 M_\odot$</td>
</tr>
<tr>
<td>White Dwarf Mass</td>
<td>$M_1 M_\odot$</td>
</tr>
<tr>
<td>Binary Separation</td>
<td>$a$</td>
</tr>
<tr>
<td>Temperature of disc edge</td>
<td>$T_{out}$</td>
</tr>
<tr>
<td>Accretion Rate</td>
<td>$\dot{M}$</td>
</tr>
<tr>
<td>System's Distance</td>
<td></td>
</tr>
<tr>
<td>$i$</td>
<td>$65^0 \pm 1^0$</td>
</tr>
<tr>
<td>$M_K(2)$</td>
<td>$5^m 0 \pm 0^m 5$</td>
</tr>
<tr>
<td>$V - J = 3.37$ $V - K = 4.27$</td>
<td></td>
</tr>
<tr>
<td>$R_2/a$ $R_2$</td>
<td>$0.43 \pm 0.04$ $0.58 \pm 0.09 R_\odot$</td>
</tr>
<tr>
<td>$R_{out}/a$ $R_{out}$</td>
<td>$0.33 \pm 0.03$ $(3.1 \pm 0.5) \times 10^{10}$ cm</td>
</tr>
<tr>
<td>$M_2 M_\odot$</td>
<td>$0.2 &lt; M_2 &lt; 0.5$</td>
</tr>
<tr>
<td>$M_1 M_\odot$</td>
<td>$0.1 &lt; M_1 &lt; 0.5$</td>
</tr>
<tr>
<td>$a$</td>
<td>$9 \times 10^{10}$ cm $&lt; a &lt; 1 \times 10^{11}$ cm</td>
</tr>
<tr>
<td>$T_{out}$</td>
<td>$(6500 \pm 1700) K$</td>
</tr>
<tr>
<td>$\dot{M}$</td>
<td>$(48 \pm 132) \times 10^{16}$ g s$^{-1}$</td>
</tr>
<tr>
<td></td>
<td>$(340 \pm 110)$ pc</td>
</tr>
</tbody>
</table>
REFERENCES


FIGURE CAPTIONS

Fig. 1.a. Simultaneous J and V light curves of UX UMa. The data on each side of the break at phase \( \approx 1.1 \) were obtained on different nights.

Fig. 1b. Simultaneous K and V light curves of UX UMa. Data from phase \( \approx 0.15 \) to \( \approx 0.7 \) and from phase \( \approx 0.9 \) to \( \approx 1.02 \) were obtained on a single night; plotted on the same figures are continuous data from phase \( \approx 0.57 \) to \( \approx 1.15 \) obtained on another night.

Fig. 2. The model of composite primary eclipse (solid lines) compared with the VJK observations of Figs. 1a,b. The V and K data are binned over ten points, the sparser J data over six points. In the V plot the dotted line is the initial fit without bright spot. In the K and J plots the dashed curve corresponds to the absolute flux levels predicted by the fit, and the solid curves are the predicted curves shifted to show agreement in eclipse shape. At K the predicted level (K = 12.0) outside eclipse in fact agrees well with the observed mean K level outside eclipse: the shift of \( 0.1 \) between this curve and the solid curve probably reflects the effects of varying atmospheric extinction through the night. At J the discrepancy in levels is probably real and can only be eliminated by assuming a secondary star brighter at J by \( 0.3 \) than quoted mean main-sequence colours allow, or by changing the colours of the bright spot.

Fig. 3. The computed V light curve is shown here in comparison with a white light eclipse. Adapted from Fig. 5 of Nather and Robinson (1974).

Fig. 4. The spectrum of the components of UX UMa. The solid and the dotted lines indicate the contributions of the disc \( (R_{\text{in}}/R_{\text{out}} = 0.004) \) plus the isotropic part of the bright spot and the secondary (M2V) respectively. The total flux (dashed line) is shown together with the
observed KJV values with 10% error bars. Fluxes are in arbitrary units.

Fig. 5a. Simultaneous J and V light curves of U Gem. The data on each side of the break at phase $\sim 1.17$ were obtained on different nights.

Fig. 5b. Simultaneous K and V light curves of U Gem. The data on each side of the break at phase $\sim 0.45$ were obtained on different nights.
Infrared and Optical Light Curves of the Dwarf Nova EM Cygni

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Summary
We report simultaneous infrared and optical light curves of EM Cygni. The infrared curves are dominated by ellipsoidal variations of the late-type star in the system, which must have spectral type near K2V. The distance to the system is estimated as ~320 pc and the accretion disc shown to be close to the minimum size expected from angular-momentum considerations.
1. **Introduction**

The dwarf nova EM Cygni is unique amongst cataclysmic variable systems in being both an eclipsing binary (Mumford and Krzeminski, 1969) and a double-lined spectroscopic binary (Kraft 1964), having a period $P = 6.98\,\text{h}$. Robinson (1974) was able to use these observations to estimate the masses of the two components. Unusually for cataclysmic variables the late-type secondary star (observed to have spectral type G or K, Kraft, 1964) is more massive than the white dwarf which is accreting from it, the mass ratio being $q = M_2/M_1 = 1.3$. Depending on the precise value of the inclination $i$ estimated from the photometry of Mumford and Krzeminski (1969), Robinson (1974) obtained a mass $M_1 = (0.70 \pm 0.18)M_\odot$ for the white dwarf. He also showed that if the secondary fills its Roche lobe, its mass $M_2 = (0.90 \pm 0.17)M_\odot$ places it on the main sequence mass-radius relation.

We report here simultaneous observations of the optical and infrared binary light curve of EM Cyg. These show clear evidence for ellipsoidal variation of the late-type secondary. Our observations provide support for many of Robinson's (1974) conclusions, in particular his estimate of the inclination $i$ and the main-sequence nature of the secondary, which allows us to estimate a distance $D = 320\,\text{pc}$ to the system. The accretion disc surrounding the white dwarf however seems to have a radius $R_{\text{out}}$ considerably smaller than Robinson's estimate $R_{\text{out}} = 0.4a$, where $a$ is the binary separation, and appears to be close to the minimum value allowed by angular momentum considerations ($R_{\text{out}} = 0.1a$).
2. Observations

We observed EM Cygni on 1979 August 19/20 simultaneously at V and K (2.2 μm), on 1979 August 20/21 at V and J (1.25 μm), and on 1979 August 21/22 at V and K again. All observations were made at the 1.5m IR Flux Collector at the Cabezon Observatory, Tenerife, using the Leicester University optical/infrared photometer. All these data, with error bars derived from observations of non-variable stars of similar magnitude, are shown in Fig. 1. The binary phases are computed from the ephemeris of Mumford and Krzeminski (1969). The standard star (B.S. 7678) was observed before and after each light curve; heliocentric corrections have been applied at all phases and the magnitudes are corrected for atmospheric extinction. EM Cyg was close to quiescence with a mean V ~ 13.6 throughout most of the observations, although the run on 1979 August 19/20 (shown as phases 0.05 < φ < 0.75 on the V, K curves) had V somewhat brighter (V ~ 13.5). This is in keeping with the erratic low-amplitude variability noted by Wachmann (1961) and von Beyer (1967).

3. Interpretation

Our infrared light curves are shown in Fig. 2. Each point is the mean of fifteen 20 secs integrations, thus reducing the effects of instrumental noise and intrinsic flickering. They show, particularly clearly for the J curve, a sinusoidal shape with two nearly equal minima at φ = 0.0, 0.5. This contrasts with the V curve, whose two minima differ in depth by ~ 0.2. The deeper minimum, centred near φ = 0.97, is interpreted as an occultation of the primary (probably of part of its accretion disc (Robinson (1974)) and is preceded by a hump of height about 0.1 centred on φ = 0.85, presumably due to the presence of a 'bright spot' where the gas stream from the secondary strikes the accretion disc. This hump is also discernable in the J and
K curves, where the bright spot clearly makes a much smaller contribution to the total light.

The characteristic sinusoidal shapes of the infrared light curves suggest that at these wavelengths the system is dominated by the late-type secondary and its ellipsoidal variation. This is a familiar pattern for long-period (P > 4 hr) cataclysmic binaries with comparatively low accretion rates, another example being U Geminorum (Frank et al., 1980). This idea is strongly supported by the observed colour indices of the system: V-J is never less than 1.3 throughout the cycle, implying that the J flux is always more than 50% higher than the V flux. Similarly the K flux exceeds the V flux. Moreover, J-K = 0.6 throughout the cycle, very close to the value J-K = 0.58 for a K2V star (Johnson, 1966). The only plausible interpretation is therefore that a secondary of this type provides essentially all the J and K light of the system; a large contribution from the primary at J would force the secondary to be later than its observed G-K spectral type and cause either the V-J or J-K colour indices to disagree with observation for any reasonable primary continuum spectrum. It appears that the primary contributes comparatively little even at V, for a K2V star has V-J = 1.57, compared to EM Cygni's V-J > 1.3, with V-J = 1.5 at primary minimum (φ = 0.97). Thus the primary contributes of order 40% of the V light outside eclipse, a few percent at eclipse, and very little at J and K, presumably because it is hot and of small effective area. On the other hand, Mumford and Krzemiński's (1969) observations show that the eclipse of the primary cannot be total: the B-V colour at primary minimum is consistently bluer (< 0''65) than that of a K2V star (B-V = 0''92), while the shape and residual depth of primary minimum vary considerably from cycle to cycle, contrary to what would be expected for a total eclipse by the late-type secondary. This
explanation implies that the smooth variation in our V curves between maxima at $\phi = 0.25, \phi = 0.75$ is also caused by ellipsoidal variation of the secondary; the decline after $\phi = 0.75$ is reversed by the onset around $\phi = 0.8$ of the hump due to the bright spot. These considerations suggest that, as usual, the primary's light is dominated by the contributions of accretion disc and bright spot, the white dwarf's light being negligible (see below).

4. **Discussion**

Our identification of the secondary as a K2V star allows us to estimate the distance D to the system, since the mean magnitude $m_K = 11.7$ now represents solely the light of this star. Adopting $M_V = 6.3$ from the tables of Allen (1973) and $V-K = 2.15$ for a K2V star (Johnson, 1966) gives $M_K = 4.15$ and hence $D = 320$ pc, as interstellar reddening is certainly negligible at K (and indeed probably also in the optical for such a small distance D).

The uncertainties in this estimate are due largely to the possible deviation of the secondary from the main-sequence assumptions. Secondaries close to the main sequence are found for many cataclysmic variables (Warner, 1976). Here the G or K type optical spectrum, the agreement of J-K colours, inferred mass, and radius (see below) with those of a K2V star suggest this is a reasonable assumption. If it is adopted, the errors on our J-K colour allow spectral types in the range G8 - K6 (the best agreement of course being at K2). The corresponding distances are in the range 360 - 260 pc.
The absence of a detectable secondary eclipse at any wavelength means that the surface brightness of the primary considerably exceeds that of the secondary. Adopting an effective temperature of 5000 K (Johnson, 1966) for the secondary implies an average brightness temperature $T_{br}$ in excess of $10^4$ K for the primary at optical and infrared wavelengths; this is probably a lower limit to the temperature at the outer edge of the primary's accretion disc. This temperature estimate is also consistent with the B-V colours of the system and the increase of eclipse depth towards shorter wavelengths seen in the observations of Mumford and Krzeminski (1969). The brightness temperature estimate also implies a limit on the effective area of the primary $A_{eff}$ Taking the primary to contribute 40% of the mean V flux and therefore about two-thirds of the contribution of the K2V star implies an effective area $A_{eff} = 3.0 \times 10^{24} \ T_{br}^{-1} \ cm^2$, where we have assumed $M_V = 6.3$ for the K2V star. If the major contributor to the primary's light is an accretion disc of radius $R_{out}$ in the orbital plane of the binary, we have $A_{eff} = \pi R_{out}^2 \ cos i$. 
Using Robinson's value \( q = 1.3 \) and the consequent Roche lobe radius \( R_2 = 0.4a \) for the secondary (Paczynski, 1971), the inclination \( i \) cannot be much larger than about 73° without causing a total eclipse of the primary, contrary to our assertion above. On the other hand we require \( i \geq 55° \) for an occultation to occur at all (Robinson, 1974). These limits imply

\[
1.3 \times 10^{10} T_4^{-\frac{1}{3}} \text{ cm} < R_{\text{out}} < 1.8 \times 10^{10} T_4^{-\frac{1}{3}} \text{ cm},
\]

where \( T_4 = T_{\text{br}}/10^4 \text{ K} \). Since the binary separation \( a = 1.5 \times 10^{11} \text{ cm} \) (Robinson, 1974), we must have \( R_{\text{out}} \sim 0.1a \), in contrast to Robinson's estimate \( R_{\text{out}} \sim 0.4a \). However the latter estimate used the velocity splitting of the emission lines, which does not necessarily give direct information about the size of the optically thick disc region. It would seem that there is considerable optically thin line-emitting material orbiting just inside the primary's Roche lobe. The value \( R_{\text{out}} \sim 0.1a \) is very close to the minimum value allowed if one assumes that specific angular momentum about the primary is conserved within its Roche lobe (Warner, 1976).

To cause the near-total primary eclipse we have inferred, the inclination \( i \) must obey

\[
\cos i = R_2/(a + R_{\text{out}}),
\]

With \( R_2 = 0.4a, R_{\text{out}} = 0.1a \) we obtain \( i = 69° \). This is slightly higher than Robinson's upper limit \( i = 67° \), derived by assuming that the white dwarf was not eclipsed. The latter condition is necessary to account for the variable nature of the eclipse if one assumes the white dwarf to be the major contributor to the primary's light; however this assumption would mean that the primary made a large contribution at all orbital phases, in disagreement with our deductions above from the infrared and optical photometry. If instead the accretion disc is assumed, as here, to be the major contributor to the primary's
light the restriction $i \leq 67^\circ$ may be dropped. Using $i = 69^\circ$ we adopt the lowest values from Robinson's mass ranges, viz. $M_1 = 0.52 \, M_\odot$, $M_2 = 0.73 \, M_\odot$. This latter value agrees rather well with the main-sequence mass one would deduce from the K2V spectral assignment. We note finally that the near-total eclipse geometry we have inferred can account naturally for the erratic changes in eclipse shape and depth observed in the optical light curves of this system; these would be caused by changes in brightness of the disc rim during phases of increased accretion.

Acknowledgements

We thank the Science Research Council for observing time and travel funds for the Tenerife telescope. MRS has an SRC research studentship.
References


Figure Captions

Fig. 1. V, K and V, J light curves of EM Cyg. The break in the V, K curves indicates a change of night. The J, K observations are binned to reduce instrumental noise and intrinsic flickering. Each point is the mean of fifteen 20 sec integrations.
INFRARED AND OPTICAL OBSERVATIONS OF CATACLYSMIC VARIABLES

by

Madeline Sherrington

This thesis presents infrared and optical photometry of the binary light curves of several cataclysmic variables. The results are discussed in terms of the accepted model of cataclysmic variables, comprising a Roche lobe filling late type secondary and a white dwarf primary. The secondary star loses matter from the inner Lagrangian point and this matter forms an accretion disc around the white dwarf.

Our observations have shown that sometimes the late type secondary dominates the infrared luminosity of the binary. With further accurate observations over many cycles such systems will provide an excellent opportunity for the analysis of ellipsoidal variations in late type stars.

In other systems the accretion disc spectrum, which current theories predict should vary as \( v^4 \), dominates the luminosity of the system from the ultraviolet right through to the near infrared. Then our observations, combined with ultraviolet and further optical measurements, allow us to discover the size and outer rim temperature of the accretion disc.

Alternatively a combination of the disc spectrum, dominating at short wavelengths and the spectrum of the late type secondary, becoming bright at long wavelengths is observed. Observations of the light curves, simultaneously at infrared and optical wavelengths, then enable us to show that the results can be modelled in terms of an accretion disc of standard brightness distribution being eclipsed by a late type secondary. This provides support for current disc theories.

Finally our observations out to 3.6 \( \mu m \) combined with 2 - 2.5 \( \mu m \) spectrophotometry of one system have shown clearly the presence of a dust cloud around the binary and allowed us to find the temperature of this dust. Similar observations of other systems will be of interest.