CATACLYSMIC VARIABLES IN THE EXTREME ULTRAVIOLET

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ABSTRACT

The UK ROSAT Wide Field Camera was used to carry out the first all-sky survey at extreme-ultraviolet wavelengths (EUV). In this thesis, an optimised method for the extraction of survey light curves is developed and applied to an all-sky sample of eighty-one cataclysmic variables. Twenty-two sources were detected with high confidence.

The sample of detected systems is dominated by AM Hers, which are found to be exceptionally strong EUV sources. Six of these are new systems, identified through optical follow up of survey sources, and these EUV-selected systems are found to have the most extreme EUV/optical flux ratios. Orbital periods are detected in most AM Hers, and the implications of the new orbital-period distribution of AM Hers are discussed. Phase-folded light curves of a flux limited sample are presented and spectral constraints are applied. Three AM Hers show evidence of spectral modulation with phase.

Three intermediate polars are detected, though a distinct EUV emission component is required only in the case of RE0751-14. Upper limits to other systems show that RE0751 is unusually bright within the bandpass of the WFC. Limits are placed on temperatures and absorption columns of similar components in other systems, but the WFC does not provide useful limits on the luminosities of such components. The energy balance of intermediate polars remains an open question.

Six non-magnetic cataclysmic variables were detected, four of which are dwarf novae caught in their outburst state. These include VW Hyl and SS Cyg, which are discussed in the context of extensive multi-wavelength coverage; incorporating optical, ultraviolet and X-ray observations. SS Cyg was detected as a strong EUV source during decline, which was found to be faster than the optical decline. VW Hyl was observed throughout an optical outburst, with but no enhancement of EUV flux. This suggests the EUV flux detected by EXOSAT must lie softwards of ~70 eV. WFC limits show that the boundary layer of VW Hyl during outburst must be less luminous than the disk. In VW Hyl and SS Cyg the hard X-ray flux is suppressed during outburst, and remains low until the very end of optical decline. This is taken as evidence that the hard X-ray flux is regulated by the boundary layer.
A schematic diagram of an AM Her type system. The white dwarf is the foreground, the red dwarf in the background. The diagram is to scale, and a possible trajectory for the accretion flow is marked with a thin line. Plotted with a program by A.P. Boardmore.
to my parents
Contents

Abstract ii

1 Extreme ultraviolet astronomy 1

2 Introduction to cataclysmic variables 3
   2.1 What are the cataclysmic variables? 3
   2.2 Magnetic classification 5
      2.2.1 Non-magnetic systems 6
      2.2.2 Polars 9
      2.2.3 Intermediate polars 12
      2.2.4 Relationship between polars and intermediate polars 13
   2.3 Optical classification 14
   2.4 Conditions for stable mass transfer 18
   2.5 Orbital periods and evolution 19
      2.5.1 Long period cut-off 20
      2.5.2 Short period cut-off 21
      2.5.3 The period gap 22
      2.5.4 The period spike 24
   2.6 X-ray and EUV emission 25
      2.6.1 Non-magnetic systems 26
      2.6.2 Polars 29
      2.6.3 Intermediate polars 31
      2.6.4 Summary 32

3 The ROSAT Wide Field Camera and the all-sky survey 34
   3.1 The first all-sky EUV survey 34
      3.1.1 The ROSAT Wide Field Camera 35
Chapter 1

Extreme ultraviolet astronomy

The extreme ultraviolet (EUV) waveband stretches from the Lyman limit, at 13.6 eV (912 Å), to a poorly-defined boundary with the soft X-ray band at around 124 eV (100 Å). Photoelectric absorption by hydrogen and helium is very efficient at these wavelengths, and for a long time it was thought that observing EUV radiation from cosmic sources was impractical. Early models of the interstellar medium (ISM), which assumed a cold uniform medium, predicted an optical depth greater than unity within one parsec. It wasn't until the 1970s that interest in EUV astronomy began when optical and ultraviolet spectroscopy of bright stars revealed that the ISM is highly inhomogeneous. It was found that the neutral hydrogen density in the solar neighbourhood is \( \sim 0.07 \text{ cm}^{-3} \) (Paresce, 1984); far less than the mean density of \( 1 \text{ cm}^{-3} \) calculated from observations of the 21 cm line. Also, measurements of the soft X-ray background revealed large quantities of hot gas in the solar neighbourhood (\( T \sim 10^6 \text{ K} \)); suggesting that the sun lies in a bubble of high temperature, low density gas. Paresce showed that this bubble must extend up to 200 pc in some directions, but only 10 pc towards the galactic centre. As a result of this work, models of the ISM were developed in which supernovae explosions heat and sweep out large bubbles in the ISM, leaving a complex structure of hot tenuous regions and cooler dense regions in quasi-thermodynamic equilibrium (e.g. Innes & Hartquist, 1984; Frisch & York, 1983).

Clearly, with an inhomogeneous ISM, the EUV opacity to individual objects can be much lower than that predicted by homogeneous models, especially for sources within the proposed local bubble. Revised estimates of EUV opacities to nearby objects suggested that EUV detections were possible, and to test this a modest EUV telescope was flown aboard the Apollo-Soyuz mission in July 1975. This instrument had a 37 cm diameter aperture with nested grazing-incidence mirrors. It had no imaging capacity, a 2.3° field of view and four
EUV filters. Several discrete sources were detected (e.g. Lampert et al., 1976) confirming the relatively low density of the local ISM, and setting EUV astronomy on a sound footing. A strong EUV background was also detected (Stern & Bowyer, 1979), confirming the existence of hot gas in the ISM, and supporting ideas of a hot bubble.

The interplanetary Voyager spacecraft, launched in 1977, carried ultraviolet spectrographs which were sensitive shortward of the Lyman limit. Three hot white dwarfs were detected in the EUV portion of the spectrometers, but no cataclysmic variables, although the upper limit for the dwarf nova VW Hyi proved useful. Holberg (1989) reviews these observations.

The European satellite EXOSAT, whilst being basically an X-ray mission, had a low energy response that extended well into the EUV (e.g. White, 1989). Interpretation of EUV detections was complicated because all filters were also transparent to soft X-rays, but this instrument provided the first detailed EUV observations and detected many cataclysmic variables, hot white dwarfs and cool stars for the first time. The low energy instrument also carried a transmission-grating spectrometer, sensitive in the EUV, which measured the spectra of several objects including the cataclysmic variables AM Her and QQ Vul (e.g. Van Teeseling, Heise & Paerels, 1994).

The flight of the first true EUV imaging telescope had to wait until 1990 and the ROSAT Wide Field Camera (WFC). The WFC surveyed the entire sky in two EUV bandpasses, with three hundred and eighty two sources identified at high significance in the initial data analysis (Pounds et al., 1993). An extended program of pointed observations has also been carried out (in four EUV bandpasses), in conjunction with the coaligned X-ray telescope aboard ROSAT. The WFC survey observations of cataclysmic variables are the subject of this thesis.

A second EUV survey, with similar sensitivity, was carried out with NASA's EUV Explorer mission, launched in 1992 (Bowyer & Malina, 1989; Malina et al., 1994). This spacecraft also carried out a deep survey in the ecliptic plane, and carries an EUV grating spectrometer for use during the pointed phase of the mission.
Chapter 2

Introduction to cataclysmic variables

Several excellent reviews have been published recently in the field of cataclysmic-variable stars, so I have not attempted a complete review of the field.

Cataclysmic variables as a whole are reviewed by Córdova (1995). The intermediate polars are reviewed by Patterson (1994) and the polars (or AM Hers) by Cropper (1990). Ritter & Kolb (in press) catalogue all known cataclysmic variables and tabulate important system parameters, Hack & laDous (1993) present an extensive survey of the literature on cataclysmic variables and Frank, King & Raine (1992) present a thorough discussion of accretion physics.

2.1 What are the cataclysmic variables?

Cataclysmic variables are thought to be semi-detached binary stars with a low-mass secondary star losing matter to a white-dwarf primary through Roche-lobe overflow. White-dwarfs have stellar masses but radii of only $\sim 10^9$ cm $\sim 0.01 R_\odot$, so the potential well is deep and much gravitational energy can be released through the accretion process ($L_{\text{acc}} \sim 10^{31} - 10^{34}$ erg s$^{-1}$). Being small but luminous makes them efficient ultraviolet and X-ray sources. The donor stars are often also observed directly but in the optical and infra-red, especially during periods of low accretion. They are seen to be close to the main sequence with spectral type in the range G–M. It is through measurements of the secondaries that distances are most often determined, typically 100-1000 pc.

Material lost by the secondary has too much angular momentum to fall immediately onto the white dwarf, so tends to form a disk around the white dwarf where this angular momentum can be dissipated. The exceptions are systems with highly magnetic white-dwarfs (the AM Hers), where the field is strong enough to dominate the motion of the
Introduction to cataclysmic variables

infalling material, passing the angular momentum directly to the white-dwarf and allowing the material to fall quasi-radially.

The accreted material is hydrogen rich and, when enough has accumulated on the white-dwarf surface, can ignite in a thermo-nuclear runaway process, resulting in a cataclysmic “nova” explosion in which the system brightens by \( \sim 9 \) magnitudes. Much material is ejected during a nova explosion, and it is thought that the accretion process results in a net decrease of the white-dwarf mass.

In addition to these occasional outbursts, cataclysmic variables exhibit less-dramatic variability at all observed wavelengths and timescales. The best known features are the dwarf-nova outbursts, in which some systems undergo quasi-periodic brightenings of 3–5 magnitudes on timescales of weeks. It is through variability that most systems are discovered.

Cataclysmic variables have been observed for centuries through nova explosions, and dwarf novae have been known for more than a century (Hind, 1856), but it wasn’t until the 1950’s and ’60’s that even their basic nature was established. Kraft (1990) documents the advances made at this time (apparently - if you can find the reference). Radial velocity measurements and optical photometry eventually revealed the binary nature and orbital periods were identified; typically in the range 1.5–10 hrs. These periods relate to the separation of the binary components through Kepler’s third law, which can be written as

\[
a/R_\odot = 0.5 \left( \frac{M_{\text{tot}}/M_\odot}{P_{\text{hrs}}} \right)^{1/3} \rho_{\text{hrs}}^{2/3}
\]

where \( a \) is the binary separation, \( P_{\text{hrs}} \) is the orbital period in hours and \( M_{\text{tot}} \) is the total mass of the system. This shows that the separation must be very small (\( \lesssim R_\odot \)), whatever the stellar masses. Only with extremely low masses could one squeeze two main-sequence stars within such a binary, and such a configuration cannot explain the highly-luminous hot emission seen from all cataclysmic variables. Clearly the binary must contain a compact star, and Patterson (1981) shows that we can distinguish between white-dwarf and neutron-star components in interacting binaries through the X-ray/optical flux ratio. They find a clear bimodal distribution, through which they associate white dwarfs with cataclysmic variables and neutron stars with the X-ray binaries.

The gravitational energy released by accretion onto the white dwarf is given by

\[
L_{\text{acc}} = \frac{GM_{\text{wd}} \dot{M}}{R_{\text{wd}}}
\]

where \( G \) is the gravitational constant, \( M_{\text{wd}} \) is the mass of the white dwarf, \( \dot{M} \) is the mass accretion rate and \( R_{\text{wd}} \) is the radius of the white dwarf.
Introduction to cataclysmic variables

For a typical accretion rate of $10^{16} \text{ g s}^{-1}$ this gives luminosities of order $10^{33} \text{ erg s}^{-1}$. For comparison, the same accretion rate onto a neutron star would yield $\sim 10^{36} \text{ erg s}^{-1}$. The total luminosity of the Sun is $4 \times 10^{33} \text{ erg s}^{-1}$.

Since the 1960's, rocket and satellite borne experiments have shown that all cataclysmic variables are significant ultraviolet and X-ray sources; confirming the accretion-onto-compact-object scenario. It has become increasingly clear that most of the accretion luminosity is released outside the optical waveband (e.g. Fig. 2.1), and in the last fifteen or so years, observations at X-ray, ultraviolet and infra-red wavelengths have transformed our understanding of cataclysmic variables.

2.2 Magnetic classification

Before space flights, observations of cataclysmic variables were restricted to the small fraction of the accretion luminosity released in the optical band. Detailed analysis in this restricted waveband resulted in a mass of phenomenological knowledge of the optical variability (e.g. Hack & laDous, 1993), and a complex system of categorisation, but little insight into the
Introduction to cataclysmic variables

physics of the accretion process. In particular this restriction led to the mis-categorisation of the strongly magnetic cataclysmic variables, which can be rather unremarkable at optical wavelengths, but are spectacular EUV and X-ray sources. It is now clear that the single most important parameter for a cataclysmic variable is the magnetic moment of the white-dwarf star ($\mu_1$), and that the most appropriate system of categorisation comes from considering this field. Accordingly I describe cataclysmic variables from this modern perspective, and base my introduction on this categorisation. Afterwards I introduce the optical classification scheme since it is still universally employed and valid within the study of the non-magnetic cataclysmic variables.

2.2.1 Non-magnetic systems

In all cataclysmic variables, matter leaves the Roche-lobe-filling secondary star at the L1 point, and falls towards the white dwarf. It carries angular momentum so leads the secondary star in phase. The majority of known systems show no evidence for a magnetic white dwarf, and the stream of matter follows a Keplerian trajectory; attempting to form a ring around the primary at the circularization radius, given by

$$R_{\text{circ}}/a = (1 + q)(0.500 - 0.227 \log q)^4$$

where $q$ is the mass ratio of the binary ($M_2/M_1$).

This ring is smoothed out by viscosity which carries angular momentum outwards and allows material to approach the white dwarf, forming an accretion disk. Material also moves outwards, carrying the angular momentum, until it reaches a stability limit governed by tidal forces. This limit depends only weakly on system parameters, and is always close to

$$R_{\text{tides}} \approx 0.9 R_1$$

where $R_1$ is the primary’s Roche-lobe radius.

The accretion disk gets hotter towards the centre as more and more gravitational energy is released, and this large hot structure dominates the optical and ultraviolet emission of non-magnetic cataclysmic variables (Fig. 2.1). There is also significant optical emission from the hotspot where the accretion stream hits the edge of the disk. Figure 2.2 is a schematic diagram of this accretion geometry.

\(^{1}\)“non-magnetic” refers to the white-dwarf and not the system. It is thought that the magnetic field of the secondary star plays an important role in driving the mass transfer in all classes of cataclysmic variable (Section 2.5).
Direct evidence of the disk structure of non-magnetic cataclysmic variables is available through the optical emission line spectrum (see Fig. 2.3). These lines are strong, revealing the presence of hot, diffuse gas. They are also broad, showing that this gas is moving faster than the orbital velocities of the two stars. Most importantly the lines are double peaked, showing that the material is moving in circular orbits; indicating the presence of an accretion disk. Horne (1991) summarises efforts to image the disks through eclipse mapping and doppler tomography of the emission lines.

The orbital decay of disk material is on a much longer timescale than its orbital period, so material throughout the disk orbits according to Kepler's laws. These must be circular orbits, the minimum energy configuration, because radiation removes energy more efficiently than viscosity removes angular momentum. The angular velocity in these circular orbits is given by

\[ \Omega_K = (GM_{wd}/R^3)^{1/2} \]  

so the kinetic energy of a gas element of mass \( m \) in the innermost orbit is

\[ E = \frac{GM_{wd}m}{2R_{wd}} \]  

The energy of the outermost orbit is negligible so

\[ L_{disk} = \frac{GM_{wd}\dot{M}}{2R_{wd}} = L_{acc}/2 \]
Figure 2.3: Optical spectra of OY Car, a non-magnetic cataclysmic variable, and EF Eri (2A 0311-227) a polar. Figure from Wade & Ward (1985)
Introduction to cataclysmic variables

Hence, half of the accretion luminosity will be released in the disk, and half must be released in a thin layer between the disk and the white dwarf. This boundary layer is the most probable origin of the X-ray emission seen from non-magnetic cataclysmic variables (see Sect. 2.6), and probably powers the wind seen in several systems (e.g. Córdova & Mason, 1982).

2.2.2 Polars

Polars, or AM Her type systems\(^2\), have a very different accretion geometry from the non-magnetic systems. Here the magnetic moment of the white dwarf is probably in the range \(5 \times 10^{32} < \mu_1 < 5 \times 10^{33} \text{Gcm}^3\) (King, 1994), which is strong enough to dominate the flow of the infalling material at large radii. The defining feature of these systems is that the field is also strong enough to synchronise the spin of the white dwarf to the orbital period of the binary. Hameury et al. (1987) discuss the various processes proposed for the synchronising torque, which must be larger than any of the other torques on the white dwarf, most notably the spin-up torque from accretion (their discussion is based largely on the work of Campbell, see references in Hameury et al.\(^3\)). They conclude that the most efficient process is the interaction of the white dwarf’s field with that of the secondary star. We may expect this field to be considerable as the secondary is, after all, a fast-rotating late-type star; indeed Dulk, Bastian & Channugam (1983) measure a surface field strength of \(\sim 1000 \text{G}\) for the secondary in AM Her, implying a magnetic moment comparable with that of the primary. For close systems, synchronisation is also possible simply through dissipation of the primary’s field in a non-magnetic secondary star (it is thought that this field of is switched off, or at least weaker, in very low mass stars, \(M \lesssim 0.2 M_\odot\)). Systems which show evidence for a magnetic primary but which are not synchronised are classed as intermediate polars (or DQ Her stars), and are discussed in the next section.

The effect of the field on the infalling material is complex, and has not been tackled theoretically as yet. Many physical processes will be competing here, and modelling is hampered because there are so few direct observational constraints (emission from the accreting portion of the white dwarf dominates at most wavelengths). We can, however, be reasonably confident about the basic accretion geometry. The optical emission lines are not double peaked (Fig. 2.3), so we know an accretion disk does not form. They are broad, and exhibit an “S-wave” when plotted with binary phase, indicating that the stream must be accreted within

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\(^2\)I use these terms interchangeably.
one orbit of the primary. We also see high-excitation lines in this spectrum: HeII, CIII and NII; which indicate a strong source of ionising radiation.

Accretion within one orbit is possible because the (photoionised) accretion stream will experience a strong drag force as it passes through the stationary magnetosphere of the white-dwarf. This provides a very effective method for passing angular momentum directly to the white-dwarf (and hence back to the binary orbit through the synchronising force). Robbed of its angular momentum, the flow will fall directly towards the white dwarf. As it approaches the white dwarf the field strength increases with \( R^{-3} \), so it is quickly threaded by the field. Once it is frozen to the field lines it must follow them, so the flow lifts out of the orbital plane and follows its field line down to the footprint on the white-dwarf surface (close to a magnetic pole). Figure 2.4 shows this accretion geometry.

The result of this geometry is that the whole flow is collimated by the magnetic field and is accreted quasi-radially at very high velocities (1000's of km/sec). The stream shocks close to the white-dwarf surface and releases all the accretion luminosity in a very small region. The post-shock gas is heated to very high temperatures (\( \sim 10^8 \) K), placing polars among the brightest X-ray sources in the sky. Most known polars were discovered through their X-ray emission, and many have been found through the ROSAT surveys (see Watson, 1993; Beuermann & Schwake, 1994).

The magnetic field is so strong at the white-dwarf surface (10–70 MG) that cyclotron emission can compete with thermal bremsstrahlung in cooling the post-shock gas. Cyclotron radiation is emitted by the hot electrons, gyrating round the magnetic field lines. It is emitted as "lines" at harmonics of the plasma gyration frequency, and is strongly polarised. Taking magnetic field strength in units of \( 10^7 \) G, the wavelength of the \( n \)th harmonic is given by

\[
\lambda = \frac{10.7 \mu m}{nB^7} \quad (2.8)
\]

Thus cyclotron emission peaks in the infra-red for relatively low field strengths, and in the ultraviolet for strong fields. In general this emission is optically thick for low harmonics, so is thermalised and appears with a black-body form, but is optically thin for higher harmonics, where individual lines can be identified (e.g. Wickramasinghe, 1988). Detection of cyclotron lines is the most common method for determining the magnetic field strength of polars (e.g. Schwake & Beuermann, 1990). Field strength can also be measured through Zeeman splitting of photospheric lines, seen at times of low accretion rate. The two methods give consistent results.

The most important observational property of cyclotron emission is its polarisation. This
Figure 2.4: Schematic representations of *polars*. The first taken from Frank, King & Raine (1992), the second plotted with a program by A.P. Beardmore. In this second plot the accretion stream (represented by the line from the left) follows a Keplerian trajectory until its flow becomes dominated by the magnetic field of the white dwarf. It is then shown following the dipole field lines. The vertical line from the white-dwarf indicates its spin axis, the second line represents the magnetic axis (inclined at 20°).
has been used extensively to constrain the size, shape, location and orientation of the emission region in AM Hers (e.g. Cropper, 1989). Typically AM Hers are seen to be 10–50% circularly polarised in the optical, with the polarisation modulated at the orbital period. Detection of this polarisation is the usual requirement for inclusion in the class, and gives rise to the title “polars”.

2.2.3 Intermediate polars

Intermediate polars also exhibit magnetic properties, but are not synchronised. Only ~13 such systems are known, and the membership of individual systems is often disputed. Patterson (1994) looks at the evidence on a system-by-system basis.

Evidence for the field is usually the detection of an X-ray modulation at the white-dwarf spin period (e.g. Norton & Watson, 1989). Just as in AM Hers, any magnetic accretor will channel the flow to its magnetic poles. Since the spin axis is not aligned with the magnetic axis, the X-rays will tend to be modulated through occultation by the body of the white dwarf, and absorption by the infalling material. One of the main observational differences in intermediate polars is that the asynchronous rotation causes accretion at all longitudes, and so over a large region of the white dwarf (Norton & Watson suggest at least one quarter of the white-dwarf surface). In the non-magnetic systems, material will be accreted around the equator, so the emission will not be pulsed as the white dwarf rotates.

There are three reasons why a magnetic white dwarf may rotate asynchronously in a cataclysmic variable. First, the magnetic moment of the primary may be strong enough to dominate the accretion flow, but not enough to synchronise the binary. King (1994) suggests magnetic moments $\mu \lesssim 10^{23}$ Gcm$^3$ can never lead to synchronism. Secondly, the separation of the binary components may be too great for synchronisation, even though the same field strength would lead to synchronism in a closer binary. And finally, the system may be synchronised most of the time but be thrown temporarily out of synchronism, perhaps through a period of increased accretion or a nova explosion. This final explanation may account for some systems where $P_{\text{spin}}$ is within a couple of percent of $P_{\text{orb}}$, such as BY Cam and V1500 Cyg (Schmidt, Liebert & Stockman, 1995; Pirola et al., 1994; Hameury, King & Lasota, 1989), but not the majority of systems in which the spin is typically an order of magnitude faster than the orbit.

The accretion geometry of intermediate polars is a matter of debate. Opinion is split
between a standard accretion disk, truncated by the field at small radii; or a direct stream-fed geometry where the material is accreted before it can circularise and form a disk, rather like AM Hers. There is compelling evidence on both sides, probably indicating that the geometry in any individual system is a function of system parameters. The evidence for disks is summarised by Hellier (1991), and comes from emission-line studies and eclipse mapping. Double peaked emission lines are often observed. King, Mouchet & Lasota (1991) also consider the evidence for and against disks. They argue that the evidence for disks is rather weak, and that it is possible to have disk-like structures that do not carry a significant fraction of the accretion flow (originally King & Lasota, 1991). The evidence for direct, stream-fed accretion comes from the detection of an X-ray beat between the white-dwarf spin and orbital periods (e.g. Tuohy et al., 1986), which Wynn & King (1992) show is incompatible with dominant accretion via a disk. In a stream-fed model the beat arises as the flow flips from one pole to another with the white-dwarf rotation.

2.2.4 Relationship between polars and intermediate polars

It is striking that the AM Her systems are concentrated at short orbital periods, while the intermediate polars are predominately long period systems (e.g. King, Frank & Ritter, 1985; Hameury et al., 1987). Hameury et al. show that the period distribution of the combined magnetic cataclysmic variables (pre-ROSAT) is statistically indistinguishable from that of the non-magnetic systems, while the AM Her distribution must be different (Schmidt & Liebert, 1987; who also find that the intermediate polars alone are not distinguished from non-magnetic systems). Since cataclysmic variables are thought to evolve to shorter periods, and smaller separations, King et al. suggested that this separation in period represents an evolutionary link, with intermediate polars the progenitors of AM Hers; i.e. that the second of the above reasons for asynchronism is dominant. King (1988) reviews the evolution of cataclysmic variables as it was understood at the time.

The problem with this interpretation is that intermediate polars have stubbornly refused to offer evidence of magnetic fields as strong as AM Hers. No Zeeman features have been observed, and, until the discovery of RE 0751 in the WFC survey (Chap. 4), only one system was found to exhibit (rather weak) optical polarisation (BG CMi; Penning, Schmidt & Liebert, 1986). It was suggested that the larger accreting regions in intermediate polars could wash-out the polarisation, making it unobservable (Changmugam & Frank, 1987); but more
Introduction to cataclysmic variables

recently is has been shown that a non-detection of optical polarisation at the 10% level con­strains the surface field strength to $\leq 5\,\text{MG}$ (Wickramasinghe, Wu & Ferrario, 1991), whereas polars have typically a few $\times 10\,\text{MG}$. If one accepts this constraint it presents a near impossible problem for the evolutionary link, since low-field systems can not evolve into high-field systems. In Sect. 5.1.2 I suggest a possible way round this.

Accepting that intermediate polars have weaker magnetic moments leaves the problem of the missing long-period AM Hers (or rather their progenitors; see Sect. 2.5), since Hamery et al. showed that AM Hers have a different period distribution to the total sample of cataclysmic variables. The equivalent problem of the short-period intermediate polars doesn't arise as Schmidt & Liebert (1987) found that the intermediate polar period distribution could be the same as the total sample (though they consider just eleven systems, not all of which are accepted by Patterson, 1994).

A rather confusing side issue to the question of asynchronous rotation in intermediate polars is an apparent relationship between the orbital and white-dwarf spin periods in a subset of systems ($P_{\text{spin}} = 0.1P_{\text{orb}}$; noted by Barrett, O'Donoghue & Warner, 1988; Warner & Wickramasinghe, 1991). This relation has received much attention from theorists, who have used it to constrain the accretion process and evolution of intermediate polars (e.g. Wickramasinghe, Wu & Ferrario, 1991; King & Lasota, 1991; Wu & Wickramasinghe, 1993 and King, 1993). However, Patterson (1994) claims that this relationship is based entirely upon an inaccurate list of systems.

Clearly, the status of intermediate polars in the CV family tree is rather uncertain. This is likely to remain so until a larger sample of these systems can be identified unambiguously.

2.3 Optical classification

Cataclysmic variables have a low space density, so are generally distant ($d > 70\,\text{pc}$ and typically $100-1000\,\text{pc}$) and have faint apparent magnitudes. The brightest have $m_v \sim 8 - 10$, while they are typically observed fainter than $12^{\text{th}}$ magnitude. The majority were distinguished from the background stars through nova explosions and dwarf-nova outbursts, which makes studies of cataclysmic-variable populations subject to strong selection effects.

A wide variety of optical outburst behaviour has been observed which led to a complex system of categorisation, even before the binarity of these variables was established. The following are the main categories; Fig. 2.5 illustrates the outburst behaviour. It is possible for an individual system to be a member of more than one category.
Introduction to cataclysmic variables

Classical Novae (N)

- **speed class**
  - very fast: $< 10$
  - fast: $11-25$
  - moderately fast: $26-80$
  - slow: $80-150$
  - very slow: $> 151$

- **normal outburst** typically 2-5 mag

Dwarf Novae (UG)

- **normal outburst**
- **superoutburst**

Dwarf Novae (ZC)

- **normal outburst**
- **standstill**

Dwarf Novae (SU)

- **normal outbursts**

Figure 2.5: Examples of the optical outburst behaviour of cataclysmic variables; from Ritter (1992).
Introduction to cataclysmic variables

- **Classical novae** are the most spectacular cataclysmic variables. The optical brightness increases by ~ 9 magnitudes in a matter of hours, then declines over the course of tens to hundreds of days. These events, though violent, do not destroy the system, hence the title *cataclysmic* variable. Pre- and post-novae are indistinguishable from other cataclysmic variables. The generally accepted explanation for these eruptions is thermonuclear runaway in the accreted material just below the surface of the white dwarf. By definition classical novae are observed to exhibit just one nova outburst.

- **Recurrent novae** are the small subset of systems (four to date) in which the nova explosion has been observed to recur. Since it is typically the weakest novae which are seen to recur it has been proposed that all novae are recurrent and that there is a relationship between the energy of the explosion and the recurrence time. Allowing for selection effects, novae are not seen as unusual cataclysmic variables in any other way. It seems likely that all cataclysmic variables are recurrent novae.

- **Dwarf novae** are systems which exhibit less spectacular but more regular optical brightenings, referred to as *outbursts*. Outburst amplitudes are typically 3-5 magnitudes with recurrence times of weeks to years, and the outburst amplitudes and durations are highly repeatable for individual systems. Outbursts are not thought to be due to nuclear burning, but rather an increase in the rate of accretion onto the white dwarf. Two models have been proposed, both of which remain the subject of current debate. The first is a simple increase in mass transfer from the secondary. The mechanism for driving this is not understood. The second model requires a disk instability. The mass transfer rate from the secondary is constant and material accumulates in the disk, with very little or no transfer onto the white dwarf. When the disk reaches a critical density the viscosity increases dramatically, enabling the disk to move angular momentum outwards and matter in and onto the white dwarf.

Dwarf novae in turn are divided into sub-classes based on the nature of their outbursts and named after prototype systems. Figure 2.5 gives examples of the outburst behaviour described here.

- *U Gem* systems exhibit just one kind of outburst. They do not occur periodically, but there is a well defined interoutburst timescale. Each outburst has approximately the same brightness and duration. Typically the brightening is by 3-5 magnitudes and the duration is a 2-3 days.
Introduction to cataclysmic variables

- SU UMa systems exhibit two kinds of outburst: normal outbursts, which are similar to U Gem-type outbursts, and superoutbursts which are less frequent, occur more predictably, are brighter and last longer.

- Z Cam systems exhibit outbursts but also occasional standstills on decline from outburst. Here they can remain at an intermediate brightness level for days to months.

- Anti-dwarf novae spend most of their time in an outburst state with just short duration drops to the quiescent level. In other aspects they are indistinguishable from dwarf novae.

- Nova-like variables are a mixed bag of objects, simply the systems which show all the optical characteristics of cataclysmic variables except for outburst behaviour. Most of these systems appear to be dwarf novae “stuck in outburst”. Formally this subclass also includes the magnetic cataclysmic variables but, since it is now understood that magnetic systems have entirely different accretion geometries, I will reserve the title nova-like for the non-magnetic variety.

With a minimum of speculation, the range of behaviour of non-magnetic cataclysmic variables can be understood as continuous. All are likely to be recurrent novae, while the outburst characteristics may be a simple function of mean mass transfer rate. High accretion rate systems appear as dwarf novae in permanent outburst, and very low accretion rate systems, though hard to detect, appear as dwarf novae in permanent quiescence. Both would be classed as nova-like variables. Dwarf novae are the systems in the intermediate case, and constantly switch between the two stable accretion states. They appear to be the most numerous simply because this behaviour makes them the easiest to detect.

The range of dwarf-nova outburst behaviour also fits into this picture. The higher the mass-transfer rate the longer the system spends in the brighter of the two stable states. Anti-dwarf novae are the most luminous, U Gem-type systems the faintest. SU UMa’s and Z Cam’s are intermediate. Mass-transfer rate is thought to correlate with orbital period (Patterson, 1984), and this is reflected in the orbital period distribution; with most U Gem’s below the period gap (Sect. 2.5) and most SU UMa’s above.
2.4 Conditions for stable mass transfer

Mass transfer between the components of binary stars can occur through the stellar wind of a massive component, or through Roche-lobe overflow of one of the two stars. We have already seen that the binary separation in cataclysmic variables is very small (Eqn. 2.1), ruling out the presence of a massive mass donor.

For stable mass transfer through Roche-lobe overflow there are two conditions:

1. The donor star must be the lower-mass star (the secondary).
2. The secondary must expand or the binary orbit must decay.

These conditions can be understood very simply. Eggleton (1983) gives an approximate formula for the radius of the sphere which has the same volume as a Roche-lobe filling star, which illustrates the point,

\[ R_2/a = \frac{0.49 q^{2/3}}{0.6 q^{2/3} + \ln(1 + q^{1/3})} \]  

(2.9)

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

If the primary were to fill its Roche-lobe then any mass transfer would move material further from the centre of mass, forcing the binary closer to conserve angular momentum. This would shrink the Roche-lobe further onto the primary, driving more mass transfer. In this case the mass transfer will occur on dynamical timescales, which are much faster than the thermal timescales on which the two stars can adapt to their changing masses. The result is catastrophic unstable mass transfer. This is violent but short lived, and so can not drive the stable mass transfer we observe in cataclysmic variables. Mass transfer from the primary is thought to be important for cataclysmic variables, but at an earlier stage in their evolution, when the progenitor of the white-dwarf first evolves off the main sequence. As it expands into a giant it fills its Roche-lobe and undergoes a period of unstable mass loss. Since this occurs faster than the secondary can react the material will not be accreted but expands into a large envelope, surrounding both stars. It is through this common envelope phase that the pre-cataclysmic binary can shed enough angular momentum to reduce its separation to values which will allow future stable mass transfer.

As the donor star in cataclysmic variables must be less massive than the primary (i.e. \( q \lesssim 1.0 \)), Eqn. 2.9 tells us that any mass transfer will expand the Roche-lobe and cause the

\(^{3}\text{Mass transfer from the secondary can also be unstable, when } q \text{ is close to unity, since mass loss forces the star to expand.}\)
Introduction to cataclysmic variables

binary to detach and cease mass transfer. We need a mechanism which can either expand the secondary, or shrink the Roche-lobe, such that the system can stay in contact. The obvious mechanism is nuclear evolution of the secondary, but the secondaries in cataclysmic variables are low mass, and will not begin to evolve within a Hubble time. Expansion of the secondary can be important only in the longest period systems, which have the greatest separations and highest-mass secondaries. For most cataclysmic variables we need a mechanism to shrink the Roche-lobe; requiring a reduction in separation, which is only possible by shedding angular momentum. The relationship between the three important parameters is

\[
\frac{\dot{a}}{2a} = \frac{J}{J} + \frac{-M_2}{M_2}(1 - q) \tag{2.10}
\]

where \(J\) is the orbital angular momentum of the binary.

Two mechanisms for angular momentum loss have been proposed, both of which are probably important in cataclysmic variables. For short-period systems, \(P_{\text{orb}} \leq 2\) hrs, gravitational radiation is efficient, and can sap angular momentum at a rate capable of driving the observed accretion luminosities (calculated by combining equations 2.10 and 2.2). At longer periods, gravitational radiation is less efficient, and yet cataclysmic variables are observed to be more luminous, so a second process is required. This probably occurs through a spin-down torque on the secondary star, and is transferred to the binary orbit through the strong tidal forces that keep the star rotating synchronously (the tidal forces on a Roche-lobe filling star are very strong). In the favoured model, magnetic braking, angular momentum is carried off in the stellar wind of the secondary. The wind is forced to rotate with the magnetosphere of the secondary out to large radii, and applies a strong torque as it interacts with the interstellar medium (Verbunt & Zwaan, 1981; Rappaport, Joss & Verbunt, 1983; and Mestel & Spruit, 1987). This effect is well documented in isolated late-type stars (e.g. Mestel, 1990).

2.5 Orbital periods and evolution

An important consequence of \(J\)-driven mass transfer is that individual systems will evolve to shorter periods (and smaller \(a, P_{\text{orb}}\) and \(M_2\)). This, and the dependence of \(P_{\text{orb}}\) evolution on the efficiency and relative importance of the two \(J\) mechanisms, makes the orbital period distribution of cataclysmic variables crucial to our understanding of their evolution.

King (1988) shows that combining Kepler's third law (Eqn. 2.1) and Roche-lobe geometry (Eqn. 2.9) gives an expression for the orbital period of a cataclysmic variable as a function
Introduction to cataclysmic variables

only of the density of the secondary, i.e.

\[ P_{\text{orb}} \propto \rho_2^{-1} \propto \frac{R_2^3}{M_2} \]  \hspace{1cm} (2.11)

If we assume that the secondary is close to the main sequence we can use \( M_2/M_\odot \approx R_2/R_\odot \) and express the mass of the secondary as function of the orbital period

\[ M_2/M_\odot \approx 0.11 P_{\text{orb}} \approx R_2/R_\odot \]  \hspace{1cm} (2.12)

Spectroscopic and eclipse observations show that this is a reasonable assumption, so Eqn. 2.12 is a useful rule of thumb. It does not hold in all cases however; indeed the generally accepted explanations of the minimum observed periods and the period gap require significant deviations from the main-sequence (below).

The orbital periods of cataclysmic variables can usually be detected through radial velocity measurements. In AM Her-type systems, orbital modulation also tends to be obvious in optical and X-ray photometry. Periods in the range 1.5–10 hrs are typical, suggesting secondary masses in the range 0.1–1.0 \( M_\odot \). Figure 2.6 shows the cumulative period distribution of all systems known before the launch of ROSAT. Also plotted is the distribution of AM Her systems (dotted). ROSAT has had a huge impact on the study of AM Hers in particular, more than doubling the number of known systems. Here I discuss the pre-ROSAT distribution and describe the evolution of cataclysmic variables as it was understood at the time. I discuss the implications of the new sample in Chap. 5.

Four features are obvious in Fig. 2.6; long and short period cut-offs, a dearth of systems between two and three hours (the famous period gap) and a spike in the AM Her distribution at the lower edge of this gap (the ‘infamous’ period spike).

2.5.1 Long period cut-off

The high period cut-off is a simple consequence of the first condition for stable mass transfer (above). If the secondary has to be less massive than the white dwarf, then its mass is also limited to the Chandrasekhar limit (1.44 \( M_\odot \)). Equation 2.12 then gives a maximum orbital period of 13 hrs.

Only one cataclysmic variable is confirmed with a longer period, GK Per, with a period of 48 hrs. In this case the secondary must have evolved off the main-sequence and have a radius many times greater than that of a main-sequence star of the same mass. It is likely that mass-transfer is being driven by the expansion of this star, in which case the system will be evolving to longer periods.
2.5.2 Short period cut-off

According to the conditions for stable mass transfer (Sect. 2.4) most systems must evolve from right to left in Fig. 2.6; as $J$, $a$, $R_2$, $M_2$ and $P_{\text{orb}}$ all decrease.

If the secondary could continue to obey the main-sequence mass-radius relation then nothing would prevent gravitational radiation driving the binary closer and closer until the components finally merged. This doesn’t happen because at short periods the secondary is driven off the main-sequence by the effects of mass loss.

The effect of any mass loss will tend to drive a secondary out of thermal equilibrium. It will have the thermal energy of a higher-mass star, so will be over-large and over-luminous for its
mass, and its luminosity will be greater than its nuclear luminosity \( (L > L_{\text{nucl}}) \). The star will attempt to return to equilibrium and the main-sequence at the thermal (Kelvin-Helmholtz) timescale

\[
t_{KH} = \frac{GM_{2}^{2}}{R_{2}L_{2}}
\]

(2.13)

If this is shorter than the mass transfer timescale \( (t_{QH} \text{ at short periods}) \) then the star will stay close to the main-sequence. This becomes more difficult as system evolves since the thermal time increases (decreasing \( L_{2} \text{ dominates} \) and gravitational radiation becomes more efficient. Figure 2.7 shows these timescales as a function of orbital period. Below two hours the secondary reacts too slowly to the mass-loss rate and can no longer stay close to thermal equilibrium and the main-sequence.

Further mass transfer makes the star increasingly over-sized and luminous; which in turn reduces the core temperature, reducing \( L_{\text{nucl}} \) and exacerbating the effect. The secondary leaves the main-sequence, hydrogen burning ceases as the core temperature drops, and the star becomes degenerate. Once degenerate the radius varies inversely with the mass

\[
R_{2} \propto M_{2}^{-1/3}
\]

(2.14)

so from Eqn. 2.11

\[
P_{\text{orb}} \propto M_{2}^{-1}
\]

(2.15)

Thus the orbital period must increase with further mass transfer, giving the observed minimum in the orbital period distribution. The precise period of this stationary point depends on the luminosity of the star as it leaves the main sequence. This in turn depends on the opacities of the stellar atmosphere, which are rather uncertain for such cool stars \( (\lesssim 3000 \text{ K}) \). Paczynski & Sienkiewicz (1981) and Rappaport, Joss & Webbink (1982) find values consistent with the observed minimum of 80 mins.

2.5.3 The period gap

The period gap is probably due to an abrupt reduction of magnetic braking as the binary reaches 3 hrs (Rappaport, Joss & Verbunt, 1983; Spruit & Ritter, 1983). Beyond this point the binaries continue to evolve to shorter periods, but more slowly, now under the influence of gravitational radiation. This interpretation comes from the result that low mass stars become fully convective at \( \sim 0.2 M_{\odot} \); the mass of secondaries around 3 hrs. A significant change in the stellar dynamo is plausible at this point, and a reduction of the field or the stellar wind could cause a discontinuity in magnetic braking.
A period gap is a natural consequence of a sudden reduction of orbital braking, so long as the secondary is out of thermal equilibrium. This stands for any braking law, not just magnetic braking. The gap forms because a sudden drop in angular-momentum loss gives the secondary time to return to equilibrium; allowing it to shrink to its main sequence radius. As long as \( t_M > t_{KH} \) after the discontinuity then the radius will shrink more quickly than the Roche-lobe and the binary will detach. The radius will stabilise at the main-sequence value and the binary can re-establish mass transfer once gravitational radiation has reduced the Roche-lobe to this new radius. This defines the lower edge of the gap at \( \sim 2 \) hrs. At this point the secondary must be on the main sequence, so Eqn. 2.12 holds, giving a mass of
The mass will not have changed since the upper edge of the gap, where the star must have been oversized by about 70%.

Rappaport, Joss & Verbunt (1983) present detailed calculations of binary evolution, and try different magnetic braking laws. More recently Hameury et al. (1988) show that the braking law of Mestel & Spruit (1987) is in good agreement with the observed period distribution and mass-transfer rates.

Hodgkin, Jameson & Steele (1995) have found indirect evidence of a discontinuity in magnetic braking. They show that chromospheric and coronal activity in late-type stars increases with decreasing mass until around $0.4-0.2 \, M_\odot$ where they find evidence of a reduction in activity. This turnover may reflect the change in the magnetic dynamo due to full convection.

Note that the period gap is more a deficit than a gap, with several systems lying between two and three hours (Fig. 2.6). Systems in this range were most probably "born" in the gap; that is, they emerged from common-envelope evolution with $0.2 \leq M_2 \leq 0.3$ and first made contact in this period range. They experienced magnetic braking and then gravitational radiation, but don't experience a gap because there was no mass loss to pull the secondary out of equilibrium at $> 3$ hrs. Studies of the numbers and distribution of systems within the gap have the potential to constrain the birth-rate and initial-period distribution of cataclysmic variables.

### 2.5.4 The period spike

In the pre-ROSAT AM Her period distribution (Fig. 2.6), six of the seventeen systems lay within two-minutes of each other at the bottom end of the period gap. Hameury et al. (1988) suggested that this spike occurs at the point where the binaries re-gain contact after traversing the period gap.

This is attractive as the secondary must undergo a period of adiabatic expansion and enhanced mass-loss immediately after regaining contact, as it is once again driven out of thermal equilibrium. The enhanced mass-transfer increases the probability of detecting systems in this state. These systems will also evolve towards longer periods and greater separations, as the mass-transfer rate is higher than that demanded by orbital decay. Once the secondary settles into thermal quasi-equilibrium, gravitational radiation dominates the mass loss and the system evolves again to shorter periods. The resulting stationary point in the $P_{orb}$ evolution will also enhance the probability of detection.
Introduction to cataclysmic variables

The problem with this interpretation is that the narrowness of the spike demands extreme constraints on the primary and secondary masses. Ritter & Kolb (1992) show that the secondaries must have been born with $M_2 \geq 0.5 M_\odot$, also requiring initial white-dwarf masses $M_1 \geq 0.7 M_\odot$; they show that the range of secondary masses in the spike is limited to $\delta M_2 \lesssim 0.002 M_\odot$, and that this demands that the initial white-dwarf masses were constrained to $\delta M_1 \lesssim 0.05 M_\odot$ and that they maintain this narrow dispersion throughout their evolution. Such tight constraints are hard to swallow; though they are not conclusively contradicted by observation.

Haméury et al. (1989) suggest that AM Hers may evolve abnormally through nova explosions. The strong magnetic fields may inhibit mass loss and maintain a narrow distribution of primary masses. Haméury et al. do not explain the initial distribution, though nova explosions could, conceivably, focus white-dwarf masses to an equilibrium value.

A further problem is the absence of the spike in the $P_{orb}$ distribution of non-magnetic cataclysmic variables. Ritter & Kolb (1992) simply accept that the non-magnetic systems are not bound by the same constraints as the AM Hers, and that the spike is washed out; but they do not offer an explanation as to why this should be so, or indeed, why the constraints do apply to the AM Hers.

A way around both problems may be found in selection effects. The explanation of the spike depends on spike systems being preferentially selected, essentially through high accretion luminosity. This effect will be much stronger in AM Her systems, which are primarily discovered through their soft-X-ray brightness. Non-magnetic systems are usually discovered optically, through their outburst behaviour. This selection through high-luminosity will also bias the AM Her discoveries to high-mass white dwarfs, which will act to narrow the observed spike. This effect is rather strong, as the detection probability goes as $M_1^{7/2}$ (Haméury et al., 1988). To my knowledge the constraints on system masses have not yet been calculated including this selection effect.

Finally, the ROSAT surveys have extended the sample of AM Hers from ~17 to ~40, but without adding any spike systems. I discuss the new distribution in Sect. 5.1.2.

2.6 X-ray and EUV emission

Since the late 1970's, sensitive X-ray observations of large samples of cataclysmic variables have been made for the first time. The Einstein, EXOSAT and now ROSAT observatories have shown that X-ray emission is a ubiquitous feature of cataclysmic variables. IUE, HUT,
Voyager and the HST have provided insights into the accretion luminosity at ultraviolet and far- and extreme-ultraviolet wavelengths.

2.6.1 Non-magnetic systems

Eracleous, Halpern & Patterson (1991) consider the observations of thirty-two cataclysmic variables made with the Einstein (HEAO-2) observatory. They find hard X-ray emission in all cases, to which they find acceptable fits with a thermal bremsstrahlung model. Temperatures are typically in the range 1–5 keV, with some systems at temperatures >10 keV. They find 0.1–3.5 keV luminosities in the range $10^{30} - 10^{33}$ erg s$^{-1}$. The exceptions to this behaviour are dwarf novae in their outburst state (Mason et al., 1978; Pringle et al., 1987; Jones & Watson, 1992). These tend to show a reduced hard X-ray flux, and often a strong soft X-ray component is seen to develop. The soft component has been modeled as a black-body with temperatures 10–30 eV, and luminosities at least as high as the hard components.

As described in Sect. 2.2.1, systems accreting through Keplerian disks will release half of the potential accretion luminosity in the disk, but one half remains available as kinetic energy in the inner disk. So long as the white dwarf is not spinning close to break-up one would expect all of this energy to be released in a narrow boundary layer, where the material slows and settles onto the white-dwarf surface. With so much energy released in a small volume this is the natural site for the observed X-ray emission.

Pringle & Savonije (1979) discuss the conditions for hard and soft X-ray emission from a boundary layer. They find that strong shocks can develop in this region, heating material to the observed hard X-ray temperatures. For accretion rates $\geq 10^{16}$ g s$^{-1}$ they find that the boundary layer becomes optically thick to hard X-rays, which are thermalised and appear as a soft X-ray component similar to that observed in dwarf novae in outburst. They also point out that the flow timescale through the boundary layer is very short, just a few seconds, explaining the observed fast and strong variability that is typical of these objects. Figure 2.8 illustrates this picture of the boundary layer. Since this time theorists have been busy working on boundary layers; recent papers include Glatzel (1992) and Narayan & Popham (1993). Patterson & Raymond (1985) compare the Einstein observations with theory and find reasonable agreement.

In recent years it has become clear that the boundary layer is under-luminous, when compared with the optical and ultraviolet flux from the disk. This is most clearly demonstrated by Van Teeseling & Verbunt (1994), who study ten cataclysmic variables with ROSAT and
Figure 2.8: Picture of the boundary layer for (a) high accretion rates (e.g. dwarf novae in outburst) and (b) low accretion rates. The dotted region is optically thin and radiates hard X-rays. The shaded region is optically thick and radiates soft X-rays. Figure from Patterson & Raymond (1985)

show that the X-ray discrepancy is an increasing function of accretion rate (see their Fig. 11). They also find that the ROSAT spectra (0.1–2.5keV) generally require multi-temperature models, despite the low spectral resolution of ROSAT.

The dwarf nova VW Hyi has the lowest interstellar column measured for any cataclysmic variable (Polidan, Mauche & Wade, 1990), allowing tight constraints on X-ray and extreme-ultraviolet luminosities. It is now clear that the combined X-ray and EUV flux is less than the optical and ultraviolet during quiescence (Belloni et al., 1991), during outburst (Wheatley et al., 1995b; and Chap. 7) and during super-outburst (Mauche et al., 1991; Van Teeseling, Verbunt & Heise, 1993).

Several explanations for the lack of boundary layer luminosity have been proposed:

- The white dwarfs may be spinning at close to break-up velocities. This would allow accreting material to settle gently onto the surface without liberating its kinetic energy. However, Sion et al. (1994) use HST ultraviolet spectroscopy to measure the rotation velocity in U Gem, the first time such a measurement has been made, and find a slowly rotating star.
Introduction to cataclysmic variables

○ In many systems evidence is seen of a strong wind, probably originating in the boundary layer (e.g. Córdova & Mason, 1982). The bulk of the boundary layer luminosity may be carried as kinetic energy in this wind, rather than radiatively.

○ With the exception of VW Hyi, interstellar absorption is sufficient to allow an unobserved high-luminosity optically-thick EUV component to the boundary layer emission.

○ Measurement of the under-luminosity of the boundary layer depends on a clear separation of disk and boundary layer emission either side of the Lyman limit. Until the ultraviolet disk emission is better understood, it must be possible that the boundary layer contrives to radiate its energy below the Lyman limit.

Van Teeseling & Verbunt (1994) also found evidence for orbital modulation in three of their ten cataclysmic variables. This is very hard to understand in the context of boundary layer emission, since the inner accretion disk should have no knowledge of binary phase. If this result is confirmed we will have to look to other sites in the system for at least some of the X-ray flux. Four possible sites have knowledge of binary phase:

1. The secondary star. Essentially all secondaries in cataclysmic variables are rapidly rotating main-sequence stars, and as such have X-ray coronae. Star spots, or the asymmetry inherent in a Roche-lobe filling star, would explain the orbital modulation. However, Patterson & Raymond (1985) point out that the X-ray emission from main-sequence stars is simply too feeble to account for that observed.

2. Re-processing/reflection of boundary-layer X-rays at the secondary or in vertical disk structure (such as the hotspot). The large amplitude of the modulation tends to rule out this possibility.

3. Shocks in an asymmetric wind, driven by the boundary layer. Though this mechanism could drive variability, is seems unlikely that this would be periodic and coherent.

4. The hotspot, where the accretion stream meets the disk. Pringle (1977) shows that sufficient energy is available at the hotspot to power the observed hard X-ray emission, and that the temperatures of shocks in the hotspot will be of order those observed. Pringle then goes on to argue that these shocks will be hidden by the large absorbing column of the accretion stream itself. This argument has been used to rule out X-ray emission from the hotspot, despite the demonstration that these X-rays must be generated. If the visibility of these X-rays depends on the geometry chosen, then the
hotspot is a possible site of hard X-ray production. The absorption described by Pringle will be phase dependent, providing a natural explanation of the observed modulation.

2.6.2 Polars

Polars have qualitatively similar X-ray spectra to the non-magnetic systems. Optically-thick emission is seen in soft X-rays (0.1–2 keV) and thin emission in hard X-rays (2–20 keV). This is not surprising because the temperatures are most strongly influenced by the mass accretion rate and the nature of the compact object; the accretion geometry is less important. The effect of quasi-radial accretion (Sect. 2.2.2) is to raise the temperatures of both components by a factor of a few; since the flow is collimated by the magnetic field and accreted at close to the free-fall velocity \( v_{ff} > v_{Kep} \). In general, soft as well as hard X-ray components are observed in all systems at all accretion rates, unlike non-magnetic systems. It is not clear whether this is just because the temperature of the soft component is higher in polars, moving all systems up into the range of our detectors; or because there is a second source of luminosity for the soft component in AM Hers (below).

Figure 2.9 shows the broad-band spectrum of VV Pup, one of the first AM Hers to be identified. It can be seen that the unobservable range in the EUV (0.01–0.1 keV) covers a large part of the luminosity of the soft component. Thus the relative importance of the two components and the total luminosities of AM Hers are rather uncertain. Ultraviolet observations reveal strong emission, but the spectra are too soft to be the tail of the soft X-ray emission (assuming a black-body form; Raymond et al., 1979; Raymond et al., 1995).

Watson (1986) reviews the “standard” model of X-ray emission by magnetic cataclysmic variables, which is illustrated in Fig. 2.10. The accretion stream suffers a strong shock close to the white-dwarf surface, and is heated to hard X-ray temperatures \( (kT \approx 10 \text{ keV}) \). The post-shock settling flow cools predominantly through competing thermal bremsstrahlung (hard X-rays) and cyclotron (IR/opt/UV) emission processes. The soft X-ray component is emitted from the heated surface of the white dwarf around this region. The cooler ultraviolet flux is probably emitted from much larger region surrounding this. Our inability to fit the ultraviolet and soft-X-ray spectra with the same model, illustrates the uncertainty in the luminosity carried by the lost EUV flux.

This simple picture clearly limits \( L_{\text{soft}} / L_{\text{hard}} \) to unity. Though hard to constrain, the luminosity of the soft component is often shown to exceed that of the hard component (the so-called soft excess; e.g. Ramsay et al., 1994). King & Watson (1987) prefer to think of this
as a hard X-ray deficit, since without the high-luminosity soft component we would think these systems under-luminous when compared with the expected accretion rates.

Two further observations show conclusively that the bulk of the soft X-rays must be fueled by accretion separate from that responsible for the hard X-rays. The first is that flickering in soft X-ray light curves is stronger than, and only weakly correlated with, the hard X-rays (Watson, King & Williams, 1987). The second is the soft X-ray mode changes seen in several systems (Osborne, 1988). Between different modes the soft X-ray light curves can change radically, even moving 180° in phase, but with no apparent effect on the hard X-rays light curves. Both observations are incompatible with the idea that the soft X-rays are a reprocessed fraction of the observed hard X-rays.

Kuijpers & Pringle (1982) proposed a solution to this problem, which has been extended by Hameury & King (1988) and Frank, King & Lasota (1988). Essentially, if part of the accretion flow is made up of dense “blobs”, these can penetrate the surface of the white-dwarf and deposit the bulk of their energy at large optical depths. The post-shock hard X-rays will then be thermalised and emitted as soft X-rays.

This decoupling of the two components clearly explains the observed luminosity ratios
and the lack of correlated flickering. It has not been fully appreciated that it also explains the soft X-ray mode changes. Diffuse material in the accretion flow will be threaded by the magnetic field more quickly than the blobs, which allows a phase separation of the flow based on "blobiness". In the geometry shown in Fig. 2.4, diffuse and blobby material fall to the same magnetic pole. However, if the density of the blobs (and/or the accretion rate) increases, the flow can penetrate further into the magnetosphere before threading. The result will be something like Fig. 2.11, where the diffuse material is threaded first and accreted at one pole, emitting hard X-rays and some soft X-rays. The blobs are threaded later, and accreted at the other pole, giving rise to soft X-rays only. A switch between the geometries of Figs. 2.4 and 2.11 would be observed as a soft-X-ray mode change.

2.6.3 Intermediate polars

Intermediate polars are all hard X-ray sources (e.g. Norton & Watson, 1989), but no soft components had been observed until the discovery of RE 0751 in the ROSAT WFC survey (Chap. 4). It is not clear if the lack of soft X-rays is due to low temperatures resulting from
Introduction to cataclysmic variables

Figure 2.11: The accretion geometry of the system shown in Fig. 2.4, but with a higher accretion rate, and/or more blobby stream (plotted at different orbital phase). The figure was produced with a program written by A.P. Beardmore.

a larger accretion region (Norton & Watson find $\sim 0.25A_{\text{wd}}$), or because of absorption by the infalling material, which is seen to be considerable in hard X-ray spectra (e.g. Norton & Watson and Rosen, Mason & Córdova, 1988).

One would certainly expect strong soft emission from intermediate polars. King & Lasota (1990) use the results of Norton & Watson to show that the measured luminosities are below those expected from the evolutionary models of Hameury et al. (1988). Models predict an increase in accretion rate with period, which is observed in non-magnetic systems (through ultraviolet disk emission) but not in intermediate polars, where the EUV and X-rays must dominate. King & Lasota conclude that the bulk of the accretion luminosity must lie unobserved in the EUV.

2.6.4 Summary

All cataclysmic seen as hard X-rays sources (2–10keV), but in all three sub-classes this flux is under-luminous when compared with simple predictions of the X-ray flux (polars: King & Watson, 1987; intermediate polars: King & Lasota, 1990; non-magnetic cataclysmic
variables: Van Teeseling & Verbunt, 1994). In both intermediate polars and non-magnetics the deficiency is seen to increase with accretion rate.

In AM Her the missing luminosity is seen in the form of an over-luminous EUV/soft-X-ray component. Similar components may still explain the missing luminosity in the other systems; thus knowledge of the EUV spectrum of cataclysmic variables is central to our understanding of their energy balance.
Chapter 3

The ROSAT Wide Field Camera and the all-sky survey

The UK Wide Field Camera, mounted aboard the ROSAT satellite, carried out the first all-sky survey in the extreme ultraviolet. In the initial survey analysis three hundred and eighty two sources were detected at high significance, a thirty-fold increase in the number of known extreme-ultraviolet emitting objects. The majority of these objects were found to be white-dwarf and late-type stars, but the list also includes seven extra-galactic objects and eighteen cataclysmic variables. A full source list is published in the Wide Field Camera bright source catalogue (Pounds et al., 1993). In this chapter I introduce the Wide Field Camera and the survey, discuss the development of a procedure to reduce light curves from the survey database and present the results of the testing of this reduction method. In the following chapters I present the observations of all cataclysmic variables detected in the WFC survey.

3.1 The first all-sky EUV survey

The Röntgensatellit (ROSAT) is the result of a collaboration between Germany, the United Kingdom and the United States. It consists of two instruments, the large German X-ray telescope (XRT) and the smaller UK EUV telescope (the WFC). The telescopes are coaligned and operated together, sharing spacecraft power supplies and data handling facilities. Figure 3.1 is a schematic representation of the ROSAT spacecraft.

The primary objective of the mission was to carry out a survey of the entire sky in soft X-rays and the extreme ultraviolet; the soft-X-ray survey being the most sensitive survey to date (by several orders of magnitude), and the EUV survey being the first at those wavelengths.
The bandpasses of the two instruments overlap, and span the range 50–2500 eV (in survey mode). Pre-launch estimates of the number of EUV sources to be discovered were complicated by the uncertainty in the local HI distribution, so predictions ranged between $10^3$ and $10^4$, while it was expected that the XRT would catalogue approximately $10^5$ soft-X-ray sources.

In this thesis I discuss the EUV survey as it relates to cataclysmic variables. A significant fraction of the accretion-released energy, for all classes of cataclysmic variable, is thought to be radiated as EUV photons, and the spectra of AM Her systems in particular are known to be dominated by emission in the EUV. Given this, the first survey of the EUV sky clearly has the potential to identify new cataclysmic variables, which should be among the brightest sources. In addition, for sources over the whole sky, the WFC survey can constrain the EUV spectra and measure variability on timescales of hours to weeks.

3.1.1 The ROSAT Wide Field Camera

The WFC is a grazing incidence telescope with three nested Wolter-Schwarzschild Type I, gold-coated aluminium mirrors and two curved micro-channel-plate detectors (one redundant). Scattered solar radiation is excluded by baffles mounted in front of the mirrors, and background electrons are deflected away from the focal plane detector by a magnetic diverter system. The instrument also has two particle detectors which protect the focal plane detector by switching it off during passages of the South Atlantic Anomaly and the auroral zones. Figure 3.2 is a cutaway diagram of the WFC, showing its major subsystems.

Since micro-channel plates have little energy resolution the WFC is equipped with a filter wheel. This has eight filters, two calibration and six science filters. The calibration filters consist of a narrowband ultraviolet filter for use with the ultraviolet calibration system, and an “opaque” filter which was intended to be used to determine the particle component contribution to the WFC background. Of the science filters, two are specifically designed for pointed observations (P1 and P2), and the other four consist of two redundant pairs of filters which are used in both survey and pointed modes (S1a/S1b and S2a/S2b). Figure 3.3 shows the overall energy response of the WFC with each of these science filters. It can be seen that the filter responses span the full range of the EUV; with the survey filters towards the hard end of the waveband where the effect of interstellar absorption is least severe.

The properties of the two survey filters are also tabulated below. The S1 filter has the hardest response. The gentle drop of area with energy is due to the response of the mirrors, while the two absorption edges are of Boron and then Carbon. The S2 hard response is
Figure 3.1: Schematic representation of the ROSAT spacecraft.

Figure 3.2: Cutaway diagram of the UK Wide Field Camera (WFC).
Figure 3.3: The effective area of the WFC with each of the four science filters. The inset panel shows the survey filters, S1a and S2a, on linear energy and area scales.

cut-off by Beryllium and the soft response of both filters is controlled by the carbon content of the Lexan. The following table shows the bandpass of each filter at 10% of peak efficiency.

<table>
<thead>
<tr>
<th>Filter</th>
<th>Material</th>
<th>Bandpass(eV)</th>
<th>Bandpass(Å)</th>
<th>Mean energy(eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>C/Lexan/B</td>
<td>90–206</td>
<td>60–140</td>
<td>124</td>
</tr>
<tr>
<td>S2</td>
<td>Be/Lexan</td>
<td>62–110</td>
<td>110–200</td>
<td>90</td>
</tr>
</tbody>
</table>

The Wide Field Camera has a field of view (FOV) of 5°, an angular resolution which falls from ~ 1' at the centre of the field to ~ 3' at the edge, and it has a geometric area of 456 cm². Sims et al. (1990) provide a more detailed description of the WFC. The XRT is described by Trümper (1984), and its focal plane instrumentation by Pfeffermann et al. (1987).

The satellite was launched successfully on a Delta II rocket from Cape Canaveral on June 1st 1990. The orbit is circular with an inclination of 53° and an altitude of 580 km.
3.1.2 Survey method

During the survey the sky was scanned by rotating the spacecraft such that the telescopes always pointed away from the Earth. The spacecraft solar panels must be kept within $\sim 12^\circ$ of the sun, so the scan path was orientated to lie in the plane of the Earth's night-day terminator. The resulting scan path was a great circle of the sky which passed over the ecliptic poles, and advanced by $\sim 1^\circ$ per day to follow the night-day terminator. Since the scan path was not in the plane of the spacecraft orbit, the precession of the orbit made it necessary to reverse the scan direction every thirty-three days to avoid Earth pointing.

The $1^\circ$/day advance in the scan path meant that the whole sky was scanned in six months, and that, since the WFC has a FOV of $5^\circ$, all sources were scanned for at least 5 days. The coverage increases inversely with the cosine of the ecliptic latitude of a source, so sources at the ecliptic poles remained in the scan path for the full six months of the survey.

In this scan method each point in the great circle is observed once per satellite orbit, $\sim 96$ min, the duration of the scan of any particular point depending on its path across the FOV of the telescope. As the scan path advances, a source first cuts the edge of the FOV and is scanned at low exposure. The exposure rises to 80 s per spacecraft orbit when the source is passing through the centre of the FOV, and then drops again to zero as the FOV advances past the source.

Figure 3.4 shows exposure profiles for two objects observed in the WFC survey, one at high and one at low ecliptic latitude. The difference in total coverage between these objects, and the rise to maximum exposure in each are obvious.

Also obvious from these profiles are gaps in coverage. These are caused by passages through the South Atlantic Anomaly and the north and south Auroral Horns when the focal plane detector is switched off to protect it from the enhanced charged particle background. Some passes of usually low exposure can be caused by a switch on/off during a survey scan; while passes with unusually high or low exposures are also observed due to the minor spacecraft slews used to correct the scan path.

The two survey filters, S1 and S2 (above), were swapped daily, ensuring at least two measurements of each source with each filter. This is helpful when trying to measure filter ratios without contamination from variability. The exposure points in Fig. 3.4 are marked as either S1 or S2.

Finally, it is worth considering the effects of this scan method on observations of cataclysmic variables. The 96 min sampling is a problem for AM Her systems since they have
Figure 3.4: Effective exposure profiles for two objects observed in the WFC all-sky survey. Note the increase to maximum exposure as the objects' path across the detector approaches the centre; also the differences in total coverage and data losses between the two observations. S1a points are marked as circles, S2a as triangles.

orbital periods typically in the range 80 — 250 min. This usually prevents direct detection of the orbital period which is instead observed through its beat with the sampling period. The non-simultaneity of S1 and S2 measurements is potentially a problem as cataclysmic variables are so variable; making it difficult to derive filter ratios free of contamination from variability. The scan method does have an advantage, however, in that the exposure is spread over a long period, up to one month. This provides the opportunity to monitor cataclysmic variables over a much longer period than is usually possible at X-ray wavelengths, allowing study of dwarf novae through outbursts, and of the stability of AM Her light curves.

3.1.3 Execution of survey

The ROSAT all-sky survey began on July 30th 1990, and ninety-six percent of the sky had been covered by January 25th 1991. On this day spacecraft attitude control was lost and instruments were damaged, probably when the Sun entered the telescope FOV. The survey
The ROSAT WFC all-sky survey was completed in August 1991, albeit at a lower sensitivity, by employing the redundant S2 filter.

The background during the survey was highly variable, but for much of the ROSAT orbit was of order 20 count s$^{-1}$ across the FOV, which is consistent with that predicted, and well below the telemetry saturation limit of 200 count s$^{-1}$. In the S1 filter the background consists largely of charged particles, whilst S2 has extra background from scattered solar photons (geo-coronal background). A third and unexpected background component has also been identified, which is strongly correlated with the velocity-view angle of the satellite (West, 1994). This has been attributed to a spacecraft glow effect, similar to that observed in other missions (e.g. the Space Shuttle).

The final effective exposure for sources, in each filter, ranged from ~ 1.5 ksec at the ecliptic equator to ~ 20 ksec at the poles. Useful data were collected for ~ 74% of each day, with losses due to detector switch-offs during periods of high background. A further 10% of time was lost due to various hardware problems.

### 3.1.4 Results

The entire survey database was searched for point sources with two independent algorithms, backed up with manual inspection of all images. Three hundred and eighty four sources were detected with high confidence in this initial analysis, which is published as the WFC bright source catalogue (the “RE” catalogue) by Pounds et al. (1993). Two of these sources have since been found to be spurious detections (RE 0516 and RE 0521). Most of the sources in the catalogue have been optically identified and there are 181 late-type stars, 119 hot white dwarfs, 17 cataclysmic variables and 7 active galaxies.

Work is continuing on a more extensive analysis of the survey database, employing an improved attitude solution, exposure correction and source-searching algorithm. This new catalogue (“2RE”) contains 25% more sources and an increased proportion of detections of sources in both filters. The most recent account of this work is given by McGale et al. (1994). Barber et al. (1995) present a comparison of this catalogue with the bright source catalogue of the second EUV sky survey, carried out with NASA’s EUV Explorer mission.
3.2 Reduction of survey light curves

The WFC survey was designed to scan the EUV sky for new sources and not for detailed timing or spectral analysis of individual objects. Problems arise when trying to use the survey database for such studies, but the importance of EUV emission from cataclysmic variables has led to some considerable effort being spent optimising the survey reduction system.

In this section I discuss the problems associated with timing studies with the WFC survey database and present the solutions employed in the work for this thesis.

3.2.1 Timing studies with the survey database

The scan method employed during the survey is described in Sect. 3.1.2. This results in sources passing along a chord across the detector once per satellite orbit (~ 96 min). These passes last ~ 10 s at first as the chord cuts the edge of the detector, and increase to 80 s once the chord has advanced to the centre of the detector. The exposure in each pass then drops again to 10 s as the source gradually leaves the FOV. This process takes at least five days, and lasts for the whole six months of the survey for a source near an ecliptic pole.

Figure 3.5 illustrates the situation. This image, in detector co-ordinates, includes all the events counted while the brightest survey source (HZ 43) was in the FOV and the S2a filter in use. The scan path lies vertically in this image and has advanced across the detector over ~ 5 days, leaving broad bands of source counts when the S2a filter was in use. The S1a source counts would lie in the place of the light bands which here contain only background counts. In the dark bands one can see strips of events from individual scans of the source. These are most obvious at the centre of the detector where the point spread function is sharpest.

The following is a list of the problems presented by timing analysis with the WFC survey database.

- The response of the WFC to a point source varies considerably across the field of view (FOV). The point spread function (PSF) and vignetting are functions of off-axis angle, whilst the quantum efficiency of the detector varies considerably, and in a complex manner, across the detector. The PSF especially is not well known. It changes shape as well as size towards the edge of the FOV, and PSF corrections are sensitive to any small attitude errors remaining in the survey database. The added complication for survey data reduction is that the effects of these processes, for each scan, are integrated along a different chord of the detector.
The detector efficiency is a function of time as well as of position.

Determining the background with an annulus around the source is not appropriate in the survey. This annulus would sample a different strip of the detector than the source region, implying different detector efficiency, vignetting and exposure corrections; exacerbating systematic errors in these corrections. This problem would be particularly serious towards the edge of the detector.

The short exposure in individual passes results in very low numbers of counts, even for relatively bright sources. Count rates and confidence intervals must be calculated without the approximation of Gaussian statistics. The usual method of rebinning to
increase the number of counts per bin is not possible here because the passes are so widely spaced it would result in an unacceptable loss of timing information.

- The orbital period of AM Her systems are uncomfortably close to the orbital period of ROSAT. This means that detection of the orbital period is usually through observation of the beat between these two periods. The orbital phase-averaged light curves can be reconstructed, but it is essential that all available timing information is retained. This leads to practical problems in that much existing software uses even-length time bins. Retaining all timing information with this software would require enormous and largely empty files.

- There are a large range of source count rates and background levels in the survey database. In order to maximise signal to noise it is necessary to optimise the size of source and background accumulation regions. This must be done individually for each source, ideally for each scan of each source, since cataclysmic variables are highly variable.

- Given the large number of sources for which timing information is required, it is important that this data reduction system be automated. It is also desirable to test for variability and periodic signals in every source as part of this automatic process. These tests must remain statistically sound for very low count rates.

Some of these problems have been solved within the standard WFC data reduction software; provided by the ROSAT WFC consortium. For other problems I have had to add my own software. In the following section I describe the solutions I have applied to each of the above problems, concentrating on those not dealt with by the standard software.

3.2.2 Reduction method

Source accumulation region

The PSF of the WFC is approximately axially symmetric, so I use a circular source accumulation region. I determine the optimum radius for this region numerically, calculating a signal to noise ratio for given background and source count rates at many points along the radial PSF.

This is a simple calculation, but the choice of inputs is more complex. Ideally, for a variable source, an optimum accumulation radius should be calculated for every bin in the light curve.
The ROSAT WFC all-sky survey

The source count rate will be different in every bin and the point spread function will be different since each survey pass samples a different path across the detector. In practice I chose not to calculate a different radius for each bin because this would not make efficient use of existing software and because the uncertainty in the spatially resolved PSF is too great for this to provide a significant advantage. The uncertainties in the PSF are discussed below.

For all the survey light curves presented in this thesis the source accumulation radius was optimised to the mean count rate of the source, and to the mean background count rate. The ‘survey averaged’ PSF was used (see below). These mean count rates were determined using a standard accumulation region radius of 3' and a large background annulus. For very weak sources the optimum radius is ~ 2.5', which increases to 20' for the brightest source observed in the survey (HZ 43). For cataclysmic variables, values in range 3' - 6' are typical.

Background determination

A large annulus around the source is used for determining the mean background used in the optimisation process described above, but this is not the best method for determining the background for the final light curve (Sect. 3.2.1). During a survey pass a large annulus will sample a different path across the detector than the small source circle and will suffer different vignetting and efficiency effects. For passes near the edge of the detector there is the added problem that the annulus will cut the edge of the detector before the source circle, resulting in inaccurate exposure determination.

To overcome these problems I use a large number of background regions (between 4 and 16, depending on the source circle radius), all of which are the same size as the source circle and are aligned along the scan path. In this way I ensure that the background is sampled by the same strip of the detector as the source, and that the exposure will be the same for source and background. Figure 3.6 illustrates a typical example.

Count rate corrections

There are five corrections that must be applied to raw counts from a source.

- Exposure correction
- Vignetting and filter transmission correction
- Correction for non-uniform detector efficiency across the FOV.
- Correction for gradual loss of detector efficiency with time.
Figure 3.6: Source and background count accumulation regions for a typical survey observation. The background circles are aligned along the scan path so that the same strip across the detector is used for source and background.
Correction for counts lost outside the source circle (PSF correction).

The exposure, vignetting and detector efficiency corrections are calculated by the standard WFC software. The limitation is that these factors are calculated for a point at the centre of the source circle, with no regard to its extent, and for a large circle (or a background annulus) the exposure correction will be wrong when part of the region extends beyond the edge of the detector. I have quantified the significance of this effect using simple geometrical calculations to determine the true exposures for a point, a circle and an annulus at different off-axis angles. My results show that this effect is important for extremely bright sources, such as HZ 43, where the optimum source circle radius is a significant fraction of the area of the entire detector; but that is negligible for cataclysmic variables, where the optimum source circles are much smaller (< 6'). Accordingly I make no correction for this effect in the light curves presented here.

The detector efficiency drop with time (Sect. 3.2.1) is well known from observations of HZ 43. The effect is small (~ 10% over six months) and no correction is made to the light curves presented here. Corrections are applied to count rates used for spectral constraints because the drop in efficiency was greater in S2a than S1a. This would otherwise lead to a small but systematic bias in spectral constraints.

The PSF correction is a little more complex and the situation is described by Sansom (1991). The PSF varies in size and shape across the detector, leading to a complicated function when integrated along a survey scan path. In her paper Sansom calculates a survey-average point spread function for several bright sources and finds that they are not the same. This is probably due to uneven sampling of the detector and possibly residual errors in the survey attitude solution which would act to broaden the PSF.

Given this uncertainty in the PSF it seems that individual, spatially resolved corrections for each light curve bin are not justified. This is supported by the lack of any obvious rollover at the ends of the light curves, which would be expected if the broadening of the PSF at the edge of the detector had a significant effect on the count rates. For the light curves presented in this thesis I simply apply a single correction to each light curve, derived from Sansom’s survey-average PSF; ensuring a correct mean count rate.

Timing information

The traditional approach to light curves in X-ray astronomy is to sort events into constant duration bins. The mass of data analysis software already available for this data type makes
The ROSAT WFC all-sky survey

it an attractive option for the WFC survey light curves, but the sparseness of the survey sampling presents problems.

The obvious storage method is to bin events into ROSAT orbit bins (96 min), with survey scans (up to 80 s duration) situated at the centre of each bin. The exposure time in each bin is stored separately. This approach would be perfectly adequate for all applications if the survey scans were strictly periodic. Unfortunately they are not. The survey scan is controlled by an onboard feedback system which makes discrete corrections to the satellite attitude. The result is that, whilst the mean scan period equals the satellite orbital period, individual scan periods can be several hundred seconds longer or shorter than this. A several hundred second error in the timing of the scan pass within each bin is not acceptable since it prevents the reconstruction of phase average behaviour for periods close to the scan period.

The solution to this problem is to calculate an independent measurement of the timing of each survey scan. These timings can be used when the full timing information is required, e.g. for the reconstruction of phase averaged AM Her light curves; while the simple evenly binned light curves and existing software can be used when this precision is not required, e.g. for studies of dwarf-nova outbursts.

We can make this independent timing measurement by searching the WFC attitude files for times when the source is within the field of view. This method, although simple, was not used because of the practicalities of accessing these data. Instead I sort 'event data sets', which are simply lists of photon arrival times within the source accumulation region. These times are searched for groups of events indicating the precise time of each scan. The timing error from this method is twice the exposure, less the interval between the first and last photon time; close to the nominal timing accuracy of the survey. The only shortcoming of this approach is that no measurement can be made when zero events are detected during a pass of a source. In these cases a less accurate determination of the pass time is made from a second event data set covering a larger area of sky.

A heliocentric correction is made to all the pass times calculated by this method. No correction is made to the one orbit binned light curves since the uncertainty in the position of the pass within the orbit is greater than the heliocentric correction.

Low number counting statistics: a Bayesian approach

I have already pointed out that very few counts are observed during a typical survey pass, and that the sparseness of the survey scans makes rebinning inappropriate. It is necessary then
The ROSAT WFC all-sky survey

to tackle the complex and difficult problem of confidence intervals in the case of low numbers of counts and a non-zero background. Luckily, this problem has already been considered in an astrophysical context in an excellent paper by Kraft, Burrows & Nousek (1991). In this paper the authors consider two approaches to the problem, ‘classical’ and ‘Bayesian’, and argue that

"...the Bayesian definition of confidence intervals reflects common astronomical usage better than the classical definition does, and that the Bayesian method provides a more intuitively satisfying result".

They also describe several commonly used, but incorrect methods of determining confidence intervals.

The classical definition of confidence intervals is that they reflect the fraction of observers who's measured confidence intervals include the true flux. Thus the classical approach makes a statement about the population of observations. The Bayesian approach turns this round and uses the measured data and a priori knowledge of the physical system to constrain the source population. In other words, rather than asking what fraction of observers would obtain confidence intervals that include the true rate, the Bayesian approach determines the probabilities that sources of different flux could produce the observed rate. It is tempting to be suspicious of statistics that assume a priori knowledge, but Kraft, Burrows & Nousek (1991) assume only that the source flux is non-negative; hardly controversial. Far from being a weakness, this is actually the major advantage of this approach because it allows an intuitive interpretation of the case where the observed counts fall below the expected background level.

It is in these cases that the benefits of the Bayesian approach become obvious (i.e. the number of observed counts equals one or zero, or the number of observed counts is less than the expected number of background counts). For these cases the classical treatment gives an upper limit of exactly zero. This is not wrong within the classical definition of confidence intervals, merely unhelpful. The limits imply that the source count rate is such that most observers will observe zero counts. The Bayesian approach, on the other hand, never gives an upper limit of zero. It gives the probability that a particular source flux could have given zero counts; clearly a more intuitive treatment of upper limits. It also naturally produces a smooth transition between the upper limit and and detection cases; proving invaluable for WFC survey light curves where the individual scans are invariably hovering between the two
cases. For higher numbers of observed counts the classical and Bayesian approaches produce identical results.

For a more detailed discussion of the problem of confidence intervals in experiments with low numbers of counts I strongly recommend the paper by Kraft, Burrows & Nousek (1991). For completeness, I include a mathematical derivation of the Bayesian confidence intervals in appendix A. The confidence intervals presented in this thesis are calculated using software supplied by the authors.

Variability and periodicity testing

A typical approach to testing light curves for variability is to use the $\chi^2$ statistic to evaluate the significance of deviations from the mean level; i.e. to attempt to disprove the null hypothesis that the light curve is consistent with its mean level. In this context $\chi^2$ is given by

$$\chi^2 = \sum \left[ \frac{x_i - \bar{x}}{\sigma_i} \right]^2$$

(3.1)

The same approach is often made to periodicity searching, except that here the light curve is first folded into phase bins at a trial period. After folding, a significant deviation of phase bins from the mean level indicates the presence of a coherent period (Leahy et al., 1983).

This test is still widely used, though Davies (1990) & Davies (1991) has shown that the $\chi^2$ test is only valid in this context for large sample sizes; i.e. at least ten observations in each phase bin. This is not generally the case, especially for unevenly sampled data, and Davies goes on to propose a new test statistic, the L-statistic, which is valid for all sample sizes. He also shows that the L-statistic provides a more sensitive test for periodicity than $\chi^2$. The L-statistic is given by

$$L = \frac{(N - M)\chi^2}{(M - 1)((N - 1) - \chi^2)}$$

(3.2)

where $N$ is the number of observations and $M$ is the number of phase bins. $\chi^2$ is written $\chi^2_Y$ because the L-statistic is valid even where $\chi^2_Y$ is no longer distributed as $\chi^2$ (e.g. where $N \neq M$). The L-statistic has an $F$ distribution with $(M - 1)$ and $(N - M)$ degrees of freedom, so the significance of periodicity detections can be tested easily. I have calculated the L-statistic for all possible trial periods for each EUV source as part of the automatic data reduction process.

Unfortunately, both the $\chi^2$ and L statistics assume normally distributed data, which is not a valid assumption for WFC survey scans. I've largely ignored this problem for periodicity
testing since the survey scans are binned in phase before the statistic is calculated, although for period detections which are either marginal or of particular scientific interest I confirm the significance of the detection through numerical simulations (e.g. Sect. 5.1).

The variability test, of course, provides no opportunity for rebinning, and the problem of low count rates must be tackled head on. The simple $\chi^2$ test is hopelessly inadequate for the survey light curves, since the number of counts in each pass can easily be as low as zero (above). In these circumstances $\chi^2$ is highly insensitive to variability since it takes no account of the asymmetric nature of the confidence intervals. From the shape of the Poisson distribution it is clear that the lower limits are more tightly constrained than the upper limits. Thus, when inappropriately assuming Gaussian statistics one overestimates the significance of data points below the mean and underestimate those above, underestimating the weighted mean and finding that all light curves appear variable.

The solution is to use a statistic equivalent to $\chi^2$, which takes non-Gaussian confidence intervals into account. Unfortunately, to the best of my knowledge, no such statistic has been formulated and I have been forced to define my own statistic and determine its distribution through simulations.

To do this I have taken the simplest approach available, and modified the $\chi^2$ statistic to use the Bayesian confidence intervals discussed above. This new statistic I have called the $P$-statistic, and defined as:

$$P = \sum \left( \frac{x_i - \bar{y}}{A_i} \right)^2$$

where $A_i = \left\{ \begin{array}{ll} S_{\text{max}} - x_i & \text{if } x_i < \bar{y} \\ x_i - S_{\text{min}} & \text{if } x_i \geq \bar{y} \end{array} \right.$

(3.3)

This is simply $\chi^2$ with the Gaussian sigma replaced by a two sided (asymmetric) 'sigma'. $S_{\text{min}}$ and $S_{\text{max}}$ are the upper and lower Bayesian confidence limits, derived in appendix A. The advantage of this approach is that in the regime where $\chi^2$ is valid, $P$ equals $\chi^2$. This is because the 68% Bayesian confidence intervals equal the Gaussian standard deviation when the count rate is high. Where $\chi^2$ is not valid I believe the $P$-statistic provides a better measure of variability since it is based on a sound estimate of the significance of deviations from the mean. Ideally each deviation from the mean should be afforded its correct Bayesian weight, but this calculation would be far more complicated and costly of computing resources so I have retained this slightly messy idea of an 'asymmetric sigma'.

Clearly, for this statistic to be of any use, I have to derive its distribution through numerical simulations. These simulations have been carried out for two cases. The first is the general case, where the median and upper limits of the distribution are calculated as a function of
mean source and mean background counts per bin; the second is tailored specifically to WFC survey light curves. The method and results are described below, while tables of the general case are reproduced in appendix B.

Numerical simulations

Large numbers of simulated light curves have been calculated. Each has constant mean source (S) and background (B) count rates, with Poissonian noise simulated after Press et al. (1986). The simulated observed light curve (O), is background subtracted with B to give the simulated measured light curve (M); note that I subtract using the mean background, i.e. I assume the error on the background determination is negligible. The ‘Gaussian’ error on M was taken as \( M \sqrt{O}/O \), except when \( O = 0 \) where the error was set to \( M/\sqrt{O} \); as is the case in the standard WFC software. This is not statistically correct, as the true ‘classical’ error is zero (above), but is necessary in order to allow a \( \chi^2 \) value to be calculated (otherwise zero count bins attain infinite weight). Of course, once this little trick has been applied the resultant statistic is not \( \chi^2 \), but I will persist in calling it \( \chi^2 \) because, as this is the only “\( \chi^2 \)” value that can ever be calculated for WFC light curves, it must be the statistic used by other authors claiming to use \( \chi^2 \). In fact, this trick has a similar effect as using Bayesian errors, but less successfully and without the statistical validity of the Bayesian approach. The Bayesian errors are calculated as described above.

The \( \chi^2 \) and \( P \) statistics have been calculated using these errors, and a large number of simulated light curves have been used to determine the \( \chi^2 \) and \( P \) distributions as functions of S and B. One thousand light curves are simulated for each count rate point. The results show clearly that the \( \chi^2 \) test overestimates variability when applied to low count rate light curves. The left-hand panels in Fig. 3.7 show how the true \( \chi^2 \) distribution deviates from the analytical distribution as the count rate drops into the Poisson regime. To some extent, these simulations can be used to calibrate the \( \chi^2 \) test so that it can be applied to non-Gaussian data, although the inappropriate errors bars are likely to make this an insensitive test for variability. The right-hand panels of Fig. 3.7 show the distribution of the \( P \)-statistic. It can be seen that this is distributed as \( \chi^2 \) in the Gaussian regime, and is much flatter than \( \chi^2 \), dropping away as the count rate becomes so low that little variability information is left. The \( P \)-statistic is also less sensitive to the background level (indicated by the vertical dotted lines), as the background fluctuations are treated properly by Bayesian statistics. The 95%
Figure 3.7: P-statistic and $\chi^2$ distributions for low count rates. The central line in each plot is the median of the distribution; the upper and lower lines are the 95% and 5% limits respectively. Each point is the result of 1000 simulated constant light curves, with a constant background level shown by a vertical dotted line. The horizontal dotted line shows the 95% limit for the $\chi^2$ distribution, valid for high count rates.
upper limits of the $P$-statistic distribution are tabulated in Appendix B as functions of source counts/bin, background counts/bin and number of degrees of freedom.

These general simulations cannot be applied to the WFC survey light curves because the exposure in each scan is not the same; i.e. each bin has different mean source and background levels. For the survey light curves I have calculated a second set of simulations, in the same manner as above, but with the addition of a simulated WFC exposure profile. The simulation of this profile is trivial, it is simply length of a chord of circle taken at regular radius steps.

The results of this second set of simulations are similar to the first, but are now calculated in counts/sec rather than counts/bin and are appropriate to the WFC survey. Figure 3.8 shows the results of these simulations. Again, each point in each of these graphs is calculated from one thousand simulated light curves.

In the following sections the 95% upper confidence bound to the $P$-statistic distribution is used as a threshold for the test of variability. $\chi^2$ and $P$ statistic values were calculated for all sources as part of the automated light curve reduction method.

### 3.3 Testing of reduction method

To test the data reduction system described above I have made light curves of twenty nine white dwarfs. White dwarfs are the obvious choice because they are numerous, bright EUV sources, and are the only point sources in the WFC survey that are expected to be constant. Supernova remnants should also be constant sources but do not make good controls because they are faint and extended, posing background subtraction problems beyond the scope of this thesis.

Testing with these constant sources enabled me to study the level and nature of instrumental noise in the system, and thus to develop both a reliable variability test and to separate noise from signal in the light curves of cataclysmic variables. Of course, the assumption of non-variability of white dwarfs must be challenged as these are the first extensive observations in the EUV.

The white dwarfs used here are from the sample used by Barstow et al. (1993). These objects cover a broad range of source and background count rates and have been studied extensively.
Figure 3.8: As Fig. 3.7, except the light curves have been simulated with a typical WFC exposure profile. The 95% upper limits of these distributions can be used as detection thresholds for variability in WFC survey light curves.
### Table 3.1: White dwarfs used to test data reduction method

<table>
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<tr>
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<td>10.7</td>
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<td>77 ± 10</td>
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<td>578 ± 24</td>
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<td>PG 1234</td>
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<td>399 ± 18</td>
<td>7.7</td>
<td>730(35)</td>
<td>400(35)</td>
<td>4481 ± 51</td>
<td>4443 ± 48</td>
<td>13.1</td>
<td>46(38)</td>
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<td>1175 ± 27</td>
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<td>10994 ± 84</td>
<td>1102 ± 75</td>
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<td>BZ 43</td>
<td>10904 ± 84</td>
<td>1102 ± 75</td>
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<td>3.0</td>
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<td>52 ± 7</td>
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<td>1123(808)</td>
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<td>2.5</td>
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<td>670 ± 23</td>
<td>702 ± 24</td>
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<td>2.6</td>
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<td>28 ± 6</td>
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<td>4240 ± 52</td>
<td>4050 ± 48</td>
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<td>56(40)</td>
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</table>
3.3.1 Count rates

Table 3.1 shows, for each white dwarf, the mean count rates calculated during the initial survey analysis and those calculated by my data reduction system. These are plotted against each other in Fig. 3.9.

Whilst there is clearly an excellent correlation, there are a worryingly large number of sources for which the mean count rates are not the same as the catalogued value. This is particularly serious when one realises that the values should agree more closely than the errors imply as both methods use the same events (i.e. they are not independent). To investigate this effect I looked in detail at the source KPD 0631, which exhibits the largest discrepancy. I found that the difference arises in the exposure correction, which is now calculated differently in the standard WFC software than at the time of the initial survey analysis. Since the more recent method is believed to be superior the count rates presented here should be favoured over the catalogued values. It should be noted that a significant proportion of the count rates published in Pounds et al. (1993) must be inaccurate.

3.3.2 Excess variability

Figure 3.10 is a plot of variability against count rate for the white dwarfs listed in Table 3.1. The measure of variability is the reduced $P$-statistic divided by the 95% confidence upper limit for the $P$ distribution; calculated in Sect. 3.2. A point lying above unity can be considered to indicate variability with greater than 95% confidence.

Most light curves of white dwarfs don't exhibit significant variability, but nearly a quarter do. This variability seems to fall into two categories. There are a number of sources, lying well above the detection threshold, for which the variability is obvious by eye and usually due to a small number of outlying points. For the rest, the variability exhibits itself as gentle dips or ramps in the light curves. For this second category the significance of the variability is correlated with count rate (Fig. 3.10).

Figures 3.11 & 3.12 show the two types of variability. The top panel of Fig. 3.11 shows V471 Tau, which is a known eclipsing binary system (Barstow et al., 1992). The eclipses are obvious and periodic, as would be expected. The next three panels show the other objects that form the strong variability category. These exhibit similar dropouts, but these sources are not known to be eclipsing binaries. Dropouts like this have been seen in other objects (notably Capella) and are are known to be caused by errors in the spacecraft attitude solution. The counts from entire scans can be assigned the wrong sky co-ordinates and have even resulted
Figure 3.9: Mean count rates of WFC survey light curves plotted against the count rates published in the WFC bright source catalogue (Pounds et al., 1993). The top panel shows the fractional residuals with respect to the x=y line in the bottom panel.
Figure 3.10: The top panel shows a variability measure (see text) against count rate for the twenty-nine WDs listed in Table 3.1. Circles represent S1a points, triangles are S2a. Points above unity indicate light curves that are variable at greater than 95% significance. The bottom panel shows the same data on a linear scale. I use the second dotted line as an empirical detection threshold for 'true' variability in the WFC survey database.

in false source detections in the WFC bright source catalogue (RE 0521 and RE 0516). A poor attitude solution is the most likely explanation of the variability in the light curves of these three objects.

The cause of the less spectacular category of variability is not so obvious, in fact the cause remains unknown. There are three possibilities: either the vignetting correction is wrong, the attitude solution is inaccurate, or some white dwarfs are truly-variable EUV sources.

First, let us consider the vignetting function of the WFC, which is determined through the survey observation of HZ 43; by far the brightest EUV source. The source is assumed to be constant and the vignetting determined from the coarsely binned detector co-ordinate image. The light curve of HZ 43 is shown in the top panel of Fig. 3.12. Unsurprisingly, since the survey is calibrated from this observation, the light curve appears constant. There are departures at the very ends of the observation, due to the exposure effect mentioned in
Figure 3.11: WFC survey light curves of the four white dwarfs found to exhibit highly significant variability (see text). S1a and S2a observations are plotted on the same panels; with S1a represented by circles and S2a with triangles. The lower panel for each object shows the exposure correction applied to the light curve. This is the correction for effective on-axis exposure, so includes the vignetting function of the instrument.
Figure 3.12: As Fig. 3.11, but for four objects exhibiting less spectacular but more enigmatic variability (see text).
Sect. 3.2, and there is a single departure just after the data gap at day ~ 1.2. This departure must be a computational effect since HZ 43 was assumed to be constant. It is most likely due to the coarseness of the vignetting grid and the need to interpolate across the HZ 43 data gap.

This method of vignetting correction is hardly ideal. Although HZ 43 is exceptionally bright, it does not provide enough counts for the vignetting function to be mapped as finely or as accurately as is desired. An all survey image (i.e. all events over the six months of the survey) reveals much substructure in the vignetting function not resolved by the HZ 43 observation. Unfortunately, this image can not be used for vignetting correction since most counts are background events which are not focused by the mirrors. The uncertainty in turning this image into a proper correction is too great.

It seems then that an inadequate vignetting correction may account for the excess variability observed in many white dwarfs. The exposure profiles of Fig. 3.12 include the vignetting function (the source of the asymmetry in the exposure profile), and it is worth noting that several features in these light curves seem to be associated with the vignetting function. Unfortunately it is impossible to test this hypothesis as the current correction is the best available.

Inaccuracies in the spacecraft attitude correction could also result in excess variability. Source events assigned the wrong sky co-ordinates could fall outside the source count accumulation circle and be lost. This effect can also be thought of as a point source function effect; sources which suffered regular small attitude errors would appear to have larger point source functions than the survey-average. Sansom (1991) saw some evidence of this, with the PSF of different sources varying considerably. However, for two reasons, I do not believe the excess variability to be due to inaccurate attitude information. First, I have made light curves of several objects with a range of source accumulation radii. This does not remove the variability effect. The effect is reduced, but only in line with the drop in signal to noise expected from the increased background count rate. Second, whilst the WFC database used here is known to suffer from some attitude errors, a more recent database (used for the “2RE” catalogue, see Sect. 3.1.4) has since been created with the final and best attitude solution. I have made a light curve of Sirius B from the new database, which suffers ramping as well as the drop outs discussed above, and have found that the light curve is essentially unchanged from the light curve presented here. So, whilst attitude errors are known to exist, they do not account for the excess variability effect.
A further possibility is that background count rates are not measured to sufficient precision. It is assumed here that background errors are negligible; both in the Bayesian-error calculations and the light-curve simulations. If this assumption were not valid, it would result in apparent variability.

It is also possible that the variability is due to a hitherto unsuspected effect, perhaps short timescale changes in detector efficiency, but no independent evidence has been found for such a process.

I conclude that the most important source of instrument induced variability is probably the vignetting function, and that uncertainty in this correction is of the order required to explain the excess variability effect. Lack of precision in background determination is another plausible process. The possibility remains however that the observed effect is due to true source variability.

3.3.3 Are white dwarfs variable EUV sources?

Given that instrumental effects can plausibly account for the observed variability, it is not possible to claim true variability in white dwarfs without further evidence. A correlation between variability and a physical parameter derived through independent observations might constitute such evidence; especially if a plausible mechanism can be proposed.

Some DA white dwarfs are known to pulsate. The opacity of partially ionised material is extremely sensitive to temperature, and partially ionised hydrogen in these stars causes the atmosphere to become unstable over a well defined range of temperatures. All the white dwarfs detected in the WFC survey are far too hot to have significant levels of neutral hydrogen, but one can hypothesise that a similar effect due to partially ionised heavy elements may cause a second instability strip in white dwarfs. If this is the cause of the variability in WFC survey light curves one would expect the variability to correlate with temperature and/or the presence of heavy elements in the atmospheres of these objects.

Barstow et al. (1993) study photospheric opacity in the same sample of white dwarfs as used here. They also tabulate optically and EUV/X-ray determined temperatures. These parameters are plotted with WFC variability in Fig. 3.13.

No correlation is seen with either temperature or photospheric absorption, so I must conclude that there is insufficient evidence to justify a claim of EUV variability in DA white dwarfs. This being the case I will assume the observed variability is an instrumental effect, and use the empirical variability threshold plotted in Fig. 3.10 for further work in this thesis.
Figure 3.13: White-dwarf EUV variability is plotted as a function of temperature (taken from Barstow et al. (1993)). Points above the dotted line indicate light curves that are variability at greater than 95% significance. Points marked as circles represent objects with significant opacity from heavy elements, while points marked as crosses represent objects without heavy element opacity (Barstow et al., 1993). There appears to be no correlation between variability and temperature or opacity.
Chapter 4

CVs in the ROSAT WFC all-sky survey

In Chap. 3 I describe and test a method for the reduction of ROSAT WFC survey light curves. I have used this method to reduce light curves of all known magnetic cataclysmic variables, and a subset of the non-magnetic cataclysmic variables. In this chapter I present and discuss these observations as they apply to the entire sample of cataclysmic variables.

In the following chapters I discuss observations of the individual classes in more detail. I have attempted to provide a summary of the full set of WFC-survey observations, but my discussion is naturally skewed towards those observations with which I have been personally associated.

4.1 ROSAT survey observations of CVs

The primary aim of the ROSAT mission was to search for new X-ray and EUV sources with unprecedented sensitivity and across the entire sky. This aim has been fulfilled in the field of cataclysmic variables; especially for AM Hers for which the sample has been more than doubled.

Seven new cataclysmic variables were discovered through the WFC survey; six AM Hers and one intermediate polar (see Sect. 4.2.1). Fifteen new cataclysmic variables have been discovered to date (summer 1993) through the XRT survey, though many others probably remain unidentified in the survey database. Beuermann & Thomas (1993) summarise the XRT discoveries, and Beuermann & Schwake (1994) study the new AM Hers in some depth. Among other results they note a correlation of hardsoft X-ray component flux ratio with magnetic field strength.

The WFC survey represents the first true EUV detections of any cataclysmic variables, since previous instruments had substantial X-ray responses (e.g. the EXOSAT LEIT's). The
WFC response, in survey mode, covers the range 60 – 124 eV which is divided in two by the survey filters (see Sect. 3.1.1). The softest of these two filters, S2a, provides a spectral measurement entirely independent of the ROSAT XRT.

Ninety-six percent of the sky was covered to nominal flux limits in both filters, yielding highly significant detections of nineteen cataclysmic variables (Sect. 4.2.1). A systematic search for all magnetic cataclysmic variables (Sect. 4.2.3) has yielded several weak detections and extended the source count analysis of Warwick et al. (1993) (Sect. 4.3). Figure 4.6 demonstrates that the useful timing information is available for all cataclysmic variables above a flux limit (Sect. 4.4), and this is used in Sect. 4.4.1 to search for cataclysmic variables among the unidentified EUV sources. In Sect. 4.5 I compare the EUV fluxes with catalogued optical magnitudes.

4.2 Source list

4.2.1 Bright source catalogue

Seventeen sources are listed as cataclysmic variables in the WFC bright source catalogue (Pounds et al., 1993). This is dominated by AM Her type systems and includes a third of AM Hers known before the launch of ROSAT. In addition, seven new cataclysmic variables have been discovered through optical follow-up observations of unidentified sources. Of these, six have been found to be AM Hrs and one to be a quite remarkable intermediate polar, REO751.

The seventeen sources are listed in Table 4.1, together with WFC count rates and visual magnitudes. Where sources were detected with just the S1a filter a 3σ upper limit to the S2a count rate is listed in the error column. All figures are taken directly from the bright source catalogue. Count rates from my analysis are presented in Table 4.4, and should be favoured in cases of discrepancy (Sect. 3.3.1). In Table 4.1 I include references to the discovery papers of the new cataclysmic variables.

Of the eleven previously cataloged objects listed, three are dwarf novae, one a nova-like variable and one an intermediate polar. All three dwarf novae are known to have been in outburst at the time of the WFC observation (Wheatley et al. (1995b), Ponman et al. (1995) and Chap. 7 of this thesis).

Notable among the new systems are RE1307+53, the shortest period AM Her and the
most distant; RE 1938–46 RE 0531–46 and RE 2107–05 (an eclipsing system) all have have orbital periods in the cataclysmic-variable period gap; and RE 0751+14, the first non-synchronous system to exhibit polarised optical emission and a true soft X-ray component (both indicators of a strong magnetic field, see also Rosen, Mittaz & Hakala, 1993).

Watson (1993) discusses the detection of this sample. He describes the optical follow-up observations and discusses the properties of the new systems; both as a sample and individually. He points out that the new AM Her's have higher EUV to optical flux ratios than the previously known sample.

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1Identified as a source in Pounds et al. (1993), but not known to be a cataclysmic variable until after publication.

2This cataclysmic variable was noted in the initial survey analysis but not included in Pounds et al. (1993) as it failed to meet the strict confidence criteria applied to that source list.
Table 4.2: Predicted and observed numbers of cataclysmic variables detected in the WFC all-sky survey (c.f. Table C.1).

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<th>(N_{\text{obs}})</th>
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<td>S2a</td>
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<td>Polars (below gap)</td>
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<td>64–74</td>
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<td>Polars (above gap)</td>
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<td>I.P.s (above)</td>
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<td>2</td>
</tr>
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<td>D.N. (quies, above gap)</td>
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<td>D.N. (outburst)</td>
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<td>Nova-like</td>
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<td></td>
</tr>
</tbody>
</table>

4.2.2 Pre-launch predictions of source detections

Watson also made pre-launch predictions of the number of cataclysmic variables to be detected in the WFC survey. This was done primarily to assess the requirements of the optical identification programme. The predictions required several assumptions, but it is interesting to compare them with the observed source counts to see if we can test any of these assumptions. Watson's document was not published, so I include it as an appendix (App. C).

In Table 4.2 I list the predictions together with the survey results. These predictions were clearly over-optimistic, though the proportions of AM Hers detected above and below the period gap and in S1a and S2a agree rather well. There is an even larger shortfall of dwarf novae in outburst.

Overprediction of polars

To see why Watson's calculations overestimated detections of polars we must examine the assumptions. There are four:

1. uniform density of interstellar medium \((0.07 \text{ cm}^{-3})\)
2. black-body emission (with assumed temperatures and luminosities)
3. WFC sensitivity limit of 0.01 cts/s across the whole sky
4. 200 pc scale height for CVs, with constant space densities within this volume.
Table 4.3: Parameters assumed by Watson (1989) for the predictions of Table 4.2

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Polars below gap</th>
<th>Polars above gap</th>
<th>Dwarf novae Quiescence below</th>
<th>Dwarf novae Quiescence above</th>
<th>Dwarf novae Outburst</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity [erg/s]</td>
<td>$10^{32}$</td>
<td>$10^{33}$</td>
<td>$10^{32}$</td>
<td>$10^{33}$</td>
<td>$10^{34}$</td>
</tr>
<tr>
<td>Temperature [$10^6$ K]</td>
<td>2–3</td>
<td>3</td>
<td>0.6</td>
<td>0.6</td>
<td>1–2</td>
</tr>
<tr>
<td>Space density [$10^{-7}$ pc$^{-3}$]</td>
<td>5</td>
<td>0.5</td>
<td>40</td>
<td>10</td>
<td>2.5</td>
</tr>
</tbody>
</table>

For each class of object there are three parameters; luminosity, temperature and space density; I have tabulated Watson’s assumed values in Table 4.3. For details of the assumptions and calculations see Appendix C.

In practice, the WFC survey did not reach a sensitivity level of 0.01 cts/s across the whole sky, mainly due to a higher-than-expected background count rate. Barber (1994) shows that only ~10% of the sky was covered to 0.01 cts/s (S1a filter), but that more than 50% was covered at 0.02 cts/s. Watson (App. C) shows that the predictions are rather insensitive to the assumed luminosities of the sources, and it follows that they must be equally insensitive to the limiting count rate of the survey. Assumption 3 can not account for the difference between predicted and detected source numbers.

The assumed scale height and space densities are also unlikely to account for the deficit of sources since these assumptions are based on real soft X-ray observations of polars, and not on extrapolations from other systems (Patterson, 1984). Whilst there are bound to be substantial errors these values are unlikely to be grossly inaccurate.

We are left then with the intrinsic source spectra and interstellar absorption as sources of the overestimate. The assumption of a black-body spectrum is probably wrong in detail, but EXOSAT grating spectra and recent EUVE spectra have not revealed gross deviations from a black-body (e.g. Van Teeseling, Heise & Paerels, 1994). Assuming the black-body form, the model is most sensitive to temperature and the absorption column and is less sensitive to luminosity. This can be seen in Fig. 6.3 which shows the WFC detection threshold for a grid of absorbed black-bodies. The threshold moves only a little with a hundred-fold decrease in luminosity, but a relatively small change in temperature can move the bulk of the emission out of the WFC window.
The assumed temperatures, however, can not account for the discrepancy for the same reason as the space densities. The assumed values are based on real soft-X-ray measurements and so must be typical; i.e. the assumed space densities are calculated for sources at these temperatures. There may well be a population of sources with cooler undetectable temperatures, but these are not included in the model of Watson.

We are left finally with interstellar absorption. Here the true situation is clearly different from that assumed by Watson. Warwick et al. (1993) present evidence from the WFC survey that we sit within a tenuous bubble in the ISM. They find that the density within the bubble is similar to that assumed by Watson ($\sim 0.05 \text{ cm}^{-3}$), but that it is at least a factor of five higher than this beyond the bubble boundary. The distance to this boundary varies (with direction) between 20 and $>150\text{ pc}$. Figure 4.1 shows just how suddenly rather small column densities cut into the sensitive range of the WFC. Higher column densities will reduce the limiting radii calculated by Watson, which will in turn reduce the number of detected sources as the third power of the ratio. In Fig. 4.2 I plot cumulative column densities for three different models of the ISM as a function of radius. The horizontal lines show the column densities corresponding to 90% absorption at either side of the WFC bandpass, according to the model of Morrison & McCammon (1983). Model c) shows the ISM assumed by Watson, and a) and b) show the ISM according to Warwick et al. with boundaries at 20 and 180 pc respectively. Taking intermediate values, it is clear the the limiting radius can be reduced by a factor of a few, thus the expected number of sources can be easily reduced by one or two orders of magnitude.

If interstellar absorption beyond the local bubble is the reason for the small number of detections of polars, we may expect a correlation of source counts with the distance to the bubble boundary. Figure 4.3 shows estimates of this distance given by Warwick et al., with the positions of all known AM Hers overlaid. Sources detected with greater than 99.9% confidence are circled and labeled, those detected with confidence between 99.9% and 95% are marked with squares (Sect. 4.2.4). There is little evidence for correlation, though the sample of sources is rather small. Also, the resolution of the map is extremely low and the distribution of detections and non-detections may correlate with unresolved structure. It seems clear that the clump of detected sources at high galactic latitudes is associated with the “Lockman holes” in the ISM (e.g. Lockman, Jahoda & McCammon, 1986).
Figure 4.1: Transmission of the interstellar medium as a function of energy, for different column densities (labeled in units of cm$^{-2}$). Curves are calculated using the model of Morrison & McCammon (1983), in which cold material is assumed.
Figure 4.2: Plots of cumulative column density with distance for three models of the interstellar medium. The horizontal lines show the column densities required to absorb 90% of photons at either side of the WFC bandpass. The model marked c) is the uniform density model assumed by Watson in his predictions of WFC source counts (Appendix C), and a) and b) are after Warwick et al. (1993) with an increase in density beyond the local bubble; assumed distances to the boundary are 20 and 180 pc respectively.

Overprediction of dwarf novae in outburst

Detections of Dwarf novae in outburst are even more deficient, when compared to Watson’s predictions than are polars. As such we require a reason in addition to that which accounts for the missing polars. There are three possibilities,

1. The temperatures of the outburst emission components may be lower than that assumed by Watson. His predictions were based on just two systems detected with EXOSAT, which was sensitive to lower temperatures and could not constrain them tightly. In the case of VW Hyi, at least, the temperature must be below the sensitivity range of the WFC (see Sect. 7.1).
Figure 4.3: Positions of all known AM Hers in galactic co-ordinates, overlaid on the map of the local bubble of Warwick et al. (1993). This map shows distance to the edge of the bubble in parsecs (greyscale). The AM Hers detected as bright sources are plotted as circles and labeled; the faint detections of Sect. 4.2.3 are plotted as squares; and non-detections are plotted as stars.

2. The EUV luminosity of all dwarf novae may be lower than the value assumed by Watson. This assumption was based on the theoretical prediction that half the total accretion luminosity may be liberated in an optically-thick boundary layer (Chap 2). Several authors recently have found under-luminous boundary-layers (e.g. Van Teeseling & Verbunt, 1994; Wheatley et al., 1995b).

3. Known dwarf novae are generally more distant than AM Hers, and as such are more strongly effected by the increased absorption beyond the bubble boundary.

The lack of WFC detections of dwarf novae in outburst may be taken as evidence that one or other of the above are general properties of dwarf novae.

The detection of other sources

Given the deficiency of polars and outbursting dwarf novae it is perhaps surprising that two intermediate polars, a quiescent dwarf nova and a nova-like variable were all detected. Very
few, if any, of these systems were expected; even in the predictions which appear so optimistic for other classes.

Detections are discussed individually in later sections. I find that the two non-magnetic systems (VW Hya and IX Vel) and one of the intermediate polars (EX Hya) were probably detected through the soft tail of the hard X-ray components. Watson considered only true EUV emission components.

The other intermediate polar, RE0751, does have a true EUV emission component (Duck et al., 1994). It is the first detection of such a component in an asynchronous system (see Chap. 6).

4.2.3 Full source list

Sources listed in the Bright Source Catalogue were found using an automated point-source-searching algorithm. They were identified as cataclysmic variables through cross-correlation with catalogues (e.g. Ritter, 1990) and by follow-up optical spectroscopy. The significance threshold for this initial analysis was necessarily conservative, and it is clear that several weak detections of known cataclysmic variables are not included in the Bright Source Catalogue.

To make a more thorough analysis of the WFC survey observations I have compiled a list of all known or suspected AM Her systems and reduced light curves for each from the survey database. I have done the same for the intermediate polars, since their number is limited, but not for non-magnetic cataclysmic variables. The non-magnetics are simply too numerous, and only a tiny fraction are detected as bright sources. The few possible weak detections would not add to our understanding of the class as a whole. In Chap. 7 however, I do present a separate analysis of those dwarf novae caught in outburst during their survey coverage. A significant fraction of erupting dwarf novae are detected with the WFC.

Forty-three AM Hers and twenty-two intermediate polars have now been claimed (to the summer of 1993), and only four of these are missing from my analysis; three because they lie in the strip of the sky not covered in the main survey (V834 Cen, WW Hor & UZ For; Sect. 3.1.3), and the AM Her: RX0501, for which co-ordinates were not available.

I have compiled this list from several sources: the Ritter catalogue of cataclysmic variables and X-ray binaries (Ritter, 1990); the WFC bright source catalogue (Pounds et al., 1993); Beuermann & Thomas (1993); Beuermann & Schwope (1994) and Kolb & deKool (1994). The co-ordinates were taken from the Ritter catalogue where possible, and otherwise from the WFC Bright Source Catalogue or from the EXOSAT database at Leicester University. The
co-ordinates of the new AM Her "Paloma" were taken from a ROSAT XRT image extracted from the UK ROSAT data archive at Leicester. It must be emphasised that this is a list of objects claimed to be magnetic cataclysmic variables. Many have not satisfied the usual criteria for membership of the class (i.e. orbitally modulated optical polarisation for AM Hers, and spin modulated X-ray emission for intermediate polars). The non-magnetic cataclysmic variables included in this analysis are those listed in the WFC Bright Source Catalogue and the source discovered through the ROSAT XRT survey (RX 0640; Beuermann & Thomas, 1993).

My full source list is presented in Table 4.4. The sources are listed in order of WFC count rate, and consist of all sixty-five magnetic cataclysmic variables, five non-magnetic cataclysmic variables and three objects whose nature remains uncertain (Beuermann & Thomas, 1993). The prefix "RE" denotes discovery through the ROSAT WFC survey; "RX" discovery through the ROSAT XRT survey. The count rates were calculated using the Bayesian method described in Sect. 3.2.2 and include the most probable source count rate (0), the upper and lower 68% confidence intervals (U68 & L68) and the 90% confidence upper limit (U90). An advantage of the Bayesian method is that no distinction need be made between detection and non-detection.

Table 4.4 includes the $P$-statistic value for each light curve (Sect. 3.2.2), and the number of data points in the light curve ($N$). I have also included a flag indicating which systems were studied with the EXOSAT LEITs (Osborne, 1988; White, 1989; and Sect. 1), and have tabulated maximum and minimum observed visual magnitudes. The visual magnitudes are taken from Ritter & Kolb (in press), Beuermann & Thomas (1993), Beuermann & Schweppe (1994) and the various discovery papers referenced in Table 4.1. Most of the new cataclysmic variables have just one optical measurement to date, and there is no information as to the range of high and low states in these systems. It is also important to note that none of the EUV and optical measurements in Table 4.4 were made simultaneously.

The analysis of this extended sample of cataclysmic variables has added about twelve detections to the nineteen high significance detections of the initial survey analysis. In the next section I consider the statistical significance of these detections. In Sect. 4.3 I use the full source list to extend the source-count analysis of Warwick et al. (1993).
Table 4.4: ROSAT WFC survey observations of cataclysmic variables: the full source list.

<table>
<thead>
<tr>
<th>Object</th>
<th>Class</th>
<th>$S_{1}$ Count rate [keV^{-1} cm^{-2} s^{-1}]</th>
<th>$P_{\text{rot}}$ (N)</th>
<th>$S_{2}$ Count rate [keV^{-1} cm^{-2} s^{-1}]</th>
<th>$P_{\text{rot}}$ (N)</th>
<th>EXOSAT LEIT pointing?</th>
<th>$V_{\text{max}}$, $V_{\text{min}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>RE 1938</td>
<td>AM</td>
<td>387 366 409 423 555(34)</td>
<td>394 318 355 374 194(14)</td>
<td>-</td>
<td>15.2 16.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>QQ Vul</td>
<td>AM</td>
<td>329 315 343 351 535(43)</td>
<td>97 87 106 112 54(97)</td>
<td>Y</td>
<td>14.5 17.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SS Cyg</td>
<td>DN</td>
<td>309 298 320 327 189(58)</td>
<td>54 49 60 63 115(59)</td>
<td>Y</td>
<td>8.2 12.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BL Hya</td>
<td>AM</td>
<td>239 221 258 270 301(19)</td>
<td>219 201 237 247 135(20)</td>
<td>Y</td>
<td>14.5 17.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AN UMa</td>
<td>AM</td>
<td>174 163 186 192 76(31)</td>
<td>227 212 242 251 78(32)</td>
<td>Y</td>
<td>14.5 18.0B</td>
<td></td>
<td></td>
</tr>
<tr>
<td>VV Pup</td>
<td>AM</td>
<td>194 181 208 216 509(29)</td>
<td>211 195 227 236 312(26)</td>
<td>Y</td>
<td>14.5 18.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EF Eri</td>
<td>AM</td>
<td>202 178 226 241 110(15)</td>
<td>193 169 217 232 29(12)</td>
<td>Y</td>
<td>13.7 17.7B</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RE 1140</td>
<td>AM</td>
<td>138 128 148 154 466(29)</td>
<td>78 68 89 95 97(33)</td>
<td>-</td>
<td>16.15 17.0B</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RE 1844</td>
<td>AM</td>
<td>92 72 115 131 10(11)</td>
<td>49 33 67 80 9(11)</td>
<td>-</td>
<td>15.0 17.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RE 0453</td>
<td>AM</td>
<td>44 35 54 61 9(19)</td>
<td>15 8.3 23 29 10(21)</td>
<td>-</td>
<td>19</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EX Bya</td>
<td>IP</td>
<td>43 37 51 56 32(25)</td>
<td>41 8.3 50 56 16(17)</td>
<td>Y</td>
<td>13.0 14.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RE 1307</td>
<td>AM</td>
<td>41 35 47 50 46(38)</td>
<td>22 16 28 32 19(35)</td>
<td>-</td>
<td>17.0 21.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IX Vel</td>
<td>NL</td>
<td>9 6 11 14 24(57)</td>
<td>29 24 34 37 26(51)</td>
<td>Y</td>
<td>9.1 10.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EK UMa</td>
<td>AM</td>
<td>24 20 28 32 40(51)</td>
<td>0.3 0.9 4.1 6.9 18(41)</td>
<td>-</td>
<td>18.0 20.0</td>
<td></td>
<td></td>
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<tr>
<td>VW Hya</td>
<td>DN</td>
<td>21 17 26 29 28(51)</td>
<td>23 18 29 31 23(50)</td>
<td>Y</td>
<td>8.5 13.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>QQ Mus</td>
<td>AM</td>
<td>0.0 0.0 4.7 9.0 8(9)</td>
<td>22 11 36 47 4(10)</td>
<td>-</td>
<td>17.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RX 1940</td>
<td>AM</td>
<td>0.0 0.0 4.6 8.3 13(24)</td>
<td>20 11 30 36 11(27)</td>
<td>-</td>
<td>16</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RX 2107</td>
<td>AM</td>
<td>19 16 23 26 21(37)</td>
<td>0.4 0.0 4.5 7.6 20(47)</td>
<td>Y</td>
<td>15.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>II 1752</td>
<td>AM</td>
<td>19 5 33 42 12(22)</td>
<td>10 0.0 24 33 17(29)</td>
<td>-</td>
<td>14.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RE 0531</td>
<td>AM</td>
<td>16 13 20 23 32(57)</td>
<td>0.0 0.0 3.7 6.4 32(49)</td>
<td>-</td>
<td>17.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RX 0513</td>
<td>AM</td>
<td>15 7 25 32 13(22)</td>
<td>0.0 0.0 6.4 11 13(19)</td>
<td>-</td>
<td>15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RX 0551</td>
<td>AM</td>
<td>14 10 18 21 32(33)</td>
<td>0.0 0.0 3.0 5.7 16(31)</td>
<td>-</td>
<td>14.1 14.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Z Cam</td>
<td>DN</td>
<td>5.5 2.8 8.7 11 14(36)</td>
<td>13 8.8 18 22 17(34)</td>
<td>Y</td>
<td>10.5 14.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FO Aqr</td>
<td>IP</td>
<td>12 5 21 26 9(20)</td>
<td>0.0 0.0 4.9 9.2 7(19)</td>
<td>Y</td>
<td>13.0 14.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RX 1802</td>
<td>?</td>
<td>10 1.8 18 23 18(40)</td>
<td>0.8 0.9 13 21 15(27)</td>
<td>-</td>
<td>14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RX 1857</td>
<td>AM</td>
<td>0.0 0.0 6.2 11 10(14)</td>
<td>0.6 1.7 19 27 5(12)</td>
<td>-</td>
<td>17</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RX 0640</td>
<td>DN</td>
<td>9.5 6.7 13 15 20(40)</td>
<td>3.0 0.0 7.6 12 21(45)</td>
<td>-</td>
<td>15</td>
<td></td>
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<tr>
<td>RX 0515</td>
<td>?</td>
<td>0.0 0.0 1.7 3.3 27(30)</td>
<td>9.5 3.1 17 33 10(27)</td>
<td>-</td>
<td>15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TW Psc</td>
<td>IP</td>
<td>0.0 0.0 1.2 2.4 43(51)</td>
<td>8.4 4.5 13 16 16(49)</td>
<td>Y</td>
<td>14.3 15.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RX 0332</td>
<td>AM</td>
<td>0.0 0.0 4.1 7.7 14(19)</td>
<td>7.8 1.9 15 20 9(17)</td>
<td>-</td>
<td>19</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DP Leo</td>
<td>AM</td>
<td>7.6 4.6 11 14 15(29)</td>
<td>2.0 0.0 6.3 10 11(25)</td>
<td>Y</td>
<td>17.5 &gt;22</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SW UMa</td>
<td>IP</td>
<td>7.5 4.4 11 14 9(35)</td>
<td>5.9 2.2 10 13 15(34)</td>
<td>Y</td>
<td>9 17</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RX 1015</td>
<td>AM</td>
<td>5.0 2.4 8.1 10 8(22)</td>
<td>0.0 0.0 4.5 7.8 18(28)</td>
<td>-</td>
<td>17</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RX 2316</td>
<td>AM</td>
<td>4.8 1.8 8.4 11 8(23)</td>
<td>0.0 0.0 4.1 7.2 22(28)</td>
<td>-</td>
<td>18</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RX 1002</td>
<td>AM</td>
<td>4.6 2.3 7.4 9.5 11(37)</td>
<td>0.0 0.0 2.2 4.0 27(34)</td>
<td>-</td>
<td>17</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RX 1007</td>
<td>AM</td>
<td>1.8 0.0 4.0 6.4 9(32)</td>
<td>4.4 1.5 7.9 10 12(38)</td>
<td>-</td>
<td>18</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: The table lists the counts in channels 0, 6, 8, and 9, along with their uncertainties. The EXOSAT LEIT pointing? column indicates whether the source was observed during the LEIT pointing. $V_{\text{max}}$ and $V_{\text{min}}$ are the maximum and minimum velocities observed for each source.
<table>
<thead>
<tr>
<th>Object</th>
<th>Class</th>
<th>S1a Count rate [sec$^{-1}$]</th>
<th>P$_{\text{start}}$(N)</th>
<th>S2a Count rate [sec$^{-1}$]</th>
<th>P$_{\text{start}}$(N)</th>
<th>EXOSAT pointing?</th>
<th>$V_{\text{max}}$</th>
<th>$V_{\text{min}}$</th>
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</thead>
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<tr>
<td>RX 1313</td>
<td>AM</td>
<td>2.6 0.5 5.4 7.9 7(26)</td>
<td>4.4 1.1 8.3 11 10(22)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AE Aqr</td>
<td>IP</td>
<td>4.3 2.0 7.2 9.2 11(33)</td>
<td>2.8 0.0 6.0 9.4 18(41)</td>
<td></td>
<td></td>
<td>Y</td>
<td>10.9 11.6</td>
<td></td>
</tr>
<tr>
<td>Urea</td>
<td>AM</td>
<td>3.8 1.2 7.0 9.3 7(23)</td>
<td>0.0 0.0 6.2 11 24(83)</td>
<td></td>
<td></td>
<td>Y</td>
<td>20.4 21.0</td>
<td></td>
</tr>
<tr>
<td>AM Her</td>
<td>AM</td>
<td>1.2 0.3 2.2 2.9 1(34)</td>
<td>3.2 1.2 5.5 6.8 42(107)</td>
<td></td>
<td></td>
<td>Y</td>
<td>12.0 15.5</td>
<td></td>
</tr>
<tr>
<td>BG CMi</td>
<td>IP</td>
<td>2.9 0.9 5.3 6.9 10(33)</td>
<td>2.1 0.0 6.0 9.7 20(40)</td>
<td></td>
<td></td>
<td>Y</td>
<td>14.3 14.7</td>
<td></td>
</tr>
<tr>
<td>X 0022</td>
<td>IP</td>
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4.2.4 Significance of detections

I quantify the significance of detections using the light curves reduced after Chap. 3. Events were counted at the source positions within circles of optimised radii (2.5' for weak or non-detections). Mean background count rates were evaluated using a string of regions, each the same size as the source circle, aligned along the scan path. Tests have shown that annuli do not give acceptable results, since the background can ramp steeply in the direction perpendicular to the scan path. Deviations from the mean background are tabulated (expressed in standard deviations) in Table 4.5. Also tabulated are the probabilities that these deviations be equaled or exceeded by chance. The sources are listed in the same order as Table 4.4\(^1\), with the dwarf-novae sample of Sect. 7.4.2 also included; detected sources are flagged.

Twenty-two sources are detected with greater than 99.9% confidence. These include the nineteen sources found in the initial survey analysis, with the addition of RX 0640, DP Leo and SW UMa. A further eleven sources are detected with greater than 95% confidence. Several of these would be expected by chance.

4.3 Source counts

The source counts (log N-log S) of detections in the initial survey analysis are considered briefly in the Bright Source Catalogue paper (Pounds et al., 1993) and are studied in depth by Warwick et al. (1993). Warwick et al. separate the sources into four categories: white dwarfs; FGKM stars; cataclysmic variables and unidentified sources. They concentrate on white dwarfs and main-sequence stars, since these objects dominate the catalogue, and find that the log N-log S distributions are almost Euclidean (slope=−3/2) for the main-sequence stars, but much flatter for the white dwarfs. A flattened log N-log S is a natural consequence of interstellar absorption, since the source counts no longer increase with distance cubed. Warwick et al. interpret the difference in slope between the main-sequence stars and the (generally more distant) white dwarfs as evidence for a discontinuity in interstellar absorption. This supports the idea of a bubble in the interstellar medium, with a local low-density region bounded by higher density gas.

With my enlarged sample of cataclysmic variables I have been able to extended the analysis of Warwick et al. by more than an order of magnitude in flux. This analysis must carry a health warning, however, as I am no longer counting sources but measuring the count rates

\(^1\)omitting the four without coverage
Table 4.5: Deviations from background count rates at the positions of cataclysmic variables in the WFC all-sky-survey. Sources are listed in the same order as Table 4.4. Non-magnetic systems from Sect. 7.4.2 are included at the end. Sources detected with > 99.9% confidence are flagged with **; sources at > 95% with *.

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<td>-48.8</td>
<td>-1.11</td>
</tr>
<tr>
<td>TX Col</td>
<td>0.82</td>
<td>41.0</td>
<td>0.43</td>
</tr>
<tr>
<td>H 0616</td>
<td>-2.42</td>
<td>-1.5</td>
<td>-0.05</td>
</tr>
<tr>
<td>MK Ser</td>
<td>0.51</td>
<td>61.1</td>
<td>0.80</td>
</tr>
<tr>
<td>S193</td>
<td>-0.47</td>
<td>-63.8</td>
<td>0.11</td>
</tr>
<tr>
<td>1ES1113</td>
<td>0.90</td>
<td>37.0</td>
<td>0.48</td>
</tr>
<tr>
<td>BY Cam</td>
<td>0.65</td>
<td>49.9</td>
<td>-0.53</td>
</tr>
<tr>
<td>RX 0558</td>
<td>1.93</td>
<td>5.3</td>
<td>-0.56</td>
</tr>
<tr>
<td>RX 1712</td>
<td>0.14</td>
<td>89.2</td>
<td>0.01</td>
</tr>
<tr>
<td>V1223 Sgr</td>
<td>0.29</td>
<td>77.3</td>
<td>0.10</td>
</tr>
<tr>
<td>KO Vel</td>
<td>0.90</td>
<td>36.9</td>
<td>-0.29</td>
</tr>
<tr>
<td>DO Dra</td>
<td>0.73</td>
<td>46.5</td>
<td>-1.75</td>
</tr>
<tr>
<td>DR V211B</td>
<td>0.00</td>
<td>100.0</td>
<td>-0.49</td>
</tr>
<tr>
<td>GK Per</td>
<td>-0.32</td>
<td>-74.9</td>
<td>-1.37</td>
</tr>
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<td>EXO 0229</td>
<td>0.00</td>
<td>100.0</td>
<td>0.41</td>
</tr>
<tr>
<td>RU Peg</td>
<td>-0.09</td>
<td>-92.7</td>
<td>0.18</td>
</tr>
<tr>
<td>YZ Cnc</td>
<td>0.52</td>
<td>60.2</td>
<td>-0.15</td>
</tr>
<tr>
<td>AQ Eri</td>
<td>-0.16</td>
<td>-87.3</td>
<td>-0.05</td>
</tr>
<tr>
<td>V2051 Oph</td>
<td>-0.65</td>
<td>-51.7</td>
<td>-0.56</td>
</tr>
<tr>
<td>HL CMa</td>
<td>41.98e</td>
<td>0.0</td>
<td>22.85c</td>
</tr>
<tr>
<td>RX And</td>
<td>-0.58</td>
<td>-56.4</td>
<td>0.43</td>
</tr>
<tr>
<td>AB Dra</td>
<td>0.27</td>
<td>78.7</td>
<td>-0.59</td>
</tr>
<tr>
<td>WX Hyi</td>
<td>-1.06</td>
<td>-28.8</td>
<td>0.26</td>
</tr>
<tr>
<td>WW Cet</td>
<td>-0.39</td>
<td>-69.4</td>
<td>-0.56</td>
</tr>
<tr>
<td>V436 Cen</td>
<td>0.08</td>
<td>94.0</td>
<td>-0.53</td>
</tr>
<tr>
<td>V3885 Sgr</td>
<td>2.57</td>
<td>1.0</td>
<td>1.61</td>
</tr>
<tr>
<td>RW Sex</td>
<td>0.60</td>
<td>54.9</td>
<td>-0.95</td>
</tr>
</tbody>
</table>

* deviation from mean background count rate at source position, expressed in standard deviations of the background.

b probability of this deviation being exceeded by chance; zero indicates < 0.1%; negative value indicates negative deviation.

c contaminated by Sirius B.
Table 4.6: Best fit power-law indices for the differential source counts of cataclysmic variables in the WFC survey (plotted in Fig. 4.4). Also tabulated are the results of Warwick et al. (1993), who use a flux limited sample from the WFC bright source catalogue.

<table>
<thead>
<tr>
<th>Category</th>
<th>Warwick et al.</th>
<th>this analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>S1a (\gamma)</td>
<td>S2a (\gamma)</td>
</tr>
<tr>
<td>white dwarfs</td>
<td>1.48 ± 0.07</td>
<td>1.27 ± 0.09</td>
</tr>
<tr>
<td>FGKM stars</td>
<td>2.36 ± 0.11</td>
<td>2.27 ± 0.13</td>
</tr>
<tr>
<td>CVs</td>
<td>1.37 ± 0.26</td>
<td>1.09 ± 0.31</td>
</tr>
<tr>
<td>unidentified</td>
<td>1.76 ± 0.33</td>
<td>2.08 ± 0.41</td>
</tr>
</tbody>
</table>

of a pre-selected sample of sources. I must assume that this sample is complete down to my flux limit. This assumption is probably valid since I include PSPC-discovered systems, and these come from a deeper survey at similar wavelengths (and the optical identification of PSPC sources has concentrated on those with soft spectra). However, since my analysis is based on the PSPC survey, it would be better carried out with PSPC count rates.

In the top panel of Fig. 4.4 I have plotted the integral log \(N\)-log \(S\) relation for the cataclysmic variables in Table 4.4, with an arrow marking the flux limit of Warwick et al. In this formulation the number of sources (\(N\)) brighter than a flux limit (\(S\)) are plotted against \(S\). The slope of the integral source counts is clearly much flatter than that of the uniform Euclidean form (\(-3/2\)). The constancy of slope across the relation is encouraging as it suggests my sample is reasonably complete and that the data reduction does not systematically over or under-estimate count rates close to the flux limit.

The differential source counts of cataclysmic variables are plotted in the lower panel of Fig. 4.4. These are useful because in this formulation the bins are statistically independent and can be ascribed errors. These can be used to determine the uncertainty in the slope of the distributions.

I have fitted the differential source counts with the power-law relation

\[
\frac{dN}{dS} = KS^{-\gamma}
\]  

(4.1)

for which excellent fits have been found using the standard \(\chi^2\) minimisation technique. These best fits are plotted in Fig. 4.4, and the best fit values for the power-law indices (\(\gamma\)) are listed in Table 4.6, along with the results of Warwick et al. The best fit \(\gamma\) values for S1a and S2a agree very closely in my analysis which is to be expected as the source samples are not independent.
Figure 4.4: Top panel shows the integral EUV log N–log S relation for cataclysmic variables listed in Table 4.4. The solid line is for S1a; the dotted line is S2a. The arrow marks the flux limit of the analysis of Warwick et al. (1993). The bottom panels show the differential source counts which have been fitted with power laws (see text). The slopes are much flatter than those expected for a uniform distribution of unabsorbed sources, and are also flatter than those of white dwarfs.
CVs in the WFC all-sky survey

For cataclysmic variables the Warwick et al. results are consistent with those for white dwarfs, but with large errors. The results of my analysis suggest that the slope of the differential source counts of cataclysmic variables may be even flatter than that of white dwarfs, though the S2a values are compatible. There are three reasons why the cataclysmic variables may have a shallower slope:

1. The power-law slope for cataclysmic variables is truly flatter since the mean density of absorbing material in the line of sight to cataclysmic variables is greater than that for white dwarfs. This should not be surprising since cataclysmic variables are thought to be more luminous and distant than isolated white dwarfs, and so will have a higher proportion of their number lying outside the local bubble. My result suggests that a rigorous study of cataclysmic variables (perhaps with the PSPC survey) may provide better limits on the gas density outside the bubble than do white dwarfs.

2. Cataclysmic variables are detected to distances at which their scale height in the galactic disk may start to become important. Since the number of cataclysmic variables would then no longer be proportional to the limiting distance cubed, this would tend to flatten the source count distribution.

3. As noted above, I am not counting sources here, but rather measuring the count rates from a pre-selected sample that I assume is complete. An incomplete sample will act to flatten the source count distribution.

Finally, I subdivide my sample into AM Hers and IP-candidates. The integral source counts and fitted differential source counts are plotted in Fig. 4.5. There are too few systems here to measure differences in slopes with high significance, but there is a hint that the AM Hers have a distribution flatter still than the total cataclysmic-variable population. This may be because they are more luminous EUV sources and are seen more heavily absorbed at greater distances.

4.4 Variability

The measure of variability I use here is the $P$-statistic, defined in Sect. 3.2.2. The statistic is calculated for each light curve w.r.t. its mean, and the value divided by the 95% upper bound of the expected $P$-statistic distribution (a function of source and background count rates). A value greater than unity indicates a light curve variable at greater than 95% significance.
Figure 4.5: As Fig. 4.4, but separating the AM Hers (solid line) and the intermediate polars (dotted). The distribution of the total population of cataclysmic variables is also plotted (dashed).
Figure 4.6: Variability (Sect. 3.3.2) is plotted against count rate for cataclysmic variables in the WFC survey database. Points above the dotted line indicate light curves that are variable at greater than 95% significance. S1a points are marked as circles; S2a as squares.

Bright cataclysmic variables stand out clearly as variable EUV sources (c.f. Fig. 3.10). All sources brighter than 100 counts/ksec are seen to be variable, suggesting that all cataclysmic variables are variable on timescales between hours and days in the EUV. It seems most light curves of sources brighter than 50 counts/ksec contain useful timing information, below this the variability is of the same order or less than the noise, and the light curves of all cataclysmic variables are indistinguishable from those of constant sources. Accordingly I use 40 counts/ksec as my threshold for timing analysis in later chapters. One low-count-rate light curves does lie above the 95% line (the IP RE0751), but one occurrence is to be expected by chance.

It is worth noting though that even when the source variability falls to the level of the noise it can be possible to identify periodic signals. The orbital period of RE 1307 was discovered initially through the WFC S1a light curve, at a count rate of just 41 counts/ksec (Osborne
et al., 1994; Sect. 5.1). A more extreme example is the polar RX 0153, with a count rate of just 15 counts/ksec. The most significant period in the L-statistic periodogram, Fig. 4.7, is 31800 s which corresponds to an orbital period of either 81 or 117 minutes, assuming we observe a beat between the sampling period and the true orbital period (Sect. 5.1). Beuermann & Schwoppe (1994) claim an orbital period for this system of ~ 80 min.

4.4.1 A search for unidentified CVs in the survey database

The ubiquitous variability of the EUV light curves suggests the possibility of identifying new cataclysmic variables purely upon the basis of this variability.

Thirty-one sources listed in the WFC bright source catalogue remained unidentified at publication. Since ~5% of identified sources are cataclysmic variables, one might expect several of the unidentified sources to be cataclysmic variables. The unusually high EUV:optical flux ratios of the WFC-discovered cataclysmic variables (Sect. 4.5) suggest that even more extreme objects may exist which would have been hard to identify optically and may have been missed in the WFC optical identification programme (RE 1307, one of the brightest WFC cataclysmic variables, has a V-band magnitude > 17).

To test for variability in the unidentified sources I have used again the method described in Chap. 3. I have made light curves of the brightest nineteen of the thirty-one unidentified sources; drawing the line at weak S2a-only detections. Faint sources are unlikely to show
CVs in the WFC all-sky survey

Table 4.7: ROSAT WFC survey sources unidentified at publication of the WFC bright source catalogue (Pounds et al., 1993)

<table>
<thead>
<tr>
<th>Object</th>
<th>S1a—</th>
<th>Count rate [ksec⁻¹]</th>
<th>Pₚₛₜₐₜ(N)</th>
<th>S2a—</th>
<th>Count rate [ksec⁻¹]</th>
<th>Pₚₛₜₐₜ(N)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0 L68 T68 T90</td>
<td></td>
<td></td>
<td>0 L68 T68 T90</td>
<td></td>
</tr>
<tr>
<td>RE 1925</td>
<td>627</td>
<td>389 665 687</td>
<td>11(12)</td>
<td>381</td>
<td>360 413 432</td>
<td>799(10)</td>
</tr>
<tr>
<td>RE 0723</td>
<td>274</td>
<td>260 287 296</td>
<td>30(36)</td>
<td>897</td>
<td>868 926 943</td>
<td>34(28)</td>
</tr>
<tr>
<td>RE 1546</td>
<td>68</td>
<td>60 76 80</td>
<td>29(33)</td>
<td>47</td>
<td>39 56 61</td>
<td>22(31)</td>
</tr>
<tr>
<td>RE 2023</td>
<td>57</td>
<td>48 67 74</td>
<td>26(23)</td>
<td>163</td>
<td>145 181 192</td>
<td>21(16)</td>
</tr>
<tr>
<td>RE 1024</td>
<td>49</td>
<td>43 56 61</td>
<td>28(30)</td>
<td>125</td>
<td>113 130 142</td>
<td>24(31)</td>
</tr>
<tr>
<td>RE 0453</td>
<td>44</td>
<td>35 54 61</td>
<td>9(19)</td>
<td>15</td>
<td>8.1 23 29</td>
<td>10(21)</td>
</tr>
<tr>
<td>RE 1727</td>
<td>39</td>
<td>32 47 53</td>
<td>18(26)</td>
<td>50</td>
<td>50 68 74</td>
<td>41(26)</td>
</tr>
<tr>
<td>RE 0415</td>
<td>37</td>
<td>29 47 55</td>
<td>9(15)</td>
<td>29</td>
<td>19 41 49</td>
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<td>RE 1058</td>
<td>36</td>
<td>29 43 48</td>
<td>13(24)</td>
<td>138</td>
<td>97 118 125</td>
<td>24(32)</td>
</tr>
<tr>
<td>RE 0743</td>
<td>31</td>
<td>24 39 44</td>
<td>9(21)</td>
<td>47</td>
<td>37 58 66</td>
<td>12(19)</td>
</tr>
<tr>
<td>RE 0500</td>
<td>25</td>
<td>18 33 38</td>
<td>13(20)</td>
<td>45</td>
<td>37 54 60</td>
<td>18(30)</td>
</tr>
<tr>
<td>RE 2291</td>
<td>20</td>
<td>13 27 33</td>
<td>7(22)</td>
<td>0.0</td>
<td>0.0 5.5 9.7</td>
<td>10(26)</td>
</tr>
<tr>
<td>RE 2239</td>
<td>17</td>
<td>12 23 27</td>
<td>13(24)</td>
<td>0.0</td>
<td>0.0 4.8 8.6</td>
<td>15(19)</td>
</tr>
<tr>
<td>RE 0647</td>
<td>16</td>
<td>11 21 24</td>
<td>23(34)</td>
<td>6.5</td>
<td>2.8 11 14</td>
<td>13(31)</td>
</tr>
<tr>
<td>RE 0431</td>
<td>13</td>
<td>0.9 18 21</td>
<td>17(40)</td>
<td>0.0</td>
<td>0.0 3.6 6.1</td>
<td>31(44)</td>
</tr>
<tr>
<td>RE 1027</td>
<td>13</td>
<td>9.1 17 20</td>
<td>12(37)</td>
<td>23</td>
<td>17 31 36</td>
<td>15(31)</td>
</tr>
<tr>
<td>RE 0915</td>
<td>11</td>
<td>7.1 15 18</td>
<td>13(30)</td>
<td>1.4</td>
<td>0.0 5.7 9.3</td>
<td>19(37)</td>
</tr>
<tr>
<td>RE 0516</td>
<td>-</td>
<td>- - -</td>
<td>-</td>
<td>-</td>
<td>- - -</td>
<td>-</td>
</tr>
<tr>
<td>RE 0521</td>
<td>-</td>
<td>- - -</td>
<td>-</td>
<td>-</td>
<td>- - -</td>
<td>-</td>
</tr>
</tbody>
</table>

My selection of unidentified sources is listed in Table 4.7, along with count rates and P-statistic values. These P-statistic values, divided by the appropriate variability threshold (Sect. 3.2.2), are plotted in Fig. 4.8.

The sources RE 0521 and RE 0516 at first appeared extremely variable, but were found to be false detections due to errors in the spacecraft attitude solution. Counts from single survey scans of a bright source had been assigned the wrong sky co-ordinates and then been identified as separate sources by the point source searching algorithms. RE 1925 is a real source but its extreme variability is entirely due to some zero-count bins, probably also due to attitude solution errors.

The only source exhibiting significant variability is RE 1727, which lies just above the 95% significance threshold. Of course, we would expect one of the nineteen sources to exceed this threshold. By comparison with Fig. 4.6, we can be confident that all sources above 100 counts/ksec are not cataclysmic variables. I can not rule out the possibility of cataclysmic variability and S2-only detections indicate cool, unabsorbed sources; usually isolated white dwarfs.
variables in this sample below 100 counts/ksec, but this analysis does not single out any sources for particular attention.
4.5 Comparison with optical flux

The EUV count rates are snap shots of systems we know to be variable. To gain some idea of the magnitude and range of count rates we might expect it is useful to compare these count rates with measurements at previously-well-studied wavelengths. Optical magnitudes are the obvious choice because they are so readily available. This comparison also allows us to plot flux ratios, which have the advantage of being independent of distance.

In most cases, optical measurements were not made simultaneously with the WFC observations, so we have to rely on an estimate of the most probable optical magnitude for each object. This estimate depends on sub-classes. Magnetic cataclysmic variables tend to exhibit rather steady mean magnitudes, but with dips of two to four magnitudes on timescales of months or sometimes years (Feigelson, Dexter & Liller, 1978; Garnavich & Szkody, 1988). Dwarf novae, on the other hand, exhibit quasi-periodic outbursts at intervals of weeks or months.

In this section I choose to compare the WFC count rates for each system with the maximum optical brightness listed in Ritter & Kolb (in press); with the exception of intermediate polars where I use the maximum outside flares.

For magnetic systems (and probably nova-like variables) this is a good choice. It is clear that they spend most of their time in high states, with occasional dips lasting months or sometimes years. Figure 4.9 shows the brightness distribution of AM Her measured from Harvard plates in the period 1890 to 1976 (taken from Feigelson, Dexter & Liller, 1978). This distribution is believed typical, with the width a function of orbital period (Garnavich & Szkody, 1988). The maximum observed optical fluxes clearly provide a good estimate of the most common brightness. In addition, since not all known systems were detected during the survey, the WFC detections will be biased to systems in their high states.

Newly discovered systems (mainly magnetic) present a problem, since we have little information as to their range of variability. But Fig. 4.9 gives us the assurance that at least the majority of these systems will have been measured in an optical high state. Clearly we must be careful not to draw conclusions based on one or two systems.

For dwarf novae, maximum brightness means the peak outburst magnitude. It is reasonable to use these since so few systems are detected we must expect a strong bias to those in outburst. However, the WFC coverage is typically longer than a dwarf-nova outburst, so the peak magnitude will tend to be an overestimate of the mean brightness. In several cases we
have simultaneous optical light curves of the dwarf novae observations, and can do better. These aspects are discussed fully in Chap. 7.

Figures

In Figs. 4.10 and 4.11 I plot the WFC count rates of all systems of Sect. 4.2.3 against maximum observed optical magnitudes (Table 4.4). For systems detected with > 95% confidence I plot the Bayesian 'most probable' values from Table 4.4. These are the filled symbols. Polars, IPs and non-magnetics are distinguished by different symbols. For undetected systems I plot the 68% Bayesian upper confidence limit. These are marked as upper limits in the plot.

For Figs. 4.12 and 4.13 I have converted the EUV and optical measurements into energy fluxes, assuming spectra flat in energy flux units in each waveband, and have plotted the
Figure 4.10: WFC S1a count rates are plotted against maximum V magnitude for the cataclysmic variables listed in Table 4.4. Circles represent AM Her stars, triangles are IPs and squares are non-magnetic cataclysmic variables.
Figure 4.11: As Fig. 4.10, but for S2a.
ratio of these fluxes against the optical flux. The symbols are the same as in Figs. 4.10 and 4.11.

Finally, in Fig. 4.14, I have plotted the distribution of EUV/optical energy flux ratios for each subclass as a histogram. The lightly shaded regions show the contribution of upper limits to these plots. In their true positions they would broaden the distributions to the left. The heavily shaded region in the AM Her plot shows the systems discovered as a result of the WFC survey (Sect. 4.2.1).

In calculating these flux ratios I have assumed all sources are in a high state. This is clearly not the case and this assumption will tend to broaden the histograms of Fig. 4.14. I have attempted to estimate the magnitude of this effect by applying the same assumption to the optical magnitudes. I have used the brightness distribution of AM Her as a template, then broadened it, for each source, to the magnitude range listed in Ritter & Kolb (in press). This gives estimates of the distribution of observed optical magnitudes. I divided these distributions by the maximum optical magnitude to give the distribution of flux ratios and summed over all sources. The result is plotted as a solid curve in Fig. 4.14. I find that the width of the EUV/opt flux ratio distribution is not a result of my assumption that all sources were observed in a high state.

Discussion

The most obvious feature, in all three plots, is that the polars stand out as extremely strong EUV emitters. Typical energy flux ratios are 100-1000, and this is without correction for interstellar absorption (which acts to reduce the ratio). The flux ratios of the brightest systems (on an arbitrary scale) were discussed by Watson (1993) who was also the first to point out that the new systems have extreme EUV/optical flux ratios. We may expect the optical (cyclotron) emission to be well correlated with the hard-X-ray "bremsstrahlung" component, since both are from the hot post-shock gas; and less well correlated with the soft-X-ray "black-body", which seems to be the result of independent heating of the white-dwarf surface. Thus Watson concludes that the high EUV/optical flux ratios of the new systems probably indicates large soft-X-ray excesses.

The other obvious feature (concerning polars) is that there is a large range of flux ratios (Fig. 4.14); much larger than can be explained by the non-simultaneity of the observations. This must reflect the range of soft excesses, as well as the various factors required for a full bolometric correction; i.e. spectral shapes of cyclotron and soft-X-ray components, dilution
Figure 4.12: The EUV/Optical energy flux ratio of the cataclysmic variables listed in Table 4.4, plotted as a function of optical flux. Circles represent AM Her stars, triangles are IPs and squares are non-magnetic cataclysmic variables.
Figure 4.13: As Fig. 4.12, but for S2a.
Figure 4.14: Here the EUV/optical energy flux ratios are plotted as histograms for the three main sub-classes of cataclysmic variable. The heavily shaded region in the AM Her plot shows the WFC-discovered systems. The lightly shaded regions show the contribution of upper limits to these plots. The dotted line shows an estimate of the broadening due to the assumption that all systems were observed in high states (see text).
of the optical flux by other parts of the system and interstellar extinction. AM Her itself is a good example. It was observed in a low state, so its true flux ratio should be $\sim 2.5$ rather than 0.1. This is still very low for a polar, so we can see that the EUV flux falls more steeply than the optical flux during a low state. This could possibly explain the entire width of the flux ratio distribution. The EUV flux falls faster than the optical probably because the white-dwarf surface is not heated independently in a low accretion state (the presence of soft-X-rays at all indicates some accretion). This is confirmed by the PSPC survey spectrum, in which AM Her appears as a hard source, with little or no emission from the soft component (Bennerman & Thomas, 1993). The lack of independent heating is presumably because blobs either do not form in a low state, or are not dense enough to penetrate the surface of the white dwarf.

The other classes of cataclysmic variables are clearly less bright EUV sources. Only the brightest optical sources are detected, but this suggests that the EUV/optical flux ratios measured for these may be typical. It is worth noting that these ratios are not small. Typical values are 0.1–1, so polars dominate the source sample because they are exceptionally bright, not because the other classes are insignificant EUV sources.

Significant numbers of intermediate polars were not expected to be detected (Sect. 4.2.2). One would expect a similar soft component to that which makes polars so dominant, but spread over a larger area of the white-dwarf, and so emitting at temperatures below the bandpass of the WFC. With the exception of RE 0751, all detections of intermediate polars are probably through the soft tail of the hard X-ray emission.

Dwarf novae may also have been detected through the hard X-ray component, though here we do expect strong soft components during outburst; as has been observed in VW Hyi (Pringle et al., 1987) and SS Cyg (e.g. Jones & Watson, 1992). Such a component is certainly detected in SS Cyg and Z Cam, but not in VW Hyi (see Sect. 7.1). For dwarf novae we are interested in the ratio of the X-ray to optical/UV luminosities, which the simplest models of the boundary layer suggest should be equal. Unfortunately the bolometric corrections are too important to allow us to interpret safely the EUV/optical ratios in this way; especially with the added uncertainty of the outburst phase of the observations. SS Cyg is the only safe example as we know its temperature is around 20eV (Ponman et al., 1995), and so know we are observing the bulk of the EUV flux. The flux ratio is close to unity, but this is compared to the V-band, and the disk emission is known to peak in the UV. From this we
can tentatively conclude that the EUV emission is under-luminous compared to the simplest boundary-layer model.

The nova-like variable IX Vel was also detected in the survey. Here we do not have to worry about outburst phase, and can note that its flux ratio (~ 0.06) may also indicate an under-luminosity of boundary-layer emission.

The conclusions in this section are necessarily tentative, since interstellar hydrogen column densities are generally poorly known. EUV fluxes are extremely strongly attenuated by neutral hydrogen, leading to large uncertainties in the intrinsic EUV/optical flux ratios.

4.6 Comparison with EXOSAT count rates

Comparison of the WFC count rates with those of the EXOSAT LEITs is potentially very interesting. The response of the LEs covered the energy range of the WFC and included a soft X-ray response. The S1a and S2a survey filters cut the low end of this response in two, and it was hoped that survey count rates and ratios could shed light on the host of LE observations and aid interpretation.

Unfortunately this comparison is even more troublesome than with optical magnitudes. Sources were generally observed only a few times with EXOSAT, often with a very large scatter in count rates. The choice of mean, or maximum level, therefore becomes very difficult. In the above comparison with optical magnitudes, most sources have have at least been observed enough times for the overall distribution of brightness states to have been determined. Also, only about a third of the cataclysmic variables in the current sample were observed with EXOSAT, increasing the importance of scatter of individual sources.

When WFC count rates are plotted against EXOSAT count rates a simple correlation is certainly seen, but it is not possible to distinguish between sub-classes of cataclysmic variable. This is most probably due to scatter caused by the non-simultaneity of the observations, rather than genuine similarity of spectra. Comparison of WFC survey and EXOSAT LE count rates, then, can not constrain the soft X-ray/EUV spectra of cataclysmic variables.
Chapter 5

Polars in the WFC survey

5.1 Orbital periods

The soft X-ray/EUV emission of AM Hers is optically thick and emitted from a small fraction of the white-dwarf surface. The rotation of the white dwarf causes the projected area of the region to change, so the observed light curves tend to be strongly modulated. In AM Hers the rotation of the white dwarf is synchronised to the binary orbit (by definition), so this modulation is seen at the orbital period.

In Sect. 4.4 I show that the WFC light curves of all cataclysmic variables brighter than \(~ 40 \text{ cts/ksec}\) exhibit significant variability, so we can expect to detect the orbital period in these systems (including three of the six WFC-discovered systems). This is not trivial however, as the survey sampling period (\(\sim 96 \text{ min}\)) is very close to the expected orbital periods (80–250 min). This means we tend to detect a beat between the orbit and the sampling; given by

\[
\frac{1}{P_{\text{beat}}} = \frac{1}{P_{\text{sam}}} \pm \frac{1}{P_{\text{orb}}}
\]

so there are two possible orbital periods for any detected beat.

The WFC light curves of all polars brighter than 40 cts/ksec are plotted in Appendix D. The beat periods are obvious in most cases (see esp. RE1149). In Fig. 5.1 I show two examples of the detection of orbital periods in the WFC-discovered polars. The top panels are the combined S1a and S2a light curves of the brightest system, RE 1938, and its L-statistic periodogram. The bottom panels show the S1a only light curve and periodogram of RE 1307. This system is rather faint, with variability at about the same amplitude as the noise (see Fig. 4.6), and yet the period is visible in the L-statistic periodogram.
Figure 5.1: The top two panels show the WFC light curve of RE1938 (S1a and S2a), and the L-statistic periodogram. The beat frequency between the cataclysmic variable’s orbital period and the sampling period is obvious. The bottom panels show the S1a light curve and periodogram for RE1307, a much fainter WFC source. In this case the significance of the periodicity is tested through numerical simulations (see text). The histogram of simulated maximum L-statistics, from which the marked thresholds are drawn, is plotted against the y-axis.
In RE 1938 a highly significant L-statistic peak is apparent at 18 350 sec. Assuming this to be a beat period yields orbital periods of either 140.1 or 73.1 sec. Unfortunately, calculating errors from the periodograms is rather difficult. It is possible to construct an argument based on the number of different periods possible in the light curve, but this is complicated by the uneven sampling of WFC survey light curves. The best method is to simulate many light curves modulated at a known period, using the same statistics and sampling function as the observed light curve, and then apply the same period search to see how well the periods can be recovered. This approach is costly of time and computing resources, and I decided that it would be inappropriate since optical photometry can usually provide a more precise measurement of the orbital periods. In the case of RE 1938 optical photometry has indeed provided a precise measure of the orbital period of $140.02 \pm 0.02$ min (Buckley et al., 1993); in close agreement with one of the WFC periods.

The bottom panels of Fig. 5.1 show RE 1307. A L-statistic peak at 28 050 sec is clearly visible. The count rate here is too low to assume that the L-statistic has an F-distribution, so I tested the significance of this peak through numerical simulations. I simulated one thousand light curves of a constant source, including Poisson noise, with the same mean count rate and exposure profile as the source light curve and with the same corrections applied. Significance levels were determined by subjecting these light curves to the same period search as the source light curve to find the maximum L value for each simulation. The distribution of these maximum L levels, from which the significance levels are drawn, is plotted against the y-axis of the periodogram in Fig. 5.1. The initial period search was carried out using five phase bins. The significance of the detected period was confirmed with period searches using three and seven phase bins. Again assuming we observe a beat, the period of 28 050 sec is consistent with a true orbital period of either 79.7 or 120.9 min. Osborne et al. (1994) measure an optical photometric period of $79.6873 \pm 0.0004$ min, in excellent agreement with the shorter of the two possible WFC periods.

5.1.1 Periods of WFC-discovered systems

The orbital period of RE 1938 and of the other new systems, RE 2107 and RE 0531, are remarkable in that they lie within the so called "period gap" in the orbital-period distribution of cataclysmic variables (see Chap. 2). Individually these can be understood within the "standard model" of cataclysmic-variable evolution (reviewed by King, 1988), but taken together, most authors have assumed there is now a surplus of AM Hers in the period gap.
This is not true, and in Sect. 5.1.2 I show that the period gap of AM Hers is indistinguishable from that of non-magnetic cataclysmic variables.

The period of RE 1938 is greater than the maximum allowed for systems that have evolved across the gap (131 min; Hameury, King & Lasota, 1988), so the only explanation within the standard model is that it was born within the gap.

The periods of RE 2107 (124.5 min; Hakala et al., 1993) and RE 0531 are close enough to the lower end of the period gap that they may have evolved normally across the gap, and re-started mass transfer earlier than most systems due to high white-dwarf masses (Hameury et al., 1988). This is also the traditional explanation for the period of UZ For at 126.5 min. This interpretation, and thus the interpretation of the "period spike", is now in doubt, since eclipse studies of both RE 2107 (Glenn et al., 1994) and UZ For (Bailey & Cropper, 1991) have found evidence for rather ordinary white-dwarf masses.

The period of RE 1307 gives it the record for the shortest-period polar (79.7 min). This is still somewhat longer than the predicted minimum period of Rappaport, Joss & Webbink, 1982 (60–75 min), but is consistent with being the true minimum since models are rather sensitive to stellar opacities. Opacities for very cool stars are still poorly known.

5.1.2 The new AM Her orbital period distribution

The known sample of AM Her systems has been more than doubled through the two ROSAT surveys. In Table 5.1 I list the all the systems with their periods, and in Fig. 5.2 I plot the new period distribution. The periods were taken from Ritter (1990), Beuermann & Schwope (1994), Kolb & deKool (1994) and the various WFC discovery papers listed in Table 4.1.

New features are apparent in this distribution, which has prompted a flurry of theoretical papers (e.g. Wu & Wickramasinghe, 1993; Kolb & deKool, 1994; King et al., 1994; and Wickramasinghe & Wu, 1994). The features are: a) a reduced period spike; b) a new spike at the minimum period; c) a higher maximum period; d) an apparent filling of the period gap. King (1994) discusses each of these in turn (except the minimum-period spike which has only become apparent through systems identified since his paper).

Period spike

In Chap. 2 I describe the usual explanation of the period gap, and point out its weakness. The period spike has lost its dominance of the period distribution, but not its significance. There are now eight systems in a three-minute range rather than six in two minutes. King
Figure 5.2: The post-ROSAT orbital period distribution of polars. The top panel shows the cumulative distribution. The 'pre-ROSAT' distribution is also plotted; it is shaded in the bottom panel and is the dotted line in the top panel where it is plotted raw and also normalised to the new distribution. The orbital periods of all forty-three polars are listed in Table 5.1.
Table 5.1: The orbital periods, distances and magnetic field strengths of the full sample of forty-three AM Her systems. They are listed in order of WFC count rate; c.f. Table 4.4. A colon indicates an uncertain measurement.

<table>
<thead>
<tr>
<th>Object</th>
<th>$P_{orb}$ [min]</th>
<th>Distance [pc]</th>
<th>B-field [MGauss]</th>
</tr>
</thead>
<tbody>
<tr>
<td>RE 1938</td>
<td>140.0</td>
<td>47</td>
<td>QQ Vul</td>
</tr>
<tr>
<td>BL Hyi</td>
<td>113.6</td>
<td>128</td>
<td>EF Eri</td>
</tr>
<tr>
<td>VV Pup</td>
<td>100.4</td>
<td>145</td>
<td>AN UMa</td>
</tr>
<tr>
<td>RE 1149</td>
<td>90</td>
<td>-</td>
<td>RE 1844</td>
</tr>
<tr>
<td>RE 0453</td>
<td>95</td>
<td>-</td>
<td>RE 1307</td>
</tr>
<tr>
<td>EK UMa</td>
<td>114.5</td>
<td>≥ 410</td>
<td>RE 2107</td>
</tr>
<tr>
<td>1H 1752</td>
<td>112.8</td>
<td>-</td>
<td>RE 0531</td>
</tr>
<tr>
<td>RX 0153</td>
<td>81</td>
<td>-</td>
<td>DP Leo</td>
</tr>
<tr>
<td>RX 1015</td>
<td>80</td>
<td>-</td>
<td>RX 2316</td>
</tr>
<tr>
<td>RX 1002</td>
<td>106</td>
<td>-</td>
<td>EU Cnc</td>
</tr>
<tr>
<td>RX 1313</td>
<td>252</td>
<td>-</td>
<td>EP Dra</td>
</tr>
<tr>
<td>V1500 Cyg</td>
<td>201.0</td>
<td>1200</td>
<td>AM Her</td>
</tr>
<tr>
<td>&quot;Paloma&quot;</td>
<td>160.2</td>
<td>-</td>
<td>HV And</td>
</tr>
<tr>
<td>Grus V1</td>
<td>108.6</td>
<td>-</td>
<td>ST LMi</td>
</tr>
<tr>
<td>RX 0203</td>
<td>275</td>
<td>-</td>
<td>MR Ser</td>
</tr>
<tr>
<td>RX 1007</td>
<td>208</td>
<td>-</td>
<td>RX 0132</td>
</tr>
<tr>
<td>1ES 1113</td>
<td>115.9</td>
<td>-</td>
<td>RX 1940</td>
</tr>
<tr>
<td>GQ Mus</td>
<td>85.2</td>
<td>-</td>
<td>BY Cam</td>
</tr>
<tr>
<td>RX 1957</td>
<td>99</td>
<td>-</td>
<td>DR V211B</td>
</tr>
<tr>
<td>EXO 0329</td>
<td>228.0</td>
<td>-</td>
<td>VS34 Cen</td>
</tr>
<tr>
<td>WW Hor</td>
<td>114.6</td>
<td>500</td>
<td>UZ For</td>
</tr>
<tr>
<td>RX 0501</td>
<td>?</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

suggests that the spike may "follow other several-sigma results into oblivion", but it should be noted that the new spike no longer requires the extreme constraints on component masses that were demanded by the old spike (Chap. 2). Ironically, the reduction in the spike seems to strengthen the theoretical interpretation.

Minimum-period spike

A spike at minimum period has been expected, since this is a second stationary point in the evolution of cataclysmic variables (Rappaport, Joss & Verbunt, 1983). However, the observed peak should be treated with caution because: a) the period of two of the systems are labeled as uncertain in Beuermann & Schweppe (1994); b) there is no corresponding peak in the distribution of non-magnetic systems.
The period gap

The apparently reduced period gap of AM Hers has received the most attention. About 50% of cataclysmic variables within the period gap are AM Hers, which form only about a quarter of the total population.

Most authors have leapt upon this observation without considering its statistical significance. A simple back-of-the-envelope calculation shows that this is only a two-sigma result (based on 5/40 AM Hers in the gap and 6/136 non-magnetics).

Far more seriously, they also forget that AM Hers are not found at long periods. This makes it perfectly natural for a higher proportion to lie in the period gap. In Fig. 5.3 I plot the period distributions of AM Hers and the non-magnetic cataclysmic variables, but this time normalised to the number of systems below the gap, rather than the total number of systems. It seems quite clear that there is no difference between the two distributions either in or below the period gap. The only difference is that AM Hers are not found at long periods, and this is easily understood as the larger binary separations prevent synchronisation.

There is simply no need for the host of mechanisms proposed to explain the absence of the period gap in polars.

Evolutionary polar–IP link?

The old idea of an evolutionary link between AM Hers and the observed intermediate polars seems now have been consigned to the dustbin (e.g. Wickramasinghe, Wu & Ferrario, 1991; King, 1994). This is mainly because the intermediate polars have shown no evidence for magnetic field strengths as high as polars (Chap. 2). This is indeed a serious problem, but the alternative is just as troublesome. Fig. 5.4 shows the orbital period distributions of polars, intermediate polars (sample from Patterson, 1994), non-magnetic cataclysmic variables and the combined magnetic systems. Intermediate polars clearly favour long periods, and polars short periods. If the asynchronous intermediate polars do not evolve into the synchronous polars we must face the questions of the missing AM Her progenitors, and the disappearing intermediate polars.

The discovery of RE0751 at least gives us a prototype AM Her progenitor; and the rest of the problem might be solved by considering selection effects. Most AM Hers are detected through their strong soft-X-ray flux, while we have to rely on hard-X-rays for intermediate polars. This may make the intermediate polars observable only at the high accretion rates above the period gap, while AM Hers are detectable at all periods. The relative numbers
of AM Hers (\(\sim 50, \) at December 1994) to their progenitors (just one; RE 0751) may simply reflect the relative proportion of their lives spent evolving quickly under magnetic braking and more slowly under gravitational radiation. Of course, this strong selection effect predicts a large number of low luminosity intermediate polars below the period gap. These may be lurking in the PSPC survey database and it would be interesting to search for them. Another interesting experiment would be to consider which AM Hers would have been discovered on the basis of their hard-X-ray emission only.

Alternatively the surface-\(B\)-field limits for intermediate polars may be misleading and the evolutionary link may hold. This is possible if the known AM Hers have systematically higher white-dwarf masses than the intermediate polars. That would allow them to have higher surface fields for the same magnetic moment. High masses could occur if: 1) white-dwarf masses increase through the mass transfer process; nova explosions are thought to carry away more mass than is transferred, but this may be modified by a strong field; or 2) AM Hers with high white-dwarf masses are preferentially selected as they are discovered through soft
Figure 5.4: Orbital period distributions of cataclysmic variables divided by class. The top and bottom curves are for polars and intermediate polars respectively. The dotted curves represent the non-magnetic cataclysmic variables (bottom) and the combined magnetic systems (top).

X-rays. Figure 5.5 shows the white-dwarf mass–radius relation (Nauenberg, 1972), and the resulting surface field strength for a magnetic moment of $\mu_1 = 10^{34}$ Gcm$^3$. Mass estimates of primaries in cataclysmic variables are notoriously difficult, so there may be room for such a separation in masses between polars and intermediate polars.

Finally I note that the period distribution of the combined magnetic cataclysmic variables is still rather similar to that of the total population (Fig. 5.4). Especially if one accepts that polars are probably preferentially selected. I suggest the evolutionary link should not be fully rejected until the magnetic moments of significant numbers of polars and intermediate polars have been measured.
Figure 5.5: The mass–radius relation of white dwarfs (Nauenberg, 1972), and the corresponding surface field strength for a magnetic moment of $\mu_1 = 10^{34}$ Gcm$^3$. The horizontal dotted lines indicate 5, 10 and 50 MG surface fields.
5.2 Comparison of EUV fluxes with orbital period and magnetic field strength

Comparison of EUV luminosities with other fundamental system parameters is obviously important. However, use of the WFC survey count rates is troublesome, mainly because the translation of count rate into bolometric flux is rather complex. The WFC response covers typically only the hardest half of the EUV emission from polars, so bolometric flux estimates are sensitive to the assumed temperature. They are also highly sensitive to interstellar absorption, and the WFC survey does not provide enough information to measure these spectral parameters. The distances to polars are also either unknown, or poorly constrained, and my only distance-independent measure, $vF_{\text{euv}}/vF_{\text{opt}}$, is compromised because the flux measurements are not simultaneous. Accordingly, in this section, I present only a brief comparison of the raw count rates with the most basic system parameters: magnetic field strength, $B$, and orbital period $P_{\text{orb}}$.

$B$ and $P_{\text{orb}}$ are tabulated in Tab. 5.1, and in Fig. 5.6 I plot the S1a count rates against $P_{\text{orb}}$, and $vF_{\text{euv}}/vF_{\text{opt}}$ against both $P_{\text{orb}}$ and $B$.

The plots must suffer from considerable scatter, for the reasons mentioned above (and others), and I hesitate at drawing conclusions. But I will make some simple statements that should be not too controversial.

1. If the period gap is really a result of a discontinuity in $J$ (Chap. 2), then systems below the gap transferring mass by gravitational radiation should be less luminous than those above. EUV fluxes are entirely accretion driven, so one would expect the correlation to appear in the top panels of Fig. 5.6. This is not the case, and it even seems the longer-period systems are fainter EUV sources.

2. It is interesting to note that the gap is intact if one allows the gap range to be a function of $F_{\text{euv}}$ or $vF_{\text{euv}}/vF_{\text{opt}}$.

3. The $vF_{\text{euv}}/vF_{\text{opt}}$ vs. $B$ plot shows some evidence of the correlation noted recently by Beuermann & Schwope (1994) and Ramsay et al. (1994); though this becomes unconvincing when one realises the point at the bottom left is AM Her, and should be raised by about two orders of magnitude (it was observed in a low state). The correlation found by the above authors, using survey and pointed PSPC observations, is important because it links the magnetic threading process with X-ray properties for
Figure 5.6: The top two panels show the EUV flux and the EUV:optical energy flux ratio as a function of orbital period for all known AM Hers. The bottom panel shows the flux ratio as a function of magnetic field strength.
the first time. The blobs, thought to be responsible for the EUV emission, are probably formed by magneto-hydrodynamic instabilities during threading.

5.3 Orbital-phase-folded light curves

The WFC survey light curves provide us with a maximum of sixteen flux measurements per day; a time resolution close to the orbital periods of polars. Even so, the snap-shot nature of the coverage allows us to reconstruct orbital-phase-folded light curves. In Appendix D I present a complete flux-limited sample of the raw and folded light curves, and in this section I discuss these light curves.

5.3.1 EXOSAT observations

The most important previous observations of the EUV/soft X-ray light curves of polars were made with the EXOSAT low energy (LE) telescopes, reviewed by Osborne (1988).

These observations were extensive and sensitive, several new polars were discovered and the soft-X-ray light curves of many systems were measured for the first time. A particular advantage was that EXOSAT was placed in a highly elliptical orbit, yielding uninterrupted observations of up four days duration. While many systems conformed to the standard model of the time, these observations revealed a wealth of variability and asymmetry. In particular, several systems were found to have multiple soft-X-ray modes, between which the soft-X-ray light curves would change radically with no apparent change in the hard X-ray or optical light curves (e.g. Fig. 5.8). It was also found that AM Hers often exhibited asymmetric light curves, which are evidence for extended accretion regions. Asymmetry is inevitable if the accretion rate is not constant along an extended region.

EXOSAT vs. WFC

The EXOSAT LE observations (0.05–2.5 keV) spanned the EUV response of the WFC survey filters (0.06–0.12 keV), but with also a broad X-ray response and no useful spectral resolution. The interpretation of the EXOSAT light curves were hampered by this lack of spectral information since it was impossible to separate the various modulation mechanisms.

The strength of the WFC observations lie in: a) the isolation of the EUV portion of the spectrum; b) spectral resolution within this band; c) observations over more than five days for all objects; d) coverage of the new ROSAT-discovered AM Hers. The shortcomings, compared with EXOSAT, are: a) the snap-shot nature of the survey coverage, which provides
only limited information on timescales of variability; b) a maximum exposure of 20 min/day, and much less in most cases.

5.3.2 Results
I applied my standard light-curve reduction method of Chap. 3 to all known AM Hers. In Appendix D I present the raw and phase-folded light curves of all systems brighter than 0.02 cts/sec. This limit was applied since the analysis of Sect. 4.4 shows light curves of fainter systems are dominated by counting statistics.

In general the light curves are similar to those seen with EXOSAT, indicating that the modulation mechanisms in the EUV are the same as those of the soft-X-ray band. All the light curves show a $P_{\text{orb}}$ dependence, and, since each point is usually from a different binary cycle, this must indicate that the broad accretion geometry is stable on a timescale of days. Most light curves also show variability around this mean dependence, indicating strong flickering (timescales of minutes) or longer term cycle-by-cycle variations (timescales of hours to days). We can not separate these timescales, though it is possible to study the stability of the light curves on timescales of days (below).

In three systems we see evidence for spectral variation with phase; QQ Vul, BL Hyi and RE 1307. This was not detectable with EXOSAT, and is most probably the result of accretion at two magnetic poles (e.g. Fig. 2.11). BL Hyi is also the only system in which the light curve is radically different from that observed with EXOSAT. It is clear that the dominant emission does not arise from the same region as that observed with EXOSAT, though the origin of the modulation is not well understood.

Modulation mechanisms
The EUV flux from polars is thought to arise as optically thick emission from localised heated regions of the white dwarf, near the magnetic poles (Chap. 2). The EUV light curves are modulated as the white-dwarf rotates and the projected area of these regions change. In many systems the accretion region is occulted by the body of the white dwarf and the flux falls to zero for much of the orbital period. This effect dominates the WFC light curves of VV Pup, RE 1149, RE 1307 (S1a) and EK UMa. Fig. 5.7 shows the S1a folded light curves of each of these systems. In the light curve of the new system RE 1938, the flux does not reach zero, though there is no change in filter ratio. This probably represents the limiting case where the emitting region grazes the limb of the white dwarf.
Figure 5.7: The orbital-phase folded S1a light curves of five AM Hers are plotted. The dominant modulation in each is the projected area effect. In all but RE 1938 the flux falls to zero, so the emission region must cross the limb of the white dwarf. The emission region in RE 1938 probably grazes the limb.
The projected area effect is not the only modulation mechanism. EXOSAT observations showed that: a) accretion can occur simultaneously at more than one pole (e.g., Fig. 2.11); b) the emission regions can be extended and asymmetric; c) the accretion stream can eclipse the emission region. A combination of these mechanisms can lead to rather complex light curves, and examples from EXOSAT and the WFC are presented in Fig. 5.8. Emission regions have also been seen to have vertical extent, causing a sharper projected area modulation than the cosine form given by a flat region (e.g., AM Her itself; Hamerly & King, 1988).

Combinations of these processes can be seen in the WFC light curves. QQ Vul is a particularly good example: it must have two emitting poles, causing the spectral variation with phase and it has an eclipse by the accretion stream at $\phi = 1.0$. Similar features can be seen in the light curve of AN UMa, but with lower signal-to-noise. The low point in the light curve of VV Pup is at the same phase as the absorption dip (due to eclipse by stream) seen in Einstein light curves (Patterson et al., 1984); providing evidence that an absorption dip may be a regular feature, though I can't rule out the possibility that this single low point is an artifact caused by an attitude error similar to those seen in other sources (see Sect. 3.3.2).

**Soft-X-ray mode changes**

AM Her, QQ Vul, V834 Cen, and BL Hyi have all been seen to exhibit soft-X-ray mode changes (e.g., Osborne et al., 1987). That is, the soft-X-ray light curve changes radically with little or no change in the hard-X-ray and optical light curves (Chap. 2). These are probably due to shifts in accretion geometry, with a substantial fraction of the accretion flow switching magnetic poles (e.g., Fig. 2.4 and Fig. 2.11). Since it is invariably the soft X-rays that are affected, it seems likely that it is the blobby portion of the accretion flow that switches pole. This is possible because the magnetic threading time is a function of density, so blobs can penetrate further into the magnetosphere before becoming frozen to the field lines.

QQ Vul and BL Hyi are both apparently seen in new modes with the WFC, and AN UMa is seen in a new (or modified) mode for the first time. The light curve of BL Hyi is particularly unusual in that the dominant emission $S_{1a}$ and $S_{2a}$ are out of phase, and neither phase range corresponds with that of the EXOSAT observation (Sect. 5.4). AM Her was in a low state and barely detected in the WFC survey. V834 Cen lies in the strip of sky not covered by the main survey (Sect. 3.1.3).

Figure 5.8 shows the light curves of AN UMa and QQ Vul. The folded WFC survey light
Figure 5.8: The folded light curves of QQ Vul and AN UMa in both EXOSAT and the WFC. All are plotted with the absorption dip at $\phi = 0$. Note especially the striking similarity between the QQ Vul WFC light curve and the AN UMa EXOSAT light curve. The top two panels show the soft-X-ray mode change observed in QQ Vul by EXOSAT. This change in the soft-X-ray light curve occurred with no apparent effect on the hard-X-ray or optical light curves.
curves are plotted with the EXOSAT LE light curves, and all are plotted with the main absorption dip at phase zero (i.e. the two EXOSAT QQ Vul light curves are shifted in orbital phase). The top two panels show the two previously known soft-X-ray modes of QQ Vul. The WFC light curve below that is not consistent with either of these, and is strikingly similar to the AN UMa EXOSAT light curve. The AN UMa WFC light curve is also apparently inconsistent with its EXOSAT light curve, though the pulse profile is not clear.

Spectral variation with phase

Three sources exhibit orbital modulation of the S1a:S2a filter ratio; QQ Vul, RE 1307 and BL Hyi.

QQ Vul and RE 1307 have double peaked pulse profiles, with the relative strength of the peaks changing between S1a and S2a (Fig. 5.9). This is suggests a geometry with two accreting poles at different temperatures. The temperature constraints implied by this interpretation are presented in Sect. 5.4.

The second EUV pulse in RE 1307 is weak, but its existence is supported by the interpretation of the optical light curve (Osborne et al., 1994). The optical pulse is centred at $\phi = 0.0$, with a deep minimum at $\phi \sim 0.5$ and a second, shallow minimum at the pulse centre. Osborne et al. interpret the deep minimum as due to cyclotron beaming, which would place the optical emission region closest to the limb at $\phi = 0.0$; in phase with the S2a pulse. The S1a pulse apparently has no optical counterpart, suggesting a complex mode of accretion.

BL Hyi

The BL Hyi light curves are even more complex, and are not consistent with any smooth modulation. The S1a curve looks like simple projected-area modulation, but there are three low points in the ‘on phase’; this peak also occurs 0.3 cycles earlier than those observed with EXOSAT (Beuermann & Schwope, 1989). The S2a light curve shows emission at all phases, with no peak coincident with the S1a ‘peak’, and a group of four high-count-rate points, out of phase with the S1a peak. The snap-shot coverage of the WFC survey does not allow an unambiguous interpretation, but I consider three possibilities:

1. The four high points in S1a and S2a are due to flaring not related to orbital phase; the phase separation being through chance.
Table 5.2: The count rates of the broad binned light curves of QQ Vul, RE 1307 and BL Hyi (plotted in Fig. 5.9).

<table>
<thead>
<tr>
<th>Object</th>
<th>S1a Peak</th>
<th>S2a Peak</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>S1a</td>
<td>S2a</td>
</tr>
<tr>
<td>QQ Vul</td>
<td>501 ± 30</td>
<td>81 ± 12</td>
</tr>
<tr>
<td>RE 1307</td>
<td>95 ± 16</td>
<td>31 ± 13</td>
</tr>
<tr>
<td>BL Hyi</td>
<td>576 ± 49</td>
<td>110 ± 25</td>
</tr>
</tbody>
</table>

2. The four high points in each light curve represent structured emission from two poles with different EUV spectra. The inconsistency between the high and low points in each filter being due to large secular variations in accretion rate.

3. A combination of 1. and 2. Structured emission could account for the high points in one filter and flaring the other.

There is evidence of strong flaring in BL Hyi. The EXOSAT light curve showed flares during the 'off phase', and a recent ROSAT XRT observation was characterised by chaotic flaring (Schwope & Beuermann, 1993). Even so, the probability of random flaring being separated in phase in this way is not high. I have evaluated this probability through a simple numerical simulation in which I generate two sets of four random phases, and test for separation in phase. I don’t place any other requirements on the nature of this separation, since any separation in phase would have been noted as unusual behaviour. After a sufficient number of trials I find the probability for phase separation to be 13%. Whilst this is not insignificant, and flaring is a plausible explanation of the observed light curve, I nevertheless consider the implications for the EUV spectrum of BL Hyi under the assumption that the two peaks represent true structured emission (Sect. 5.4).

Figure 5.9 shows the light curves of the three systems exhibiting apparent spectral modulation. The light curves have been binned into broad phase bins and the binned count rates are tabulated in Table 5.2. In Sect. 5.4.2 I use these count rates to place spectral constraints on the emission at different phases.
Figure 5.9: The broad phase binned light curves of QQ Vul RE1307 and BL Hyi; the three cataclysmic variables to exhibit orbital modulations of their EUV spectra.
Stability of light curves

All the light curves in Appendix D show modulation as a function of phase, though the sampling is only about once per orbital cycle. This demonstrates that structured emission from AM Her is both a general and stable feature (at least on timescales of days). Several light curves, however, show considerable scatter around the mean modulation (e.g. QQ Vul & BL Hyi). The WFC survey does not allow us to separate flickering on timescales of seconds from that at hours, but we can distinguish longer timescales. This is difficult with the raw light curves because of the effects of beating, so it is necessary to model the folded light curves and compare the raw light curve with this model.

To model the WFC light curves we need good phase coverage, high signal-to-noise and, preferably, a quantitative physical understanding of the modulation. Since we don’t have such a model, and in many cases the coverage and S/N are poor, I have restricted this analysis to the S1a light curve of QQ Vul as an example.

In the absence of a physical model I have simply blurred the folded light curve. I replace each data point with a Gaussian of width \( \sigma = 0.036 \), and normalise for coverage. The top panel in Fig. 5.10 shows the S1a light curve of QQ Vul both raw and blurred. I have interpolated the blurred curve at the phase of each data point and have calculated a ratio, \( R \), as

\[
R = \frac{D - M}{D + M}
\]

(5.2)

where \( D \) is the data point and \( M \) is the interpolated model. This ratio is plotted as a function of true time (modified Julian date minus 48000 days) in the bottom panel of Fig. 5.10.

I would claim there is a clear trend in this ratio, suggesting that the light curve is actually rather stable. Most of the scatter in the folded curve is apparently the result of a gradual change in the form of the modulation, occurring over about three days.
Figure 5.10: The top panel shows the folded $S_{1a}$ light curve of QQ Vul. The solid line is the result of blurring the light curve with a Gaussian ($\sigma = 0.03$ cycles). The bottom panel shows the ratio of data (D) to model (M) in the raw light curve.

### 5.4 Spectral constraints

The WFC survey was made in two colours ($S_{1a}$ and $S_{2a}$), so it is possible to constrain parameters of simple spectral models, but not to test goodness of fit or decide between models.

The observed soft-X-ray spectra of polars are usually well approximated with a blackbody spectrum absorbed by cold interstellar material. Observed temperatures are in the range $20-50\,\text{eV}$ and luminosities $10^{31} - 10^{34}\,\text{erg}\,\text{s}^{-1}$ (Cropper, 1990; Ramsay, 1995). Deviations from this simple form have been observed (e.g. Paerels, Heise & Van Teeseling, 1994;
Van Teeseling, Heise & Paerels (1994), but these are not fully understood and certainly there is no justification for a more complex model when considering WFC data.

The absorbed black-body model is described by three parameters. The temperature of the black body, $T_{bb}$, the normalisation of the black body, $N_{bb}$, (a combination of the distance, size and luminosity of the source) and the line-of-sight interstellar column density, $N_H$. The interstellar absorption model is taken from Morrison & McCammon (1983).

I have evaluated this model as a function of $kT_{bb}$ and $N_H$ in a large grid, encompassing the expected range of AM Her parameters. These spectra have then been folded through the response of the WFC, so that comparison can be made with observed count rates. The advantage of working in the $kT - N_H$ plane is that a WFC filter ratio uniquely defines a region on this plane. No assumptions about distance or emission region size are required, so we can constrain $kT$ and $N_H$ for all polars.

As there are two data points but three parameters (four if one wishes to separate distance and emitting area), the constraints are not tight. This is improved if we add information from other sources, which can be either theoretical constraints (below) or measurements from other instruments and at other wavelengths (perhaps $N_H$ from interstellar ultraviolet absorption lines). If the distance is known, the emitting area and luminosity can be calculated from $N_{bb}$, and expected values used to further constrain temperature and $N_H$.

### 5.4.1 Theoretical limits

First, we know that the total luminosity must be less than the Eddington luminosity of the white dwarf; the luminosity at which radiation pressure prevents further accretion. Assuming a steady spherically-symmetric flow, this is given by

$$ L_{Edd} = 4\pi G M_{wd} m_p c / \sigma_T $$

$$ L_{Edd} \approx 1.3 \times 10^{38} (M_{wd}/M_\odot) \text{ erg s}^{-1} $$

This is not a tight constraint however, as it considers uniform accretion across the whole white-dwarf surface, which is not the case for polars. We know that accretion only occurs over a small fraction of the surface because of the strength of projected area modulation in the EUV light curves. A better limit comes from considering the area of the emission region, which we can estimate from the total surface area of the white dwarf. We can calculate the total area of a white dwarf, given its mass, by using the mass-radius relation of Nauenberg...
Polars in the WFC all-sky survey

(1972)

\[
\frac{R_{\text{wd}}}{R_\odot} = 0.01125 \left[ \left( \frac{M_{\text{wd}}/M_\odot}{1.45} \right)^{-2/3} - \left( \frac{M_{\text{wd}}/M_\odot}{1.45} \right)^{2/3} \right]^{1/2}
\]

(5.5)

assuming a mean molecular mass of 2. The estimated mean white-dwarf mass for polars is \(\sim 0.6 M_\odot\) (Cropper, 1990), which suggests white-dwarf radii around \(8.7 \times 10^8\) cm \((0.013 R_\odot)\). Assuming the emission region covers less than 10% of the white dwarf suggests an upper limit to the emitting area of \(9.6 \times 10^{17}\) cm\(^2\). This limit is conservative, as the emitting area is generally thought to be far smaller than 10% of the white dwarf.

This emitting-area constraint yields a lower limit to temperature, since a cooler emission region can only produce the required luminosity by increasing its size. We can use the concept of a local Eddington luminosity to define an upper limit to temperature.

For a star accreting over a fraction, \(f\), of its surface, but which is still accreting radially, the Eddington luminosity is simply \(f L_{\text{Edd}}\). So the temperature of the whole white dwarf, when accreting at the Eddington limit, is the maximum temperature for any size of emission region. This temperature is given by

\[
T_{\text{Edd}} = \left( \frac{L_{\text{Edd}}}{4\pi R_\odot^2} \right)^{1/4}
\]

(5.6)

Substituting Eqn. 5.3 for \(L_{\text{Edd}}\), and Eqn. 5.5 for \(R_{\text{wd}}\), we have an upper limit for temperature as a function of \(M_{\text{wd}}\) alone.

\[
T_{\text{Edd}} = 7.39 \times 10^{4} \left[ \frac{M_{\text{wd}}/M_\odot}{(M_{\text{wd}}/M_\odot)^{2/3} - (M_{\text{wd}}/M_\odot)^{2/3}} \right]^{1/4} \text{kelvin}
\]

(5.7)

For a white-dwarf mass of 0.6 \(M_\odot\) the temperature limit is \(6.2 \times 10^{5}\) K (53 eV); for \(M_{\text{wd}} = M_\odot\) the limit is \(8.8 \times 10^{5}\) K (76 eV).

We now have physical limits on the allowed \(kT - N_H\) region for polars, but can also consider expected luminosities. Patterson (1984) derives an empirical relation for the mass transfer rate of a cataclysmic variable as a function of orbital period,

\[
\dot{M} = 5.1^{+2}_{-2} \times 10^{-10} P_4^{-3.2+0.3} M_\odot \text{yr}^{-1}
\]

(5.8)

where \(P_4\) is the orbital period in units of 4 hours. From this we can calculate the expected luminosity from the mass transfer rate very simply,

\[
L_{\text{acc}} = G M \dot{M}/R_{\text{wd}}
\]

(5.9)

\[
= 1.3 \times 10^{33} \dot{M}_{16}(M_{\text{wd}}/M_\odot)(10^6 \text{ cm}/R_{\text{wd}}) \text{ erg s}^{-1}
\]

(5.10)

\(L_{\text{acc}}\) is the bolometric accretion luminosity and \(\dot{M}_{16}\) is the accretion rate in units of \(10^{16} \text{ g yr}^{-1}\).
5.4.2 Results

The WFC constraints on the spectra of all bright polars are presented in Appendix E. As there are more parameters than data points these constraints are not tight, and the theoretical limits are useful for constraining the allowed regions.

Figure 5.11 is a useful summary of the constraints for all sources. The allowed regions of Appendix E have been normalised by area and summed. The form of the constraints is clear from this plot. For a given filter ratio the spectrum is either cool and heavily absorbed, or hot and little absorbed. The absorbed spectra are more luminous. For bright sources the relationship between \( N_H \) and \( kT \) is well defined, and an independent measure of \( N_H \) could give a precise measurement of temperature and luminosity. In all cases the temperatures are limited to \( kT \geq 10 \text{ eV} \) by the emitting area constraint. Absorbing columns are limited to \( N_H \leq 10^{20} \text{ cm}^{-2} \) which for most polars is a factor of a few less than the total galactic value.
Figure 5.12: The spectral constraints placed on the spectrum of QQ Vul by the WFC survey observation. The two plots show the constraints for the two sets of filter ratio in Table 5.2 (S1 peak to the left). The allowed regions are shaded (68% and 95% confidence intervals), and are truncated by the emitting area limit (left) and Eddington temperature (right). The contours are of luminosity: \(7.8 \times 10^{37} \text{erg s}^{-1}\), \(10^{35} \text{to} 10^{34} \text{erg s}^{-1}\), \(10^{32.5} \times 10^{31}\) and \(3 \times 10^{31} \text{erg s}^{-1}\) are plotted (listed from the left). The dashed contour is the bolometric accretion luminosity predicted by the relation of Patterson (1984)

(Stark et al., 1984). This provides independent evidence that polars are local sources on the galactic scale. In most cases the maximum temperatures are limited by the Eddington value (Sect. 5.4.1), which also places the limit on the minimum luminosity. Allowed luminosities are usually consistent with the \(P_{\text{orb}} - \dot{M}\) relation of Patterson, 1984, (plotted as dashed contours in Appendix E), though RE 1307 is a notable exception.

**Accretion at two poles?**

Three objects show a filter ratio modulation with phase (Sect. 5.3). In QQ Vul and RE 1307 we are probably seeing distinct emitting regions at different temperatures. These could be different magnetic poles, or could be simply different longitudes around a single pole. Other models are possible, for instance, phase dependent absorption of a single temperature pole, and this is considered implicitly through working in the \(kT - N_H\) plane. In the case of BL Hyi, mean count rates demand a model more complex than the absorbed black-body.

Fig. 5.12 shows the constraints on the two emission components of QQ Vul, identified in Fig. 5.9 and Table 5.2. The difference between the components can be described as changes
Figure 5.13: The spectral constraints placed on the spectrum of RE 1307 by the WFC survey observation. See the caption of Fig. 5.12. The expected luminosity lies outside the plot area; thus RE 1307 is more luminous than predicted by Patterson.

In temperature or absorption alone. Assuming the absorption is not variable I can limit the interstellar absorption to $4 \times 10^{19} < N_H < 9 \times 10^{19}$ cm$^{-2}$. Luminosities predicted by Patterson’s relation suggest temperatures in the range 20–30 eV.

In RE 1307 the difference in spectra is more dramatic. Assuming no variable absorption, and considering the 68% confidence regions, I find temperatures in the range 10–20 eV for the S2a emitting region and 20–50 eV for the S1a region; with $10^{19} < N_H < 5 \times 10^{19}$ cm$^{-2}$. The colour of emission is well explained by this model, though the required luminosities are much higher than would be expected. RE 1307 has the shortest orbital period of all polars, and in current evolutionary models would be expected to have a low accretion rate. The empirical relation of Patterson suggests $L_{acc} \sim 6 \times 10^{31}$ erg s$^{-1}$, though both emission regions studied here must have $L_{bb} > 10^{33}$ erg s$^{-1}$; demanded by the enormous distance of $\sim 1000$ pc found by Osborne et al. (1994). It seems then that RE 1307 was probably discovered during an episode of unusually high accretion, and that its discovery was fortuitous. Indeed, it was not detected in a 20 ksec observation with the ROSAT PSPC about two years later.

This picture of the EUV emission of RE 1307 would be satisfactory, but for the measured interstellar column. This is limited to $N_H < 5 \times 10^{19}$ cm$^{-2}$; yet we know from the HI radio survey of Stark et al. (1984) that the total galactic column in the direction of RE 1307 is $2 \times 10^{20}$ cm$^{-2}$. This requires that 75% of the HI in this direction lies well above the galactic
Figure 5.14: The spectral constraints placed on the spectrum of BL Hyi by the WFC survey observation. See the caption of Fig. 5.12. The 'S2a peak' spectrum (right hand panel) requires an unfeasibly large emitting area; providing some evidence of non-black-body emission (see text).

plane, which seems unlikely. This result may be a consequence of assuming a black-body spectrum when it is inappropriate. The spectrum will be modified by opacity in the white-dwarf atmosphere, possibly significantly distorting the broadband EUV fluxes.

BL Hyi

The WFC survey observation of BL Hyi is certainly the most spectacular, though the interpretation is not clear (Sect. 5.3). Fig. 5.14 shows the constraints on the black-body model for the phase intervals of Fig. 5.9, under the assumption of course that the mean filter ratios reflect the true source spectrum.

The S1a peak is perfectly consistent with a typical AM Her spectrum; e.g. $kT \sim 30$ eV, $N_H \sim 5 \times 10^{19}$ cm$^{-2}$ and $L_{bb} \sim 10^{32}$ erg s$^{-1}$, consistent with that predicted by the $P_{orb} - \dot{M}$ relation of Patterson (1984). The filter ratio of the S2a peak is so extremely soft that it requires an unphysically large emitting area of $\sim 0.1A_{ud}$ even with $N_H < 10^{19}$ cm$^{-2}$. No fit is allowed with $N_H$ higher than this, indicating that if this really is a stable emission region then the spectrum must deviate strongly from that of a black body.

This deviation could arise from absorption by partially ionised metals, which can lead to
very effective attenuation of S1a flux, whilst allowing through radiation in the S2a band-pass. Warm absorption such as this has been shown to have a substantial impact on the EUV spectrum of some isolated white dwarfs (Barstow, 1990). In cataclysmic variables the absorption might arise from the WD atmosphere itself, or from material in the ‘stagnation region’, where the accreting material is threaded by the white dwarf’s magnetic field.

I have investigated the possible effects of such an absorber using the model of Done et al. (1992). This considers absorption from the ground states of ten elements; H, He, C, N, O, Ne, Mg, Si, S and Fe. A simple ionisation balance is calculated, under the assumption that neither radiative transfer nor collisional ionisation are important. I make no distinction between the two possible absorber locations when formulating the model, but this can be investigated through the best fitting values of the model parameters. These parameters are: the temperature of the absorbing material, $T_{\text{abs}}$ [K], the column density of the material, $N_{\text{abs}}$ [cm$^{-2}$] and the density of ionising photons; usually expressed as the ionisation parameter, $\xi$. In the following models, $\xi$ is given by

$$\xi = L/(N_e R^2)$$

where $L$ is the integrated luminosity between 5 eV and 300 keV, $N_e$ is the number density of electrons and $R$ is the distance between the absorbing material and the ionising source.

Grids of spectra in the $\xi - N_{\text{abs}}$ plane have been calculated for several $T_{\text{abs}}$. An input black body spectrum is absorbed by the opacity predicted by the warm absorber model, and the result absorbed further by a cold interstellar column. The resulting grids of spectra have been folded through the response of the WFC and normalised to the measured count rates of BL Hyi. The predicted filter ratios then constrain the fit region, while the distance to BL Hyi (128 pc, Warner, 1987) is used to calculate the input black-body and output warm-absorbed luminosities.

Figure 5.15 shows one such grid. I have assumed an input spectrum of a 20 eV black body, and an interstellar absorption column of $10^{19}$ cm$^{-2}$. For this grid I have set the warm absorber temperature, $T_{\text{abs}}$, to the same temperature as the black body spectrum (a crude approximation to a model atmosphere). It is clear that is it possible to both increase and decrease the output filter ratio through warm absorption. With no warm absorber this spectrum would yield a filter ratio of 0.6. To reduce the filter ratio to the measured value of $\sim 0.1$ I require a luminosity of $10^{34}$ erg s$^{-1}$, which is high but is allowed.

Figure 5.16 shows an example of a spectrum which yields the observed filter ratio. Its position on the grid is marked with a $\bigcirc$ in Fig. 5.15. A mass of edges attenuate the S1a
Figure 5.15: A contour plot of S1a:S2a filter ratio for a 20 eV black body spectrum absorbed by a grid of warm absorbers. Also plotted (dashed) are contours of luminosity. It is clear that the filter ratio can be reduced to that observed in BL Hyi ($\sim 0.1$) with a reasonable luminosity. The position of the spectrum plotted in Fig. 5.16 is marked with a $\oplus$. 
Figure 5.16: A spectrum taken from the grid of Fig. 5.15. A 20 eV black-body is shown unabsorbed and then absorbed by the warm absorber model of Done et al. (1992). Both spectra have been absorbed with a cold interstellar column of $10^{19} \text{ cm}^{-2}$. The S1a flux is strongly attenuated by edges of partially ionised metals, yielding the observed BL Hyi 'S2a-high' filter ratio ($\sim 0.1$).

flux, most notably that of L-shell OV, though also important are edges of OVI, NeV/VI, and MgV/VI. The HeII edge can also be important, if very strong, since the S2a bandpass extends softwards of this edge with a small effective area.

Obviously there are too many parameters to allow a unique fit to a simple filter ratio, but we can consider the parameter ranges over which we can achieve a large decrease in the filter ratio. The reduction is most easily achieved with a high $T_{\text{wabs}}$, which is set at $2.3 \times 10^5 \text{ K} \ (20 \text{eV})$ for Fig. 5.15. This is the same temperature as the input spectrum, which I take as an upper limit, and is higher than that measured for the line emitting gas in polars (Cropper, 1990). Lower temperatures are allowed, e.g. $3 \times 10^4 \text{ K}$, but the required luminosity increases uncomfortably and the observed ratio is not reproduced at all at $T_{\text{wabs}} = 1 \times 10^4 \text{ K}$. The other warm absorber parameters, $N_{\text{wabs}}$ and $\xi$ are also surprisingly well constrained. Typically I find $\xi \sim 1 - 2$ and $N_{\text{wabs}} \gtrsim 3 \times 10^{22} \text{ cm}^{-2}$. This column is consistent with the absorbing material lying in a stagnation region. This region must lie near the point at which the magnetic pressure equals the ram pressure of the accretion stream (e.g. Leibert &
Stockman, 1985; Mukai, 1988). Equating these pressures gives a radius of \(1-2 \times 10^{10} \) cm, and implies a line of sight path length through the region of order \(10^8 - 10^9 \) cm. The allowed values of \(N_{\text{abs}}\) then suggest densities of \(10^{13} - 10^{14} \) cm\(^{-3}\), consistent with that of the line emitting gas (Leibert & Stockman, 1985).

It seems than that the extreme filter ratio observed in BL Hyi can be explained through absorption by warm material in a stagnant region of the accretion flow. It is also possible for this process to occur in the white-dwarf atmosphere, though the current model is a rather crude representation of an atmosphere.

The alternative explanation (discussed above) is that the observed ratio is due to a chance accumulation of flares in S2a only. A recent ROSAT pointed observation has made this the favored explanation, as BL Hyi was seen to exhibit a soft-X-ray light curve dominated by chaotic flickering (Schwope & Beuermann, 1993).
Chapter 6

Intermediate polars

6.1 Full sample

In Sects. 4.2.3 and 4.2.4, I present the WFC survey count rates for a large sample of cataclysmic variables. The sample includes twenty-two known or suspected intermediate polars, drawn largely from the Ritter Catalogue of cataclysmic variables (Ritter, 1990; Ritter & Kolb, in press).

Identification as an intermediate polar is through the detection of coherent periods, shorter than the orbital period, in X-ray or optical light curves. As a result, cataclysmic variables originally classified differently have often later been moved to the intermediate-polar class. The membership of several systems is uncertain. Since my analysis was performed, Patterson (1994) has published a detailed object-by-object discussion of the membership of the class. The list is not identical to my sample, so in Table 6.1 I present a combined list showing the overlap between my sample and Ritter’s and Patterson’s lists.

In Table 6.2 I present a combination of Tables 4.4 and 4.5 with only the intermediate polars. Three sources are detected with greater than 99.9% confidence; two were noted in the initial survey analysis, EX Hya and RE0751; and the third found through this analysis, SW UMa. The status of SW UMa as an intermediate polar is uncertain (see Sect. 6.3). Three more sources are detected with greater than 95% confidence, FO Aqr, TW Pic and AE Aqr, but these must be regarded as doubtful, since ~ 2 such detections are to be expected by chance.

In Fig. 6.1 I plot the S1a and S2a count rates against maximum optical magnitude (from Ritter & Kolb, in press), and simple EUV/optical energy flux ratios against optical flux. The EUV/optical ratios of EX Hya and RE0751 (and perhaps FO Aqr) are higher than most of
Intermediate polars in the WFC all-sky survey

Table 6.1: A list of known or suspected intermediate polars, drawn from Ritter & Kolb (in press) and Patterson (1994) (R and P respectively).

<table>
<thead>
<tr>
<th>Object</th>
<th>R</th>
<th>P</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
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</tr>
<tr>
<td>RE0751</td>
<td>*</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>FO Agr</td>
<td>*</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>TW Pic</td>
<td>*</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>SW UMa</td>
<td>?</td>
<td>?</td>
<td></td>
</tr>
<tr>
<td>AE Agr</td>
<td>*</td>
<td>*</td>
<td></td>
</tr>
<tr>
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<td>*</td>
<td></td>
</tr>
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<td>?</td>
<td></td>
</tr>
<tr>
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<td>*</td>
<td></td>
</tr>
<tr>
<td>V345 Pup</td>
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<td></td>
<td></td>
</tr>
<tr>
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<td></td>
<td></td>
</tr>
<tr>
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<td></td>
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</tr>
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<tr>
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<td>AO Psc</td>
<td>*</td>
<td>*</td>
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<tr>
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</tr>
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</tr>
<tr>
<td>V471 Tau</td>
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</tr>
<tr>
<td>V1062 Tau</td>
<td>*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>VZ Pyx</td>
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<td></td>
</tr>
</tbody>
</table>

* Listed as an intermediate polar in the Ritter Catalogue of cataclysmic variables (Ritter & Kolb, in press). 
  * Listed in Patterson (1994).

? Listed as an intermediate polar in the Ritter Catalogue of cataclysmic variables (Ritter & Kolb, in press). *?* indicates a possible member.
Table 6.2: Intermediate polar in the ROSAT WFC survey.

<table>
<thead>
<tr>
<th>Object</th>
<th>S1a Count Rate [sec^{-1}]</th>
<th>( \sigma^a )</th>
<th>S2a Count Rate [sec^{-1}]</th>
<th>( \sigma^b )</th>
<th>Det.(^c) flag</th>
<th>( V_{\text{max}} )</th>
<th>( V_{\text{min}} )</th>
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<td>51</td>
<td>56</td>
<td>14.55</td>
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<td>10</td>
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<td>21</td>
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<td>26</td>
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<td>0.0</td>
<td>1.2</td>
<td>2.4</td>
<td>-2.11</td>
<td>*</td>
<td>14.3</td>
</tr>
<tr>
<td>SW UMa</td>
<td>7.5</td>
<td>4.4</td>
<td>11</td>
<td>14</td>
<td>3.14</td>
<td>**</td>
<td>9</td>
</tr>
<tr>
<td>AE Aqr</td>
<td>4.3</td>
<td>2.0</td>
<td>7.2</td>
<td>9.2</td>
<td>2.29</td>
<td>*</td>
<td>10.9</td>
</tr>
<tr>
<td>BG CMi</td>
<td>2.9</td>
<td>0.9</td>
<td>5.3</td>
<td>6.9</td>
<td>1.63</td>
<td>*</td>
<td>14.3</td>
</tr>
<tr>
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<td>0.4</td>
<td>4.9</td>
<td>7.1</td>
<td>1.05</td>
<td>21</td>
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<tr>
<td>DQ Her</td>
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<td>0.00</td>
<td>14.2</td>
<td>17.7</td>
</tr>
<tr>
<td>V348 Pup</td>
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<td>0.0</td>
<td>1.5</td>
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</tr>
<tr>
<td>RX 0028</td>
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<td>10</td>
<td>-</td>
</tr>
<tr>
<td>V347 Pup</td>
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<td>2.5</td>
<td>3.9</td>
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</tr>
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<td>13.6</td>
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</tr>
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</tr>
<tr>
<td>H 0616</td>
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<td>6.0</td>
<td>2.42</td>
<td>13.2</td>
<td>-</td>
</tr>
<tr>
<td>S 193</td>
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<td>0.0</td>
<td>4.2</td>
<td>7.5</td>
<td>-0.47</td>
<td>13</td>
<td>-</td>
</tr>
<tr>
<td>RX 1712</td>
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<td>-</td>
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<td>15</td>
<td>0.73</td>
<td>15.6B</td>
<td>16.7B</td>
</tr>
<tr>
<td>1H 0253</td>
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<td>0.0</td>
<td>10</td>
<td>19</td>
<td>-</td>
<td>&gt;23</td>
<td>-</td>
</tr>
<tr>
<td>GK Per</td>
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<td>0.0</td>
<td>17</td>
<td>31</td>
<td>-0.32</td>
<td>10.2</td>
<td>14.0</td>
</tr>
</tbody>
</table>

\(^a\) Bayesian count rates (Sect. 3.1.2); 0 indicates most probable value, L68 & U68 define the 68% confidence interval, U90 is the 90% confidence upper limit.

\(^b\) Deviation from background count rate (Sect. 4.2.4).

\(^c\) Detection flag, ** indicates > 99.9% confidence, * indicates > 95%.
Figure 6.1: WFC count rates against maximum V band magnitude (not including flares), and a simple EUV:optical flux ratio against the optical flux (assuming a flat spectrum in each band). For detected systems (flagged in Table 6.2) the Bayesian “most probable” count rates are plotted. For non-detected systems 90% upper limits are used. The top panels are S1a; bottom panels S2a.
the upper limits of the undetected systems, so it seems these systems are unusually bright EUV sources. SW UMa, and perhaps AE Aqr and TW Pic, have ratios consistent with the upper limits, so these may represent typical EUV/optical flux ratios for intermediate polars.

6.2 EX Hya

EX Hya has been well studied in X-rays, and consistently exhibits substantial low-temperature emission. Singh & Swank (1993) present Einstein Solid-State Spectrometer data, which require a separate low temperature component with $T \sim 0.8$ keV. Such components yield strong line emission in the bandpass of the WFC (Sect. 7.5). More recently, ASCA observations show that the postshock plasma is non-isothermal, though the spectra are too complicated to be fit with a simple two component model (Ishida, Mukai & Osborne, 1994).

Folding the fitted spectra of Singh & Swank through the response of the WFC I find count rates in the range 0.0-0.3 cts/s. The value is strongly dependent on absorption column density, which is spin-phase dependent and only poorly constrained by the Einstein data. It is clear that the soft-X-ray emission previously observed from EX Hya can explain the observed count rates. No distinct EUV emission is required.

EX Hya is the only intermediate polar with count rates high enough for useful time information to be available (see Fig. 4.6). The light curves are presented in Fig. 6.2, plotted both raw and folded at the white-dwarf-spin period. A possible modulation is apparent in both filters, peaking at around $\phi = 0.1 - 0.2$. $\phi = 0.0$ corresponds to X-ray maximum in the ephemeris of Jablonski & Busko (1985). The ephemeris phase error is indicated in the folded S1a panel, and is of the same order as the difference between the known X-ray and suspected EUV maxima.

6.3 SW UMa

SW UMa is detected with high confidence in the WFC survey (> 99.9%). It’s place as an intermediate polar, however, is less certain. Shafter, Szky & Thorstensen (1986) found optical and X-ray periods at 81.8 and 15.9 min. However, pointed observations with EXOSAT (Szkody, Osborne & Hassall, 1988) and the ROSAT PSPC (Rosen et al., 1994), have not detected these periods. They have not been detected again in the optical either, and Robinson et al. (1987) find superhumps, showing SW UMa is an SU UMa system.

Taking Rosen et al. ’s best fit to the ROSAT PSPC pointed spectrum, $N_H = 4 \times 10^{19}$ cm$^{-2}$,
Intermediate polars in the WFC all-sky survey

Figure 6.2: The raw and white-dwarf-spin folded light curves of the intermediate polar: EX Hya. All errors are the 68% Bayesian confidence intervals (Sect. 3.2.2). S1a points are marked with circles, S2a with crosses. The ephemeris, \( T_{\text{max}} = \text{JED}2437699.8905(\pm6) + N \times 0.046546514(\pm13) - N^2 \times 8.17(\pm71) \times 10^{-13} \), is that of Jablonski & Busko (1985).
Intermediate polars in the WFC all-sky survey

\( kT_1 = 0.37 \text{ keV}, \ f_1(2 - 6 \text{ keV}) = 1.7 \times 10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2} \),

\( kT_2 = 2.8 \text{ keV}, \ f_2(2 - 6 \text{ keV}) = 1.1 \times 10^{-12} \text{ erg s}^{-1} \text{ cm}^{-2} \),

and folding through the response of the WFC, I find predicted count rates of 0.006 cts/s in S1a and S2a. These are remarkably close to the observed “most probable” count rates of 0.0075 and 0.0059 cts/s. Clearly, the WFC survey detection of SW UMa is consistent with a detection of the X-ray emission components; no distinct EUV emission is required.

6.4 RE 0751

RE 0751 is the final intermediate polar detected with confidence in the WFC survey. It was first detected as a source through the initial survey analysis and identified as an intermediate polar by Mason et al. (1992). Mason et al. point out that the WFC filter ratio is very hard, \( S1a/S2a > 3 \), and argue that this requires a soft spectrum. This is because the S2a filter has a hard X-ray leak, so a heavily absorbed hard spectrum will actually appear relatively soft. This interpretation was confirmed with a pointed PSPC observation (Duck et al., 1994), in which two distinct spectral components are detected; a hard “bremsstrahlung” component and a soft “black-body” component. This X-ray spectrum, and a detection of polarised cyclotron emission by Rosen, Mittaz & Hakala (1993), shows that RE 0751 has a magnetic field comparable with the AM Hers. As such it is unique, and is becoming known as the first truly intermediate polar.

6.5 FO Aqr

The possible detection of FO Aqr may be explained by a low temperature X-ray emission component. Such a component was seen to dominate a recent ASCA observation below \( \sim 1 \text{ keV} \) (Mukai, Ishida & Osborne, 1994).

6.6 Non-detections

The WFC survey has shown that intermediate polars are not strong EUV sources. Only in RE 0751 is a true EUV emission component apparent, and the upper limits to the EUV/optical flux ratios of other systems show that this is an unusual characteristic.

This is important because the observed X-rays of intermediate polars are a factor \( \sim 4 \) under-luminous, compared with theoretical predictions (e.g. Patterson, 1994). The missing
luminosity has usually been ascribed to unobserved optically-thick emission in the EUV waveband (rather like AM Hers); Patterson describes the EUV as the "Holy-Grail of the energy balance" in intermediate polars.

Unfortunately the WFC survey does not reveal the path to the Grail. The survey covers only the hard end of the EUV waveband (Fig. 3.3), allowing room for undetected yet luminous soft emission. Lower temperatures are to be expected in intermediate polars, as the flow is less collimated than in AM Hers and the emission region is larger. In addition, hard X-ray observations of intermediate polars usually show very high line-of-sight column densities (> $10^{26}$ cm$^{-2}$; e.g. Norton & Watson, 1989; Ishida, 1991), probably due to the accreting material itself, as it follows the magnetic field lines out of the orbital plane. These column densities are high enough to wipe out any EUV flux that must traverse the same line of sight.

Though a non-detection in the WFC does not rule luminous EUV emission, it does place upper limits on the temperature of any EUV component, and lower limits on the absorption column density.

I have calculated general limits implied by a non-detection in the WFC survey, which I present in Fig. 6.3. The limits depend far more strongly on spectral parameters than on distance, so can be usefully applied to the class as a whole.

The limits are calculated by considering black-body spectra over a large range of $T_{BB}$ and $N_H$, which are folded through the response of the WFC to give expected count rates for suitable distances and emitting areas. For Fig. 6.3 I assume a detection threshold in the WFC survey of 0.01 cts/s, and a $10^6$ cm radius white-dwarf accreting over 10% of its surface. The two curves are for distances of 100 and 1000 pc.

Even at 1000 pc the accretion region must be cooler than $7 \times 10^4$ K to escape detection in the S2a filter. With absorption this temperature limit rises to $\sim 4 \times 10^5$ K at a column density of $10^{23}$ cm$^{-2}$. These limits do not depend strongly on distance. Essentially, they define the lowest temperatures to which the WFC is sensitive. These limits do not rule out a very large luminosity EUV component. At 100 pc, with little absorption, the temperature limit of $5 \times 10^4$ K implies a luminosity limit of $4 \times 10^{32}$ erg/s. With absorption the limit rises to $> 10^{35}$ erg/s.
Figure 6.3: This figure shows the limits placed on an optically thick EUV emission component by a non-detection in the WFC survey. A conservative count rate limit of 10 counts/ksec is used, and a black body spectrum is assumed. The white dwarf is taken to have a radius of $10^9$ cm and to be heated over 10% of its surface. The contours are for distances of 100 and 1000 pc (100 pc to the left), and mark the boundary between detection and non-detection in the WFC survey. Spectra to the left of the contours would not be detected.
Chapter 7

Non-magnetic cataclysmic variables

In Chap. 2 I describe the X-ray and EUV emission from non-magnetic cataclysmic variables, and discuss its origin. Here I present the relevant results from the WFC all-sky EUV survey, and some simultaneous measurements made at other wavelengths. In Fig. 7.1 I reproduce the plots of Sect. 4.5, but with only the detected non-magnetic cataclysmic variables.

Four non-magnetic cataclysmic variables were detected as bright sources in the initial WFC survey analysis (Sect. 4.2.1 and Pounds et al., 1993). Three of these are dwarf novae, SS Cyg, VW Hya and Z Cam; all of which are known to have been in outburst for at least part of their WFC coverage. SS Cyg and VW Hya are among the brightest dwarf novae, and have both been detected in the EUV previously (Pringle et al., 1987; Jones & Watson, 1992). Their detections in the WFC survey were anticipated, so multi-wavelength observations were scheduled to coincide with the survey coverage. The multiwavelength studies have proved rather successful, and I present the results in Sects. 7.1 and 7.2. Z Cam has not previously been seen as an EUV source, I discuss its detection in Sect. 7.3.

The fourth system, IX Vel, is a nova-like variable of the UX UMa sub-class. These systems appear as dwarf novae stuck in permanent outburst, so a similar optically-thick ultra-soft emission component may be expected. However, in Sect. 7.5 I show that the detection of IX Vel is probably through line emission from the optically-thin hard X-ray component.

In my extended analysis of the WFC survey database (Sect. 4.2.3) I detect a fifth non-magnetic cataclysmic variable, RX J0640-24. This source was identified as a dwarf nova by Beuermann & Thomas (1993) though nothing else has been published as yet. They find $m_o \sim 15$ which implies an extreme EUV/optical flux ratio when compared with other dwarf novae (see Fig. 7.1). However, this ratio may be understood if RX J0640-24 was in outburst during the survey but in quiescence at the time of its optical identification (see Sect. 7.4.1).
Several other dwarf novae are known to have been in outburst during their survey observations. In Sect. 7.4.2 I find upper limits to the WFC count rates of all of these, and consider the limits on their EUV/optical ratios.

7.1 VW Hyi: a detailed study

This work was carried out in collaboration with F. Verbunt, M.G. Watson, T. Belloni, T. Naylor, S.R. Duck and M. Ishida. It is published as Wheatley et al. (1995b).

7.1.1 Summary

We combine ROSAT, Ginga, and EXOSAT observations to investigate the X-ray and extreme-ultraviolet fluxes of VW Hyi in quiescence and throughout an ordinary dwarf-nova outburst. We show that the quiescent spectrum is consistent with emission from material heated to $\sim 12$ keV and cooling through the X-ray band to temperatures below our sensitivity range. During outburst the X-ray flux is suppressed, and recovers only at the very end of the optical outburst. The recovery starts intermittently with $\sim 100\%$ modulations on a timescale of about 200 s. A very soft component is detectable only in the extreme ultraviolet, after outburst maximum, and disappears before the end of the optical outburst. The luminosity of this component is limited to less than that expected from the boundary layer. The late
recovery of the hard X-ray flux indicates that this flux is regulated by processes occurring very close to the white dwarf.

7.1.2 Introduction

During outburst a dwarf nova shows large variations in flux at all observed wavelengths, ranging from X-rays via extreme ultraviolet and ultraviolet to the optical. The variations at different wavelengths are not always in concert. For example, when the rise is rapid the ultraviolet flux is delayed with respect to the optical, whereas the rise is simultaneous in slowly developing outbursts, (for a review, see Verbunt, 1987).

The intervals between dwarf-nova outbursts are unpredictable, and the outbursts last several days to weeks; both factors hampering efforts to obtain complete coverage of X-ray light curves throughout an outburst. As a result our knowledge of the variation in X-ray flux during a dwarf-nova outburst is limited to only a few systems, and is sketchy in those (for reviews, see Córdova & Mason, 1984; Córdova, 1995). Study of the extreme-ultraviolet flux variations is further impeded by interstellar absorption. Knowledge of the extreme-ultraviolet and X-ray fluxes is required to obtain an overall view of the energy emission of a dwarf nova, both in quiescence and in outburst.

The dwarf nova VW Hya is relatively bright in the optical, with $m_v$ ranging from 14 in quiescence to 9.5 at peak of ordinary outburst, and 8.5 at peak of superoutburst. The system also shows outbursts rather often, every 28 days on average. It is therefore an obvious target for the study of dwarf-nova outbursts at various wavelengths and accordingly was observed in a large campaign that lasted more than two months. This study combined ground-based optical data from the observers of the Variable Star Section of the New Zealand Royal Astronomical Society with ultraviolet data from IUE, extreme-ultraviolet data from Voyager and X-ray data from EXOSAT (Pringle et al., 1987). The interpretation of the extreme-ultraviolet data and X-ray data could be improved after it was discovered that the interstellar absorption towards VW Hya is the lowest determined for any dwarf nova (Polidan, Manche & Wade, 1990). As a result, it is now clear that the flux at X-ray and extreme-ultraviolet wavelengths is an order of magnitude lower than the flux at ultraviolet and optical wavelengths during superoutburst (Manche et al., 1991; Van Teeseling, Verbunt & Heise, 1993). A ROSAT pointed observation shows that the X-ray flux is smaller than the ultraviolet and optical flux also in quiescence (Belloni et al., 1991; Van Teeseling & Verbunt, 1994).
Table 7.1: Journal of observations for VW Hyi giving, for each instrument, the Julian dates of the beginning of the first and the end of the last observation, the total effective exposure time obtained, and the average count rate.

<table>
<thead>
<tr>
<th>Instrument</th>
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<th>Last Observation</th>
<th>Texp(s)</th>
<th>Cts/s</th>
</tr>
</thead>
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<td>0.34-3.2</td>
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<td>0.021(5)</td>
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<td>2448211.025</td>
<td>2559</td>
<td>0.023(6)</td>
</tr>
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<td>2448202.645</td>
<td>22432</td>
<td>0-10</td>
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<td>IUE</td>
<td>2448198.553</td>
<td>2448201.047</td>
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</table>

In this section we analyse data obtained during the ROSAT all-sky survey, as well as a pointed ROSAT observation, to study the behaviour of the X-rays of VW Hyi in quiescence and during ordinary outburst (Sects. 7.1.3 and 7.1.4). Our results are used to re-interpret the EXOSAT data from the three ordinary outbursts observed during the multi-wavelength campaign (Sect. 7.1.5). A discussion of our results follows in Sect. 7.1.6.

7.1.3 Observations and data reduction

ROSAT all-sky-survey data

VW Hyi lies close to the southern ecliptic pole, and as such was observed over an unusually long period during the ROSAT sky survey: 8 days with the Position Sensitive Proportional Counter (PSPC) and 26 days with the Wide Field Camera (WFC). A log of the observations is given in Table 7.1.

The PSPC, sensitive to photons with energies in the range of 0.1-2.5 keV, scanned VW Hyi between 1990 Nov 1 and 1990 Nov 9. Nominally, the position of every source in the scan plane is observed for up to thirty seconds every orbit of the spacecraft (96 minutes). However, observations of VW Hyi were badly affected by data losses due to passage of the South Atlantic Anomaly (SAA), and only a few scans were made per day, typically three or four consecutively. In total, 32 scans are available with exposures ranging from 11 to 27 seconds. The total exposure time is 676 s. Since the scans are naturally grouped in days, we improve statistics by re-binning the light curve in 9 bins. The analysis was performed with the EXSAS package (Zimmerman et al., 1992) using the techniques described by Belloni, Hasinger & Izzo (1994). Source photons were extracted from a circular region of 6.7 radius around the
Figure 7.2: Light curves of VW Hyi obtained during the time of the ROSAT all-sky survey. From top to bottom at decreasing wavelengths: visual energy fluxes ($\lambda F_{\lambda}$) measured at the South African Astronomical Observatory (squares), by the Royal Astronomical Society of New Zealand (circles) and by the Fine Error Sensor aboard IUE (crosses); ultraviolet energy fluxes ($\lambda F_{\lambda}$) measured by the Short Wavelength Primary camera of IUE, averaged over 1250–1950 Å; EUV count rates measured with the S1a (circles) and S2a (triangles) filters of the ROSAT WFC; soft X-ray count rates measured with the ROSAT PSPC; and hard X-ray count rates measured with the Ginga LAC.
centroid of the photon distribution. The background was determined through two circular regions of the same radius displaced along the scan direction.

VW Hiy was observed with the WFC between 1990 Oct 22 and 1990 Nov 17, during which 101 scans were made, each with an exposure in the range 10-80 sec. The same scans as with the PSPC were lost due to passages of the SAA. Light curves were extracted using the techniques of Chap. 3. An optimised source-circle radius of 2.5" was used, and the background was determined using twelve regions, each the same size as the source region, aligned along the scan path. In total VW Hiy was observed for 2577s with S1a and 2559s with S2a. These exposures yielded detections in both filters, with mean count rates of $21 \pm 4$ cts/sec$^{-1}$ in S1a and $23 \pm 5$ cts/sec$^{-1}$ in S2a (Sect. 4.2.3). The scans coincident with the PSPC observations have been binned in the same way as these, giving one point per day.

Other observations made during the survey

The Ginga satellite carried a large area proportional counter (LAC) sensitive in the range 2-30 keV (Turner et al., 1989). A one-day pointed observation of VW Hiy was scheduled to coincide with the PSPC survey coverage, and carried out on 1990 Nov 6/7 (Table 7.1). The Ginga data are continuous except for losses due to earth occultation and passage through the SAA, with a total exposure of 22.4 ksec. The data were background subtracted using a local background pointing and methods described by Hayashida et al. (1989) and Williams et al. (1992a).

VW Hiy is routinely monitored in the optical by amateur observers of the Royal Astronomical Society of New Zealand. During the ROSAT survey, additional coverage was obtained from the South African Astronomical Observatory. Notice of the outburst during the ROSAT survey triggered a target-of-opportunity observation with the International Ultraviolet Explorer (IUE), and this process occurred rapidly enough for IUE to catch the full ultraviolet rise. The Fine Error Sensor (FES) aboard IUE, part of the attitude control system, also provides optical monitoring of sources. The optical and ultraviolet data are used in this paper mainly to determine the phase in the outburst cycle during which the X-ray and EUV observations were obtained. A more detailed description of the ultraviolet data will be given elsewhere.
ROSAT pointed data

VW Hyi was also observed with a pointing during the Performance Verification phase with which ROSAT started its active life. The pointing on VW Hyi was obtained on 1990 July 22/23 (Table 7.1). The PSPC data have been published by Belloni et al. (1991) and Van Teeseling & Verbunt (1994); we use the data as reduced by the latter authors, and combine it with the previously unpublished WFC data of the same pointing. The total exposure with the WFC was 8.5 ksec, for which the S1a filter was used throughout. The ROSAT WFC standard analysis yields a count rate of 18.7 ± 2.7 cts ksec⁻¹, after a small correction for the drop in detector efficiency and including a 10% systematic error (Willingale, 1991).

7.1.4 Results

The outburst light curve

In Fig. 7.2 we show the light curves in optical (ground-based and IUE), ultraviolet (IUE), extreme ultraviolet (ROSAT WFC), soft X-rays (ROSAT PSPC) and hard X-rays (Ginga LAC). The optical data show that the outburst fell in the middle of the period during which VW Hyi was observed in the ROSAT all-sky survey. The delay between the optical and ultraviolet rise is better defined than in any previous observation of this much-studied system.

The complete WFC S1a and S2a light curves are plotted in Fig. 7.3. They are found to be indistinguishable from those of a constant source of the same mean count rate (at > 95% confidence, using the P-statistic). There is no significant enhancement of these extreme-ultraviolet light curves during outburst, though the coverage is rather poor and the exposure low. Four WFC points lie within the outburst, but only one is close to the optical and ultraviolet maxima, shortly before JD 2448200. This was made with the hard filter (S1a), so there is little sensitivity to an EUV component close in phase to the ultraviolet emission. The first S2a observation is not until well into the ultraviolet decline, at JD 2448201. The 99% Bayesian upper limits to the count rates in these bins are 0.100 and 0.049 cts/s respectively.

The soft X-ray flux (PSPC) is lower in each of the three observations obtained during the outburst, and the flux in quiescence is higher after the outburst than before. There is a suggestion in the figure that the soft X-ray flux started decreasing before the beginning of the optical outburst. However, the pre-outburst decrease is not significant, especially if we take into account that the flux of VW Hyi shows short-timescale variability of about 40% (Van Teeseling & Verbunt, 1994).
Figure 7.3: The full WFC survey light curve of VW Hyi. The time of outburst is marked by solid vertical lines. S1a points are marked with circles, S2a with squares, and the light curve has been binned up into natural bins determined by the unusually large data gaps. The top panel shows the exposure in each point. The error bars are the Bayesian confidence intervals, solid are for 68% confidence, dotted are 95%.

The hard X-ray observation (Ginga) covers the end of the optical outburst. This clearly defines the moment at which the hard X-rays recover to the quiescent flux level as occurring at the very end of the optical outburst, when the optical flux has returned to the quiescent level. A more detailed look at the Ginga data shows that the flux varied on a time scale of $\sim 200$ s with an amplitude that decreases from close to 100% in the beginning to $\sim 50\%$ at the end of the observation (Fig. 7.4). The 6–10/2–4 keV hardness ratio remains constant throughout this flaring. A dMe star situated just 18\.arcmin from VW Hyi must be considered as a possible source of contamination since it is well within the field of view of Ginga (Van der Woerd et al., 1989). However, the background subtraction to zero cts/s during outburst, the X-ray rise coinciding with the optical return to quiescence and the absence of a star-like flare all indicate that this contamination is negligible.
Figure 7.4: The Ginga LAC (2–10 keV) and pointed ROSAT PSPC light curves, binned at 128 s. The ROSAT observation was spread over more than two days, with large gaps between observing slots, so for plotting purposes the intervals between slots have been compressed and the individual observations spaced equally.

**Quiescent spectrum**

The ROSAT PSPC pointed spectrum has previously been considered by Belloni et al. (1991) and Van Teeseling & Verbunt (1994). These authors found that the spectrum was best fit with optically-thin plasma models (e.g. Mewe, Gronenschild & Van den Oord, 1985 and Kaastra & Mewe, 1993), but that isothermal models gave a deficit of counts at around 1 keV. Van Teeseling and Verbunt found acceptable $\chi^2$ by adding line emission at 1 keV or by adding a low-temperature component. We find that the Ginga observation of quiescence (immediately after outburst) is also inconsistent with a single-temperature model (reduced $\chi^2$ of 1.9 with 14 d.o.f.; Table 7.2).

In this section we extend the earlier analysis by including the WFC measurement from
Table 7.2: Spectral fits to the ROSAT data (PSPC+WFC) from July 1990, as well as to the combined spectra of all observations of quiescence: 1) ROSAT pointed, 2) Ginga post-outburst, 3) WFC survey S1+S2. Four models were used: 1) absorbed optically-thin thermal plasma ("Mewe" model), 2) absorbed "Mewe" model with added emission line, 3) two-temperature absorbed "Mewe" model, 4) cooling plasma model, in which a range of temperatures are summed after weighting with the inverse of the cooling timescale. In the fits to the combined data set the temperatures, line energies, absorbing column densities and relative strengths of components were forced to be the same for the three data sets, but the total fluxes were allowed to vary. The errors represent 95% confidence for one interesting parameter (\(\Delta \chi^2 = 4.0\)).

<table>
<thead>
<tr>
<th>Data set</th>
<th>(N_{\text{H}}) (10^{18}) cm(^{-2})</th>
<th>First component</th>
<th>Second component</th>
<th>Norm. const.(^a)</th>
<th>(\chi^2/\text{d.o.f.})</th>
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<td></td>
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<td>WFC</td>
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<td>Single temperature plus line</td>
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<td>Two temperature</td>
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<td>Cooling plasma</td>
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\(^a^\)Normalisation of Ginga and WFC-survey data sets, relative to ROSAT.
\(^b^\)Temperatures and line energy in units of keV.
\(^c^\)Flux in the band 0.04–10 keV; units of \(10^{-12}\) erg s\(^{-1}\) cm\(^{-2}\).  
\(^d^\)The pointed ROSAT observation of quiescence (PSPC+WFC).
\(^e^\)The Ginga spectrum after the sharp rise at JD 2448202 (Fig. 7.2).
\(^f^\)The ROSAT and Ginga datasets together with the mean WFC survey count rates.
the pointed observation (S1a filter only), and by making simultaneous fits to a combined data set of three observations of quiescence.

We find that including the pointed-WFC count rate in the fits to the PSPC data does not change the conclusions of Van Teeseling and Verbunt. Our best-fitting parameters for an isothermal model and their two-component models are listed in Table 7.2. The cool component in the two-temperature case does not modify the continuum, but adds significant flux only in the form of lines at around 0.1 and 1 keV (see Sect. 7.5.3 and Fig. 7.24). The single-temperature-plus-line fit is consistent with the IUE-measured interstellar absorption column ($N_H = 6 \times 10^{17} \text{cm}^{-2}$), but the extra emission also at 0.1 keV tends to force the $N_H$ to higher values in the two-temperature case ($\sim 7 \times 10^{18} \text{cm}^{-2}$).

We turn now to our fits to the combined observations of quiescence. This data set consists of: a) the pointed ROSAT observation (PSPC+WFC); b) the post-outburst Ginga spectrum; c) the WFC survey observations. The complete count-rate spectrum is plotted as the top panel of Fig. 7.5.

In Fig. 7.6 it is seen that the PSPC hardness ratios do not vary significantly before and after (and even during) the outburst; and that they are the same as those measured during the pointed observation. This encourages us that it is appropriate to fit the Ginga and pointed-ROSAT spectra simultaneously, despite the three-month interval separating them. We don’t use the survey-PSPC spectrum in our combined data set, as the exposure is too low to add useful information, but we do use the WFC survey observation since the S2a filter increases our wavelength coverage. For each model we force all parameters to be the same for each data set, but allow energy-independent normalisation factors to account for different mean fluxes in the non-simultaneous observations. We ignore flux variations within data sets, since none exhibit significant spectral variability (despite strong flaring in the case of Ginga).

To this combined data set we fit the same models as to the ROSAT spectrum alone and present the results in Table 7.2. Considering the non-simultaneity of the observations we find remarkably good fits (reduced $\chi^2$ of 1.5 and 1.6 with 32 d.o.f.). The model and residuals for the single-temperature case are plotted in Fig. 7.5.

The combination of ROSAT and Ginga can not help us distinguish between models, since there is no gain in spectral resolution, but the increased wavelength coverage proves powerful in constraining the two-component models. Figure 7.7 shows the constraints derived from the combined data set and from ROSAT alone. The inclusion of the Ginga spectrum
Figure 7.5: Observed and model spectra for the fits to the combined observations of quiescence. The $\Delta\chi$ residuals are also plotted. The top panels show the single-temperature-plus-line model, the bottom panels the cooling plasma model (see text). The observed spectrum is in units of $\text{cts/s/cm}^2/\text{keV}$; the model spectra are in energy flux units of $\text{keV/s/cm}^2/\text{keV}$. 
constraints the dominant continuum temperature to close to 6 keV. This in turn allows much tighter constraints on the line-emitting components through ROSAT. The absorption column densities from the combined fits are similar to those from ROSAT alone.

Of course, it may well be that the quiescent spectrum of VW Hyi is a combination of a range of temperatures, rather than the sum of two distinct components. We can consider the effect of a range of temperatures by adopting the cooling plasma model of Mushotzky & Szymkowiak (1988), developed for clusters of galaxies. In this model we sum Mewe spectra over a range of temperatures and weight the emission measure at each temperature with the inverse of the emissivity (i.e. with the cooling timescale). This approach is well suited to cataclysmic variables since we may expect a continuous source of shock-heated material, which is then left to cool with little additional heating. The parameters of this model are simply the upper and lower temperature bounds, and a normalisation constant.

We find an acceptable fit to this model with our combined data set, with a reduced $\chi^2$ of
Figure 7.7: Constraints on the main parameters of the two-component spectral fits of Table 7.2. The dashed contours represent fits to the ROSAT-pointed data (PSPC+WFC S1a), the solid contours fits to the combined ROSAT-pointed, Ginga and WFC-survey (S1a+S2a) data. In each case the three contours represent 68, 90 and 99% confidence for two interesting parameters ($\Delta \chi^2 = 2.3, 4.61, 9.21$).
Non-magnetic CVs in the WFC all-sky survey

Figure 7.8: Constraints on the range of temperatures allowed by the fit to the cooling-plasma model of Mushotzky & Szymkowiak (1988).

1.35 (33 d.o.f.). The upper temperature bound is constrained, but the lower temperature is not. This is consistent with the picture that material is shock heated to ~ 12 keV, and then cools through the X-ray band to temperatures below our sensitivity range. The constraints on the two temperature bounds are shown in Fig. 7.8, the residuals on the best fit are presented in Fig. 7.5, and the fitted parameters are listed in Table 7.2. As in the two-temperature model, cool gas contributes lines at 0.1 keV, as well as 1 keV, so the fitted interstellar absorption column is higher than that measured with IUE. If we fix the the \( N_H \) at the IUE value we find a best fitting reduced \( \chi^2 \) of 1.66 (with 34 d.o.f.). An F-test reveals that the improvement in fit by freeing the \( N_H \) is not significant; so although a higher \( N_H \) is favoured, our results are not inconsistent with the IUE measurement.

Outburst spectrum

During the outburst the ROSAT PSPC measured a count rate of 0.4 cts/s (Fig. 7.2). The PSPC data show no evidence for a spectral change, as the hardness ratios obtained during the outburst are compatible with those measured during quiescence (Fig. 7.6). The count rates predicted by scaling from the PSPC count rate for the WFC S1a and S2a are compatible with those actually obtained, and the count rate predicted for the Ginga LAC is within
the confusion range due to background sources. The ROSAT and Ginga data thus show no evidence for spectral change during outburst, and are compatible with a variation in the emission measure only.

7.1.5 Comparison with EXOSAT data.

Quiescence

For each of our fits to quiescent spectra we calculate expected EXOSAT CMA count rates. For the two filters, thin-Lexan and Aluminium-Parylene, the ranges are 0.070–0.074 and 0.022–0.029 cts/s respectively. Figure 7.9 shows the count rate distributions of all CMA observations of VW Hyi throughout the life of EXOSAT. The peaks corresponding to quiescence are obvious, and our ranges of expected count rates are marked. This figure shows that VW Hyi was brighter in X-rays at the time of our observations than it was during the EXOSAT observations. This is possibly related to the outburst recurrence time, which was \( \sim 16 \text{d} \) during the co-ordinated EXOSAT campaign and greater than 30 \( \text{d} \) at the time of our observations.
Outburst

In a series of observations stretching over 70 days, VW Hyi was observed with EXOSAT in quiescence, during three ordinary outbursts, and during one superoutburst. The count rates obtained in the CMA detector with the Al-Par filter are consistently higher during the outbursts than in quiescence, whereas those obtained with the 3000-Lexan filter are observed in outbursts both at higher and at lower levels than in quiescence. Since the energy ranges of the CMA and PSPC show a large overlap, our result that the count rate detected with the PSPC is lower throughout the outburst seems to be in conflict with the EXOSAT results.

The observers of the Variable Star Section of the Royal Astronomical Society of New Zealand provide a good optical light curve of VW Hyi during the EXOSAT observations (see Fig. 1 in Pringle et al., 1987). We cross-correlate the optical light curve of the third outburst with the two earlier ones, to obtain a good estimate of the time intervals between the outbursts, and then shift the time axes of the outbursts to combine the optical and X-ray data of the three outbursts into a single light curve, shown in Fig. 7.10. The combined light curve shows that the count rates in both the Al-Par and thin-Lexan filters are high in the beginning of the outburst, then drop to a level below the quiescent level before recovering again after the end of the optical outburst (in Al-Par the drop below the quiescent level is not statistically significant).

In Fig. 7.11 we show the response curves for the EXOSAT CMA filters as well as for the ROSAT WFC and PSPC, to illustrate that photons with energies less than ~ 60 eV can be detected with the CMA but not with the PSPC or WFC. With this information we can explain the outburst light curves obtained with EXOSAT and with ROSAT. In quiescence, the only components present are those detected by ROSAT and Ginga, i.e. hot, optically-thin spectra discussed in the previous section. During outburst this component drops by a factor ~3-4, as seen in the ROSAT light curve (Fig. 7.2) and, perhaps but not necessarily simultaneously, a very soft component appears; too soft to be detected with the ROSAT instruments but detectable in the EXOSAT CMA with the Al-Par and Lexan filters. In the beginning of the outburst the soft component is bright and enhances the CMA count rate above the quiescent level. At the end of the outburst the soft component has disappeared, so the EXOSAT CMA detects only the hotter components, and at a flux level below the quiescent level. It is worth noting that the S2a filter is as sensitive to the soft component as was the thin-Lexan filter of the CMA. We would have expected a detection of this component if the S2a filter had been in use at peak outburst.
Figure 7.10: Composite light curve of VW Hyi made by combining data from three outbursts of Sep-Oct 1984. The times of individual outbursts were shifted to maximise the cross-correlation of the optical data (●, magnitude scale). EXOSAT CMA Al-Par count rates are shown as ○, thin-Lexan count rates as ×. (Original data from Pringle et al. 1987.)

The EXOSAT observations of VW Hyi during the ordinary outbursts were made with only two filters which, in the presence of more than one component, do not allow a temperature determination. However, during one superoutburst a third filter was used, and Van Teeseling, Verbunt & Heise (1993) showed that the count ratios observed may be obtained by combining the observed quiescent spectrum with an optically-thick spectrum of $T \sim 90000$ K. The observations of the ordinary outbursts may be explained with the same combination. The relative strengths of both components determine the various count ratios, whereas their absolute strengths determine the count rates, thus allowing for variation in both rates and ratios through the outburst. During the superoutburst the soft component has an emitting area small with respect to the white-dwarf surface, and a flux which does not
Figure 7.11: Response curves for the ROSAT PSPC and the two survey filters of the WFC as well as the thin-Lexan and Aluminium-Parylene filters of the EXOSAT CMA.

Contribute significantly at wavelengths accessible to IUE (λ > 1000 Å, see Van Teeseling, Verbunt & Heise, 1993). Its bolometric luminosity is much smaller than the ultraviolet-optical luminosity that is observed from the accretion disk.

We can use the WFC upper limits during outburst to constrain this component, now in ordinary outburst as well as superoutburst. Figure 7.12 shows the maximum allowed luminosity, as a function of temperature, for the S1a and S2a upper limits at JD 2448200 and JD 2448201 respectively. The top panel shows the corresponding emitting areas. We assume a blackbody spectrum, a distance of 65 pc and absorption by the upper limit to the IUE-measured hydrogen column (logNH = 17.18 ± 0.02; Polidan, Mauche & Wade, 1990). The maximum luminosities allowed by the Voyager UVS 650Å upper limit in outburst are also plotted (also Polidan et al.). It is clear that the luminosity must be less than 10^{33} erg/s for any temperature. For temperatures around 90000 K, that found by Van Teeseling et al. to account for the EXOSAT filter ratios, we find that the luminosity is limited to 2 \times 10^{31} erg/s by S2a and 5 \times 10^{32} erg/s by S1a. The S2a filter is far more sensitive than S1a to such low temperatures, but the S1a limit is important since it was made at peak UV flux (Fig. 7.2),
Figure 7.12: 90% upper limits to the luminosity and emitting area of a blackbody spectrum set by the WFC survey observations during outburst. The dotted line represents the S1a point at peak optical outburst, the dashed line the S2a observation during decline. The luminosities are also shown limited by the Voyager UVS 650Å upper limit (solid line). The surface areas of 1.0 and 0.6 $M_\odot$ white dwarfs are indicated with dotted lines.
Non-magnetic CVs in the WFC all-sky survey

and thus can be regarded as a firm upper limit to the EUV flux in outburst. The broadband IUE flux (Fig. 7.2) peaks at $1.2 \times 10^{-8}$ erg cm$^{-2}$ s$^{-1}$, corresponding to $6.1 \times 10^{33}$ erg/s across the IUE-bandpass at 65 pc. For temperatures all the way down to 40,000 K the EUV luminosities are limited to be less than $10^{33}$ erg/s. At this temperature the emitting area rises above that expected for the boundary layer and we enter the regime of the inner accretion disk, from which a substantial UV flux is known to be emitted. For VW Hyi at least, the extreme ultraviolet can no longer be used to hide excess luminosity.

7.1.6 Discussion

Observations of VW Hyi with the hard X-ray (ME) detector of EXOSAT gave rather low count rates and possibly suffered contamination from the M dwarf mentioned in Sect. 7.1.4. The soft X-ray (LE) detector of EXOSAT has a very broad response, extending to the extreme ultraviolet, which can complicate interpretation. The outburst light curve of VW Hyi obtained with the ROSAT PSPC during the all-sky survey, and shown in Fig. 7.2, is therefore the first one in which the evolution of the 0.1–2.5 keV X-ray flux can be followed. It is seen that the X-ray flux is low by the moment of ultraviolet maximum (when it was first measured during the outburst) and to the very end of the optical decline. The Ginga light curve shows that the X-rays start their rise immediately after the return of the optical light to its quiescent value. The PSPC light curve suggests this rise continues well after the optical returns to quiescence.

The various models for dwarf-nova outbursts agree in ascribing the decline of the optical and ultraviolet flux to a cooling of the accretion disk, which starts near the outer disk edge and ends at the inner edge near the white dwarf (e.g. Pringle, Verbunt & Wade, 1986). The end of the optical outburst is therefore defined by the return of the disk region immediately surrounding the white dwarf to its quiescent state. The rise of the X-ray flux at the very moment of this transition thus indicates that the emission of hard X-rays is regulated by, and presumably originates in, the boundary layer between accretion disk and white dwarf.

In the case of VW Hyi at least, the X-rays are not regulated by the outer disk regions, the companion star, or shocks in the wind arising from the disk.

The analysis of the X-ray spectrum and of the EXOSAT count ratios given by Belloni et al. (1991), Van Teeseling & Verbunt (1994) and in this paper indicates optically-thin emission, with line emission at around 1 keV in excess of that expected from an isothermal plasma. This line emission has been observed directly with a recent ASCA pointing (Manche & Raymond,
Line emission at these energies most likely arises from the L-shell of Iron, but this requires the presence of material much cooler than that responsible for the continuum flux ($\sim 6$ keV). We have modeled this emission using a two-temperature model, and also through a cooling-plasma model, where emission at a range of temperatures is summed. We find the observed spectra are compatible with emission from material heated to $\sim 12$ keV and cooling to temperatures below the bandpasses of our instruments. An alternative explanation of the excess line emission is fluorescence from the illuminated accretion disk or white-dwarf surface. Ross & Fabian (1993) show that strong Iron-L fluorescence is possible from a partially ionised reflector.

We find absorption column densities consistent with that measured with IUE ($6 \times 10^{17}$ cm$^{-2}$; Polidan, Mauche & Wade, 1990) when the line emission is added explicitly, but the multi-temperature models favour higher values. We don’t regard this as a problem for our cooling-plasma description since including $N_{HI}$ as a free parameter, rather than fixing it at the IUE value, results in a reduction in $\chi^2$ which is only marginally significant. An added complication is that the standard model of interstellar absorption assumes cold material (Morrison & McCammon, 1983) and this is probably inappropriate for VW Hyi which is situated within the hot gas of the local bubble (e.g. Warwick et al., 1993).

We find no evidence for spectral variability of the hard X-ray emission with ROSAT Ginga or EXOSAT and our results are compatible with a constant temperature of the soft, probably optically-thick, component as well. This is in line with the model for the boundary layer first sketched by Pringle & Savonije (1970), and discussed further by Jones & Watson (1992). The transition from quiescent to outburst behaviour apparently corresponds not to a gradual change in temperature, but to a variation in relative importance of the hot optically-thin and cooler optically-thick component, each of which may stay at a fixed temperature. This suggests that the thermal regulation of the X-ray emitting gas is such that it can exist only in one of two stable states; one hot and optically thin, the other cooler and optically thick. During the outburst, when mass accretion onto the white dwarf increases, the fraction of gas in the optically-thick state increases. Our observations suggest that the transition is rather sudden, and that it need not be made by the entire boundary layer. The large modulation during return to the quiescent X-ray flux, apparent from the Ginga observations, shows that the amount of gas in the optically-thin state may fluctuate strongly. The absence of similar fluctuations during the ROSAT pointed observation of VW Hyi in quiescence (Fig. 7.4) suggest that such modulations are probably associated with the X-ray recovery,
and die out some time after outburst. Alternatively it is possible that they are intermittent phenomena, unrelated to the outburst.
SS Cyg: a second multi-wavelength study

A similar multi-wavelength observation was made of the U Gem-type dwarf nova, SS Cyg. This work was carried out in collaboration with T.J. Ponman, T. Belloni, S.R. Duck, F. Verbunt and M.G. Watson. See also Ponman et al. (1995).

7.2.1 Introduction

SS Cyg is one of the closest and brightest dwarf novae, with a distance of ~ 75 pc (Warner, 1987) and \( m_v \sim 8 \) during outburst. It was the first cataclysmic variable detected in X-rays (Rappaport et al., 1974), where it was detected in outburst as an ultra-soft source during a sounding rocket flight (black-body fit gave \( kT < 130 \text{ eV} \)). It is ironic that the first observed X-rays from a cataclysmic variable were from the ultra-soft component that has remained so elusive in most systems.

Since this first detection, SS Cyg has been observed several times in X-rays, and these observations support a picture similar to that described above for VW Hyi. It was detected as a hard source during quiescence (1–7 keV, Heise et al., 1978) and 120 days of coverage with the Ariel-V scanning telescope established an anti-correlation of optical and hard X-ray flux (2–18 keV, Ricketts, King & Raine, 1979). The X-ray flux was seen to vary strongly throughout this scanning observation. Jones & Watson (1992) report on a series of nine observations with EXOSAT, made during outburst and quiescence. The low and medium energy instruments were capable of detecting both components simultaneously, and Jones & Watson confirmed the anti-correlation also between hard and soft emission. The hard flux was low in all outburst observations bar one, and the soft component was seen to correlate with the optical outburst light curve; but with a delay before rise and faster rise and decay time scales. All measurements of the soft component were with the same filter, so only weak constraints on the temperature were possible. Measurements with Ginga during quiescence gave a count rate of \( \sim 40 \text{ cts/s} \) and a best-fitting temperature of 18 keV (Yoshida & Inoue, 1992). The spectrum showed evidence for a multi-temperature plasma; a result recently confirmed with ASCA (Nousek et al., 1994). Mauclère & Raymond (1994) present a recent EUVE spectrum of the soft component, which they find is dominated by absorption and/or emission features, and is very poorly described with a black-body spectrum.
7.2.2 Observations

SS Cyg is regularly monitored by the American Association of Variable Star Observers (AAVSO), who supplied the optical light curve in the top panel of Fig. 7.13. The system entered outburst on MJD 48226/7, and returned to quiescence at around MJD 48233.

The WFC survey observation covers nearly the complete decline, from MJD 48225 to MJD 48233. The WFC light curves are presented in the third and fourth panels of Fig. 7.13. These were reduced using the method described in Chap. 3. Mean count rates were 0.31 ± 0.01 and 0.054 ± 0.005 in S1a and S2a respectively, making SS Cyg the third brightest cataclysmic variable in the all-sky survey.

The ROSAT PSPC covers the central 40% of the WFC coverage, as always. Light curves were reduced after Belloni, Hasinger & Izzo (1994).

Ginga observations (2-20 keV) were scheduled to coincide with the survey coverage, as with VW Hyi. One-day blocks of on-source time were scheduled for each end of the PSPC survey coverage, with a gap between for a background observation. Light curves were reduced using methods described by Hayashi and Williams et al. (1992b).

7.2.3 Results

The bottom five panels of Fig. 7.13 show the full multi-wavelength coverage. The WFC S1a, S2a and PSPC light curves all decline with the optical, though somewhat more quickly. Both S1a and the PSPC show significant variability around a smooth decline, possibly a manifestation of the remarkable soft-X-ray oscillations discussed in detail by Jones & Watson (1992). The snapshot nature of the survey coverage prevents useful interpretation of this variability.

The Ginga (2-20 keV) light curve shows no obvious trend through the decline, and has a mean count rate a factor six below the quiescent level. This light curve also exhibits significant variability.

Light curve fitting

In an attempt to quantify the rate of decline, I have fitted exponential and linear-plus-constant functions to the WFC light curves,

\[ y = a e^{-t/r} \]  

(7.1)
Figure 7.13: Light curves of SS Cyg through outburst. From the top: full AAVSO optical-flux light curve of outburst, with the ROSAT coverage indicated with vertical lines; V-band energy fluxes during WFC coverage; ROSAT WFC S1a count rates; S2a count rates; ROSAT PSPC (0.1–2.5 keV) count rates; Ginga (2–20 keV) count rates.
Figure 7.14: The WFC light curves of SS Cyg fitted with Eqns. 7.1 and 7.2.

\[ y = \begin{cases} 
  b + (m t + c) & ; \ t < -\frac{c}{m} \\
  b & ; \ t \geq -\frac{c}{m}
\end{cases} \] (7.2)

where \( t \) is time, \( \tau \) is the e-folding decay time scale and \( a, b, c \) and \( m \) are free parameters.

The best fitting curves are plotted in Fig. 7.14. Both models give acceptable fits to the S2a curve (\( \chi^2 \) of 0.4 and 0.5), but S1a can only be fit with the straight line (\( \chi^2 \) of 2.1 and 1.2). The ratios of gradients and y-intercepts for these straight line fits are \( ms_1/ms_2 = 7.0 \pm 1.3 \) and \( cs_1/cs_2 = 6.9 \pm 1.1 \), so the two light curves decline at the same rate within errors. The optical light curve is also better fitted with a straight line than with an exponential, over this time interval.

The PSPC light curve covers only the later decline, but has the highest signal-to-noise. This curve is best fit with exponential decay, \( \chi^2 \) of 1.5; the second model (Eqn. 7.2) requires
an extra free parameter but yields a reduced $\chi^2$ of 1.9. Adding a constant quiescent level as a free parameter does not improve the exponential fit.

Before MJD 48226.5 there is a marked roll-over to maximum in both the optical and WFC S1a light curves. After this time all four light curves are well fitted with the exponential function, allowing us to compare the time scales for decline. Best fits for all four are plotted in Fig. 7.15. These yield time scales of $\tau = 1.15$ ± 0.07 and 1.0 ± 0.3 days for S1a and S2a, $\tau = 0.98$ ± 0.03 days for the PSFC (0.91 ± 0.04 if a constant level is allowed), and $\tau \sim 3$ days for the optical (statistically sound errors are not available for the optical light curve). Thus it is clear that the soft-X-ray component declines far more quickly than the optical. There is weak evidence that the PSFC declines a little faster than the WFC, perhaps due to cooling; but no evidence that S1a and S2a decline at different rates.

**Spectrum of soft component**

The two colours of the WFC survey can be used to constrain the parameters of a simple spectral model, but not to distinguish between models. Accordingly I assume a black-body spectrum, despite the EUVE spectrum presented by Mauche & Raymond (1994).

As an estimate of the peak WFC count rates I have binned the light curve in days, and take the first S1a data point (MJD 48225) for the spectral constraint. For S2a I extrapolate my straight line fit to the light curve. The count rates are $1.048$ ± 0.069 cts/s for S1a and $0.180$ ± 0.018 cts/s for S2a. Applying the same constraints as in Sect. 5.4 I find the allowed region plotted in Fig. 7.16.

The temperature is rather poorly constrained, and is bounded at either end by theoretical limits. The absorption column is limited to be greater than that found by Mauche, Raymond & Córdova (1988) ($3.5 \times 10^{19}$ cm$^{-2}$, from interstellar ultraviolet absorption lines). This may represent: 1) circumstellar material, perhaps associated with outburst; 2) the effect of assuming a cold interstellar column (Morrison & McCammon, 1983), since the column is so low that a large proportion must lie within the highly-ionised local bubble; 3) the effect of assuming a black-body spectrum, which we know is inappropriate (Mauche & Raymond, 1994). Luminosities in the range $10^{32} - 10^{34}$ erg/s are allowed.

See Ponman et al. (1995) for a more detailed treatment, incorporating the PSPC spectra.

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1 Exponential fits to optical and WFC data are over slightly different intervals, see Fig. 7.15.
Figure 7.15: WFC, PSPC and optical light curves fitted with exponential functions. Data before the dotted lines were not included in the fits. E-folding time scales are 3 days for optical, 1.0 d for S2a, 1.15 d for S1a and 0.98 d for the PSPC. Units are the same as Fig. 7.13.
Figure 7.16: The constraints placed on a black-body model of the EUV spectrum of SS Cyg by the WFC survey. The shaded regions represent the 68% and 95% confidence intervals. The two vertical dashed lines mark the Eddington luminosity (expressed as a temperature) for $M_{\text{wd}} = 0.6 - 1.0 M_\odot$. The heavily shaded line is a contour of emitting area; representing an area $\sim 0.1 A_{\text{wd}}$. The other contours are of black-body luminosity, these are (from the left): $7.8 \times 10^{37}$ erg/s (the Eddington limit for a 0.6 $M_\odot$ white dwarf); $10^{35}$; $10^{34}$; $10^{33}$; $10^{32}$; $5 \times 10^{31}$ and $3 \times 10^{31}$ erg/s. The distance to SS Cyg is taken to be 75 pc (Warner, 1987). The horizontal line marks the $N_H$ value measured by Mauche, Raymond & Córdova (1988).
7.2.4 Discussion

The light curves presented in this section confirm the findings of Jones & Watson (1992), that an ultra-soft X-ray component appears during outbursts of SS Cyg, while the hard X-ray flux is suppressed (though non-zero).

We follow the hard X-ray flux to very late in outburst, almost until the optical has reached quiescence, but without observing a recovery. This fits well with our observations of VW Hyi (above), and adds weight to the idea that hard-X-rays are emitted from the boundary layer in dwarf novae.

We confirm that the soft-X-ray flux (0.06-0.5keV) declines more quickly than the optical flux, and our excellent coverage allows measurements of the decay time scales for the first time. It is hard to see why the soft flux should decay more quickly than the optical. Models suggest the boundary layer should return to quiescence after the disk (e.g. Pringle, Verbunt & Wade, 1986), so if anything, the decline should be slower. Our observations seem to suggest that the luminosity of the boundary layer actually falls below the quiescence level before the hard X-ray flux recovers. A more reasonable interpretation is that the temperature of the soft component falls, moving flux out of the bandpass of our instruments, so that the measured flux falls faster than the bolometric flux.

Fig. 7.17 shows the effect on the WFC count rates if the temperature is allowed to fall as well the flux. In this particular model the bolometric flux of the soft component falls on a time scale of three days and the temperature at ten days. An interstellar column of $9 \times 10^{19}$ cm$^{-2}$ is assumed (Fig. 7.16). The WFC count rates do indeed decline at a far faster rate than the bolometric flux, and there is a striking similarity between this model and the light curves of Fig. 7.15. The model predicts a softening of the WFC filter ratio, which is not observed. However, the softening is within the uncertainty in the observed ratio, especially as the roll-over point in the observed light curves is rather uncertain.

Finally we can compare the EUV flux from the black-body fits with the expected ultraviolet disk flux. Polidan & Holberg (1984) study the ultraviolet outburst spectra with IUE and Voyager, and in Ponman et al. (1995) we scale their fluxes to the ROSAT survey outburst through the the V-band magnitude. This gives $\sim 10^{34}$ erg/s, which is at the high end of that allowed for the EUV component. For the boundary layer emission to equal that of the disk the temperature must be around 10 eV and the black-body fit requires an interstellar column $> 10^{20}$ cm$^{-2}$ (Fig. 7.16). Including the PSPC spectrum tightens this constraint, and implies a flux substantially below that of the disk (Ponman et al., 1995).
Figure 7.17: WFC count rates and filter ratio (bottom panels) predicted by model with bolometric flux decaying on e-folding time scale of three days, and temperature falling on a time scale of ten days. An interstellar column density of $9 \times 10^{19} \text{cm}^{-2}$ is assumed, based on Fig. 7.16. Compare the third panel with Fig. 7.15.
Figure 7.18: The WFC survey and schematic V-band optical light curves of the dwarf nova, Z Cam. S1a points are marked with circles, S2a with squares. The errors bars represent the 68% Bayesian confidence intervals. The optical light curve has been taken from Duck (1993).

7.3 Z Cam: a fourth soft-X-ray source

Z Cam is the third brightest of the four non-magnetic cataclysmic variables detected with confidence in the WFC survey. It is routinely monitored by the AAVSO, who’s optical light curve shows an outburst centred on the WFC coverage (Fig. 7.18, S.R. Duck, priv. comm.).

The WFC S1a and S2a light curves are plotted in Fig. 7.18, binned in days. These are dominated by a strong detection in the S2a filter at MJD 48164, shortly after peak optical outburst. The S1a count rate also shows a significant enhancement at MJD 48163, shortly before optical maximum. At other times the source is not significantly detected in either filter.
Z Cam is then the fourth dwarf nova seen to exhibit soft-X-ray/EUV emission during outburst (the others are VW Hyi, SS Cyg and U Gem). This confirms that all three subclasses of dwarf novae can express this behaviour, and is also important because Z Cam is substantially fainter optically than the other three systems. Figure 7.19 shows the distribution of dwarf-nova outburst magnitudes (Ritter, 1990), and the magnitudes of the four EUV sources. A substantial proportion of dwarf novae are clearly in range of WFC survey detection, which has prompted the systematic search for more detections and upper limits of outbursts in Sect. 7.4.2.

The flux evolution of the outburst of Z Cam is too fast, and the statistics too poor, for measurements of EUV colour. However the high count rate of the S2a point after maximum, when compared with the S1a point before, demands either a very soft spectrum, or that the S1a measurement was made during the EUV rise. The latter explanation seems most likely, since this point is before optical maximum and we might expect a lag between optical and EUV fluxes (c.f. VW Hyi). Unfortunately the count rate is too low to use the full time-resolution data to test for a rise though MJD 48163.

Figure 7.19: The frequency distribution of the maximum V-band magnitudes of dwarf novae in outburst. Marked are the positions of the four systems known to exhibit an EUV/soft-X-ray emission component in outburst.
The low EUV flux at the beginning of the optical decline (S1a at MJD 48165 and S2a at MJD 48166) clearly indicate that the EUV component declines more quickly than the optical, as is seen in both VW Hyi and SS Cyg (above).

Finally, I note that the mean WFC S1a count rate used to calculate the EUV/optical flux ratio of Figs. 4.12 and 7.1 is an order of magnitude below that of the S2a filter at peak outburst. Using this S2a point would place Z Cam up alongside SS Cyg with a flux ratio close to unity.

7.4 Other dwarf novae in outburst

7.4.1 RX J0640-24

Nothing is yet published about the PSPC survey source RX J0640-24, besides the announcement of its optical identification with a 15.5 magnitude dwarf nova by Beuermann & Thomas (1993).

It is detected with >99.9% confidence in the WFC survey, which is remarkable considering its optical magnitude (c.f. Fig. 7.19). Most likely it was in outburst during the survey, but was optically identified in quiescence. As such it is an excellent candidate for the fifth EUV emitting dwarf nova. However, I must sound a note of caution, since there is no obvious flux enhancement in the WFC light curve (as there is for Z Cam) and no optical light curve with which to make comparisons.

If I assume it is a dwarf nova detected in outburst, and with an outburst magnitude ~ 3 magnitudes brighter than its discovery magnitude, I find an EUV/optical flux ratio similar to that of SS Cyg and Z Cam.

7.4.2 A systematic search

The EUV detection of Z Cam in outburst (Sect. 7.3) shows that a substantial proportion of dwarf novae should be within the detection threshold of the WFC survey (see Fig. 7.19). Accordingly I have conducted a systematic search through the survey database for all dwarf novae known to be in outburst during their observations. The question I ask here is: do we see VW Hyi, SS Cyg, Z Cam and U Gem because they are unusual, or because they are the tip of the brightness iceberg?

Duck (1993) and Beuermann & Thomas (1993) have both compiled lists of dwarf novae in outburst during their survey observations. The lists are not identical, but I simply combine
Table 7.3: WFC count rates for the dwarf novae seen in optical outburst during their survey coverage. Also for two bright nova-like variables (NL). Sources detected in the initial survey analysis are not discussed here (see Chap. 4).

<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>$m_\text{c}^a$</th>
<th>Det. $^b$</th>
<th>$S_\text{la}$ $^c$ 68% $^d$</th>
<th>90%</th>
<th>99%</th>
<th>$S_\text{la}$ 68%</th>
<th>90%</th>
<th>99%</th>
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<tr>
<td>RU Peg</td>
<td>U Gem</td>
<td>9.0</td>
<td>0</td>
<td>5</td>
<td>9</td>
<td>15</td>
<td>0</td>
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<td>12</td>
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<td>SU UMa</td>
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<td>?</td>
<td>0</td>
<td>3</td>
<td>5</td>
<td>0</td>
<td>5</td>
<td>8</td>
</tr>
<tr>
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<td>SU UMa</td>
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<td>0</td>
<td>3</td>
<td>5</td>
<td>8</td>
<td>0</td>
<td>7</td>
<td>11</td>
</tr>
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<td>3</td>
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<td>1</td>
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<td>7</td>
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<td>?</td>
<td>2</td>
<td>7</td>
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<td>2</td>
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<td>9</td>
<td>3</td>
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<td>NL</td>
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<td>Y</td>
<td>10</td>
<td>16</td>
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<td>4</td>
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</tbody>
</table>

$^a$ maximum visual magnitude, from Ritter & Kolb (in press).
$^b$ WFC detection flag. '?' represents a speculation based on light curve. See App. F.
$^c$ most probable count rate, in cts/ksec.
$^d$ confidence intervals, a single figure denotes upper limit.
$^*$ false detection due to contamination by Sirius.

them for this analysis. The combined list is given in Tab. 7.3, along with maximum visual magnitudes from Ritter & Kolb (in press), and WFC count rates and upper limits from my standard reduction (described in Chap. 4). I also include two bright nova-like variables in this analysis, V3885 Sgr and RX Sex. Nova-likes exhibit many of the properties of dwarf novae in their outburst state, so ultra-soft emission may be expected.

One new source is detected, V3885 Sgr, with 2.6 and 1.6σ deviations from the background in $S_\text{la}$ and $S_2a$ respectively (99% confidence). The apparent detection of HL CMa is due to contamination by Sirius B, one of the brightest EUV sources in the sky and only 9' to the North.

In Fig. 7.20 I have plotted these measurements in the same way as in Fig. 7.1; count rate against maximum visual magnitude, and EUV/optical energy flux ratios as a function of optical flux. Comparison with Fig. 7.1 is interesting as the WFC upper limits for the brightest sources lie below the detections of Fig. 7.1. On the face of it, this would suggest that the detected systems are unusually bright EUV sources, but this is where we run into...
Figure 7.20: As Fig. 7.1 but for the non-magnetic cataclysmic variables of Tab. 7.3. These are the outbursting dwarf novae not detected in the initial survey analysis, plus two bright nova-like variables. The high count rate point is a false detection.
the problem with this analysis. At the time of writing, optical light curves for these outbursts are not available, and a glance at the Z Cam light curve in Fig. 7.18 shows how important this omission can be. It is important that the upper limits be calculated for the time of outburst only. As it is, the upper limits are too tight, and without the optical light curves this effect cannot be quantified. Relaxing the upper limits in Fig. 7.20 probably leaves them consistent with the detections of Fig. 7.1, so our detected dwarf novae are most-likely typical of the class.

Of course, once optical light curves become available, comparison with the EUV light curves may reveal one or two weak detections (cases like Z Cam). To facilitate the comparison I present the eleven WFC light curves in App. F.

V3885 Sgr

V3885 Sgr was observed in a pointed ROSAT PSPC observation in Oct. 1992 (Van Teeseling & Verbunt, 1994). Extrapolating Van Teeseling & Verbunt's best fitting spectrum to the WFC I find count rates of 0.9 and 0.3 cts/sec in S1a and S2a respectively. These are more than an order of magnitude below the survey count rates, suggesting the presence of a strong EUV emission component. This detection is discussed further by Wheatley et al. (1995a).

7.5 The nova-like variable: IX Vel

7.5.1 Introduction

IX Vel is the brightest nova-like variable in the optical sky, with \( m_v \approx 9.1 \). It is also the brightest cataclysmic variable at ultraviolet wavelengths, bar one or two of the brightest dwarf novae in their outburst state (Verbunt, 1987).

IX Vel is a member of the UX UMa sub-class of nova-likes. These are the systems which exhibit the properties of dwarf novae in outburst, such as strong ultraviolet emission and optical lines in absorption, but which are never seen in the quiescent state. This picture is supported by the source counts of the PSPC all-sky survey. Beuermann & Thomas (1993) find that just 24\% of known nova-likes were detected in the survey, as opposed to 77\% and 66\% for magnetic systems and dwarf novae respectively. This shows that nova-likes are rather faint hard X-ray sources, as we have found for dwarf novae in outburst (above). Extending
the comparison with dwarf novae, we may expect strong ultra-soft X-ray emission from nova-likes. IX Vel, as the brightest nova-like, must be regarded as a prime candidate such a detection.

The system has been observed twice with EXOSAT (Van der Woerd, 1987), twice with ROSAT PSPC pointings (Van Teeseling & Verbunt, 1994; Van Teeseling et al., 1995), and once with EUVE (Van Teeseling et al., 1995); but in each case the spectra were found to be consistent with optically-thin hard X-ray emission only.

With EXOSAT, IX Vel was detected by the low energy instrument only, indicating a temperature $kT \lesssim 10$ keV, but the filter ratios implied relatively hard optically-thin emission. ROSAT pointings found IX Vel about a factor two fainter, and revealed significant spectral variability. Van Teeseling et al. found multi-temperature models were required (as in VW Hyi, Sect. 7.1.4), with $kT \sim 1-8$ keV, but found no evidence of a distinct soft component. They note that the hard X-ray flux measured with ROSAT is a factor of a thousand less than the ultraviolet flux. IX Vel was not detected in the spectrometers of EUVE, but Van Teeseling et al. (1995) found the broad-band count rate to be consistent with their fits to the ROSAT PSPC spectrum. In the ROSAT PSPC all-sky survey, Beuermann & Thomas (1993) report a count rate similar to that found in the pointings ($\sim 0.4$ cts/s), but they find the spectrum to be significantly softer with $kT \sim 1$ keV. They do not find strong evidence for a soft component, but suggest that such a component is "indicated".

### 7.5.2 Results

IX Vel was detected in the initial WFC survey analysis, with count rates of $9 \pm 3$ and $29 \pm 5$ cts/sec in the S1a and S2a filters. The combined light curve, binned in days, is presented in Fig. 7.21. Though the light curve appears variable, a $P$-statistic test shows that this is not significant (Chap. 3).

These count rates give IX Vel the title of "softest cataclysmic variable in the WFC survey". Its softness ratio of $3.2 \pm 1.2$ is much greater than any of the polars, which we know are true EUV emitters. As such, this detection seems to indicate that IX Vel is a luminous EUV source, possibly solving the boundary-layer problem.

Figure 7.22 shows the constraints on EUV black-body emission, under the assumption that contamination from the hard X-ray flux is negligible. These constraints are discussed fully in Sect. 5.4 and App. E. Allowed temperatures lie in the range $7-20$ eV, corresponding to luminosities in the range $10^{30} - 10^{33} \text{erg s}^{-1}$. The upper end of this range is far higher
than the hard-X-ray luminosity, $L_{\text{HXR}} \sim 5 \times 10^{31} \text{d}_{250}^2 \text{erg s}^{-1}$ (Van Teeseling & Verbunt, 1994), but still less than the enormous ultraviolet luminosity, $L_{\text{UV}} \sim 5 \times 10^{34} \text{d}_{250}^2 \text{erg s}^{-1}$ (Verbunt, 1987; Van Teeseling & Verbunt, 1994). The EUV luminosity could be of this order if the white dwarf were heated over its entire surface.

### 7.5.3 Discussion

The softness of the IX Vel detection is striking and highly suggestive, but we must be careful to take the hard X-ray emission into account. The PSPC survey spectrum was best fit with a Raymond-Smith spectrum of $kT = 1 \text{keV}$ (above). At temperatures as low as this the X-ray spectrum becomes dominated by line emission, and the translation of filter ratio into temperature is complex.

Figure 7.23 illustrates the situation. The two plots show WFC filter ratio (S1a/S2a) as a function of temperature and interstellar absorption column. The top panel is for a simple thermal bremsstrahlung model, the bottom panel is a full optically-thin thermal plasma model (the "Mewe" model; Mewe, 1989; Kaastra & Mewe, 1993). The effect of line emission...
Figure 7.22: Constraints on a black-body spectrum capable of reproducing the observed WFC survey count rates of IX Vel. Contamination by the hard X-ray flux is assumed to be negligible (see discussion). These constraints are fully described in Sect. 5.4 and App. E. The 68% and 95% confidence regions are shaded. The thick contour represents an emitting-area cut-off of 0.1 A_{wd} for 0.6 ≤ M_{wd} ≤ 1.0 M_⊙. The other contours are of luminosity, these are (from the left) 7 × 10^{37}, 10^{35}, 10^{34}, 10^{33}, 10^{32}, 10^{31} and 10^{30} erg/s. A distance of 150 pc is assumed. The horizontal line marks the interstellar column density measured by Mauche, Raymond & Córdova (1988).
Figure 7.23: WFC hardness ratios as a function of temperature and interstellar absorption column for: a) a thermal bremsstrahlung model (top); b) the “Mewe” optically-thin thermal plasma model. Bold contours represents a ratio of unity. Solid contours are increasingly hard spectra, and the dashed contour is $S_{1a}/S_{2a}=0.5$. The ratios apparently become softer again at high column because of a hard-X-ray leak in the response of the $S_{2a}$ filter.
is dramatic. Bremsstrahlung spectra give hard filter ratios for any combination of column and temperature, but the Mewe model yields very soft filter ratios around $kT = 1$ keV. At the interstellar column density measured by Mauche, Raymond & Córdova (1988) ($N_H = 2 \times 10^{19}$ cm$^{-2}$), the softest filter ratio is $S_{2a}/S_{1a} \approx 2.0$, which is within the error on the measured WFC softness ratio ($3.2 \pm 1.2$).

It seems that the extremely soft WFC filter ratio measured for IX Vel may be entirely due to line emission from the hot optically-thin plasma. The WFC count rates are also reasonably consistent with this interpretation. Taking a temperature of 1 keV, a column of $2 \times 10^{19}$ cm$^{-2}$, and normalising to the PSPC survey count rate (0.4 cts/s) I find predicted WFC count rates of 9.7 and 19.0 cts/ksec for $S_{1a}$ and $S_{2a}$. The $S_{1a}$ rate is consistent with the observed rate ($9 \pm 3$ cts/ksec), and the filter ratio is consistent, but the predicted $S_{2a}$ count rate is below the observed rate ($29 \pm 5$). This residual may represent a detection of a true EUV flux, though it is derived without fitting to the observed count rates. The ratio is very sensitive to absorption column, and letting the column drop a little from that measured by Mauche et al. may allow a fit to all measurements with a hard component only.

A unequivocal statement should be possible once the PSPC and WFC survey data are fitted simultaneously (Wheatley et al., 1995a).

It is not immediately obvious why the WFC filter ratio should suddenly become so soft at $kT = 1$ keV. To illustrate the effect I have made Fig. 7.24. This is a grid of model Mewe spectra, with models of increasing temperature plotted against photon energy. I have indicated the ranges over which the WFC, PSPC and Ginga are sensitive, and have also plotted the WFC $S_{1a}$ and $S_{2a}$ response curves (on a linear scale). Most strong lines are of Iron, with the K (6-8 keV), L ($\sim 1$ keV) and M ($\sim 0.1$ keV) shells dominating the plot. The reason for the soft WFC ratio is clear. At temperatures in the range 0.4-2 keV, strong lines of the Iron M-shell appear, centred on the most sensitive energies of the $S_{2a}$ filter. This plot also shows how cool emission components can account for the 1 keV residuals in PSPC spectra (Sect. 7.1.4 and Van Teeseling & Verbunt, 1994). Strong lines of Iron-L appear around this energy for temperatures in the range 0.2-0.8 keV.
Figure 7.24: A grid of Mewe optically-thin plasma spectra. The bandpasses of the WFC, PSPC and Ginga are marked, as is the effective area of the WFC with each of its survey filters, S1a and S2a (S2a is softest). The strong lines in the bandpass of the S2a filter at temperatures around 1 keV are of the M-shell of Iron.
7.6 Overview

7.6.1 Dwarf-nova outbursts

A consistent picture of X-ray and EUV emission through outburst is emerging, through observations presented here and elsewhere.

It is clear that optical outburst is associated with a suppression of the quiescent hard X-ray flux, and the emergence of a luminous EUV component. EUV upper limits are consistent with such components in all dwarf novae.

Observations of SS Cyg and VW Hyi (this chapter) show that the hard X-ray flux does not recover until the very end of the optical outburst. A late recovery is also indicated in WX Hyi, which was observed at a low flux level in late decline with a ROSAT pointing (Van Teeseling & Verbunt, 1994). These results support the idea that hard X-rays are emitted from the boundary layer, since disk models agree that the disk cools from the outside-in, whatever the outburst mechanism.

The soft X-rays in SS Cyg, and probably Z Cam, must lag the optical rise, supporting the boundary layer as their origin also. It is also clear that the soft X-rays decline more quickly than the optical, an effect probably dominated by cooling rather than bolometric flux level.

During decline the hard X-rays remain suspiciously constant in VW Hyi and SS Cyg, before recovering rather suddenly, at least in the case of VW Hyi. We may speculate that the residual hard X-rays seen during outburst represent a distinct component, perhaps unaffected by the outburst.

Finally, the fly in the ointment, U Gem has shown rather different behaviour. During its one-and-only observed outburst, the hard X-ray flux increased, as well as the soft flux (Mason et al., 1978); and the soft X-rays declined together with the optical (Córdova & Mason, 1984). This must serve as a warning, since the above summary is based on a very small number of observed outbursts. It is yet to be seen whether U Gem is atypical, whether that particular outburst was atypical, or whether our "consistent picture" is too simple.

7.6.2 Boundary layer luminosity

Though WFC and EUVE observations are consistent with luminous EUV emission from all cataclysmic variables, the flux limits are not tight enough to decide whether these component can or cannot carry the missing boundary layer luminosity.

The dwarf nova VW Hyi probably holds the key to this question, simply because it is the
only system with $N_{\text{H}}$ low enough to allow meaningful flux constraints across the whole EUV, right down to the Lyman limit. In most other systems, interstellar absorption will probably always leave room for substantial flux to remain hidden. For instance, Ponman et al. (1995) measure the EUV flux of SS Cyg in outburst and find it is less than that expected for the boundary layer, but they cannot exclude the presence of cooler EUV flux which could carry the missing luminosity. The current situation is that the combined X-ray and EUV flux of VW Hyi is measured to be less than that of the accretion disk, for all temperatures and at all outburst phases (Sect. 7.1.2 & 7.1.5). However, these results depend sensitively on the quantity and form of the interstellar absorption. They will not become safe until upper limits across the EUV band are replaced with detections.
Appendix A

Bayesian confidence intervals

The following is a derivation of the Bayesian confidence intervals used throughout this thesis. It is taken directly from Kraft, Burrows & Nousek (1991).

If we define \( N \) to be the observed number of counts in a time interval \( t \), \( B \) to be mean number of background counts in time \( t \) and \( S \) to be the mean number of source counts, then Bayes's theorem can be written as

\[
f_{N,B} \propto p(S)P_0(N)
\]  

(A.1)

where \( f_{N,B}(S) \) is the posterior probability function for \( S \) as a function of the observables \( N \) and \( B \). Throughout this work it is assumed that the background count rate can be measured independently and with arbitrary precision. \( p(S) \) is the prior distribution function, which incorporates the observer's degree of belief or prior knowledge of the possible values of \( S \); in this case it is simply assumed that \( S \) must be positive and that all positive values are equally likely. \( P_0(N) \) is the conditional probability function, which in this case is the Poisson distribution for \( S + B \). This is given by

\[
P(N) = \frac{e^{-(S+B)(S+B)^N}}{N!}
\]  

(A.2)

It is worth noting at this point that equation A.2 also forms the basis of the 'classical' confidence limits discussed in section 3.2.2. The crucial difference between the two methods is in the following step, where equation A.2 is substituted into equation A.1 to give

\[
f_{N,B}(S) = C\frac{e^{-(S+B)(S+B)^N}}{N!}
\]  

(A.3)

for \( S \geq 0 \). The normalisation, \( C \), is

\[
C = \left[ \int_0^\infty \frac{e^{-(S+B)(S+B)^N}}{N!} dS \right]^{-1} = \left( \sum_{n=0}^{\infty} \frac{e^{-B} B^n}{n!} \right)^{-1}
\]  

(A.4)
and is required so that the integral of $f_{N,B}(S)$ over all $S$ (for a given $N$) is unity for any $B$.

The crucial difference between the Bayesian and the 'classical' approach is that the roles of $N$ and $S$ are reversed. We now have a continuous probability function for the source flux, $S$, given $N$ and $B$; whereas the 'classical' approach yields the discrete probabilities of obtaining each $N$, given $S$ and $B$. The importance of this distinction is discussed in more depth by Kraft, Burrows & Nousek (1991).

The confidence limits for $S$ are obtained by integrating the probability function $f_{N,B}$ over $S$ and solving numerically for $S_{\text{min}}$ and $S_{\text{max}}$ such that

$$\int_{S_{\text{min}}}^{S_{\text{max}}} f_{N,B}(S) dS = CL$$

where CL is the probability of $S$ lying between $S_{\text{min}}$ and $S_{\text{max}}$. Of course there are an infinite number of pairs of $S_{\text{min}}$ and $S_{\text{max}}$ which satisfy this equation. Kraft, Burrows & Nousek chose the solution for which the interval $S_{\text{max}} - S_{\text{min}}$ is minimized.
Appendix B

Tabulation of upper bounds of the P distribution

The P statistic is defined in chapter 3. It is designed to be a replacement for $\chi^2$ in experiments with low numbers of counts, when $\chi^2$ is no longer valid. The following are tables of the 95% upper bound of the P distribution derived through numerical simulations. The P distribution is calculated as a function of mean number of source counts/bin, mean background counts/bin and number of degrees of freedom. One thousand simulated light curves are calculated for each point, and each has its P statistic value calculated w.r.t. the mean source level. The P statistic values have been divided by their respective number of degrees of freedom ($N_{data}-1$).

Table B.1: 95% upper bound to the P-statistic distribution with five degrees of freedom.

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Table B.3: As table B.1, but with thirty degrees of freedom.

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The \( P \) distribution

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<tr>
<td>35.99</td>
<td>1.31</td>
</tr>
<tr>
<td>46.89</td>
<td>1.31</td>
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<tr>
<td>61.25</td>
<td>1.30</td>
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<tr>
<td>80.00</td>
<td>1.29</td>
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</table>
Appendix C

Predicted numbers of cataclysmic variables in the ROSAT WFC all-sky survey

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1989 March 2

Introduction

The aim of this document is to estimate how many cataclysmic variables (CVs) are likely to be detected in the ROSAT WFC all-sky survey. The prospects should be quite good - a few CVs have already been detected in the XUV bandpass (0.01 to 0.1 keV), and there are good theoretical reasons to expect such emission to be a characteristic property of these systems.

Two categories of CV are considered here: polars (AM Her objects) and dwarf novae (taken to include related objects such as nova-like variables). Our knowledge of XUV emission from polars is much greater, both observationally and theoretically, than it is for dwarf novae, as will become apparent below.

In both categories, XUV emission results from accretion onto the white dwarf. The XUV component may correspond to almost all the accretion luminosity available in polars, and up to half of it in dwarf novae. The geometry of the accretion region determines the main differences between polars and dwarf novae. In polars the white dwarf has a strong magnetic field, and the XUV emission is produced from a small region of the white dwarf surface at the base of the 'accretion column' in the vicinity of the magnetic pole. The relatively small emitting area guarantees a high temperature if the emission is close to a black-body.

In dwarf novae an accretion disc extends almost to the white dwarf surface, and there is no strong field to channel the accretion flow. Up to half of the accretion luminosity is
Predicted numbers of CVs in WFC survey

liberated in the boundary layer between the disc and the white dwarf surface, and the XUV emission probably originates from the heated surface of the white dwarf (or possibly from the boundary layer itself if this is optically thick). The emitting area is likely to be considerably larger than in polars, thus for black-body emission with the same luminosity the temperature will be correspondingly lower.
Assumptions

In order to make predictions for the WFC all-sky survey, the following general assumptions have been made:

(i) The ISM is uniform and has a density \( n_\text{e} = 0.07 \text{ cm}^{-3} \) equivalent to a column density \( N_\text{H} = 2.1 \times 10^{17} D \text{ cm}^{-2} \) where \( D \) is the source distance in parsec. This is clearly a gross simplification.

(ii) The emitted spectrum of the XUV component in CVs has a black-body form. Again this is probably a simplification – the true spectrum may be closer to a stellar atmosphere.

(iii) The response of the WFC plus filters, and the WFC sensitivity threshold for detecting sources in the survey (~0.01 count/sec) are as quoted in the AO-1 document.

(iv) The galactic scale height for CVs is \( h \approx 200 \text{ pc} \) (Patterson, 1984) and the space density of CVs is uniform within the scale height. Using an exponential density distribution produces slightly smaller total source numbers (the maximum difference amounts to about 40% – this is much smaller than the present uncertainty in space densities).

CV parameters

The CV parameters needed for the prediction calculations are the luminosity and temperature of the black-body component, and the mean space density of the objects. The parameter choices for the two categories of CVs are discussed below.

Polars

For polars I assume \( T_{\text{bb}} = 2 - 3 \times 10^5 \text{ K} \) and \( L_{\text{bol}} = 10^{32} \text{ erg s}^{-1} \). \( L_{\text{bol}} \) here is the bolometric luminosity of the black-body component. These values are representative of the few polars whose spectra have been measured either with grating data, or by filter spectroscopy (e.g. Osborne 1989, Beuermann 1988). The luminosities are also consistent with the total accretion luminosities \( (L_{\text{acc}} \sim 10^{32.5} \text{ erg s}^{-1}) \) expected for polars below the period gap on the basis of secular evolution models (e.g. King & Watson, 1988 and references therein), assuming that most of the accretion luminosity emerges in the XUV component. For systems above the period gap the luminosities are \( \sim \) an order of magnitude higher.

Space densities for polars are uncertain. Patterson (1984) quotes \( \rho \approx 3.5 \times 10^{-7} \text{ pc}^{-3} \). The discovery of several more nearby polars since Patterson’s paper suggest this is a little
Predicted numbers of CVs in WFC survey

low. I adopt \( \rho = 5 \times 10^{-7} \text{ pc}^{-3} \). For polars above the gap (which are rarer) I assume a space density a factor of 10 lower.

Dwarf novae

For dwarf novae the parameters of the black-body component are much less certain. Good XUV measurements have only been made for a few (possibly atypical) systems (e.g. SS Cyg, U Gem, VW Hyi ...), mostly during outburst. Given this observational uncertainty, the estimates made here rely heavily on theoretical arguments.

In both outburst and quiescence the total luminosity in the black-body component is likely to be a large fraction (up to 50%) of the total accretion luminosity. Models of the secular evolution of CVs give mass transfer rates implying that the accretion luminosity for dwarf novae above the period gap should be in the range \( 10^{34} - 10^{35} \text{ erg s}^{-1} \), whilst systems below the gap should have luminosities an order of magnitude lower. Since there is evidence that dwarf novae may typically be under-luminous systems (cf. Patterson, 1984), I adopt \( L_{bol} = 10^{32} \text{ erg s}^{-1} \) for dwarf novae in quiescence below the gap, and \( L_{bol} = 10^{33} \text{ erg s}^{-1} \) for dwarf novae in quiescence above the gap. For dwarf novae in outburst the average increase in optical luminosity is a factor \( \sim 25 \). Presumably the increase in \( L_{bol} \) is of the same order. Given the uncertainties I adopt a global value \( L_{bol} = 10^{34} \text{ erg s}^{-1} \) for dwarf novae in outburst.

The black-body temperatures are even more uncertain. In outburst temperatures \( T_{bb} \sim \) few \( \times 10^5 \text{K} \) have been measured, but the non-detection of the XUV component from most dwarf novae in quiescence suggests \( T_{bb} < 10^5 \text{ K} \). Outburst and quiescent temperatures and luminosities are self-consistent (assuming black-body emission) if the emitting area corresponds to \( \sim 0.01 - 0.1 \) of the white dwarf surface. Here I adopt \( T_{bb} = 6 \times 10^4 \text{ K} \) for dwarf novae in quiescence and \( T_{bb} = 1 - 2 \times 10^5 \text{ K} \) for dwarf novae in outburst.

Space densities for dwarf novae are again uncertain. Patterson (1984) quotes \( \rho \sim 6 \times 10^{-6} \text{ pc}^{-3} \) for all CVs, \( \rho \approx 4 \times 10^{-6} \text{ pc}^{-3} \) for 'low \( \dot{M} \)' dwarf novae and \( \rho \approx 8 \times 10^{-7} \text{ pc}^{-3} \) for 'high \( \dot{M} \)' dwarf novae. I therefore adopt \( \rho = 4 \times 10^{-6} \text{ pc}^{-3} \) for dwarf novae below the gap and \( \rho = 10^{-6} \text{ pc}^{-3} \) for systems above the gap. These values are then consistent with my estimate for polars, if polars constitute 10% or less of the CV population as is widely assumed. Finally I adopt a space density for dwarf novae in outburst of \( \rho = 2.5 \times 10^{-7} \text{ pc}^{-3} \), equivalent to the reasonable assumption that dwarf novae are, on average, in outburst for 5% of the time.
Predicted numbers of CVs in WFC survey

The calculation of the numbers of CVs likely to be seen in the WFC all-sky survey is relatively straightforward. Basically all that is needed is the effective detection horizon (i.e., the maximum distance at which a source with a particular choice of parameters can be detected), the predicted source numbers are then computed from the volume inside this horizon and the assumed space density.

The table below summarises the results for polars and dwarf novae. Predictions have been calculated for the two WFC survey filters (SI and S2) and also for the XRT survey for comparison. $D_{\text{max}}$ is the detection horizon and $N_{\text{pred}}$ the predicted number of sources.

### Accuracy of the predictions

The accuracy of the predictions are most sensitive, as might be expected, to two things: (i) the shape of the assumed spectrum (i.e., black-body temperature and/or deviations from black-body spectral distribution); (ii) the density (and density distribution) of the ISM which determines the line of sight absorption as a function of distance. Surprisingly the predictions are not particularly sensitive to changing the bolometric luminosity. Varying the luminosity by a factor of 10 produces changes in the source numbers by a factor 2-4, unless the luminosity is very low.

The sensitivity of the calculations to spectral shape is evident in Table 1. At low temperatures ($T_{\text{bb}} < 2 \times 10^6$ K) the detection horizon, and hence predicted source number, is a strong function of temperature — a factor 2 change in temperature can produce a factor 10 change in source numbers. I have not attempted any predictions with spectra which are not
black-bodies, but my guess is that deviations from a black-body spectral shape will also have a strong effect on the source numbers.

The real ISM is very different from the uniform model assumed for these predictions. The actual spatial distribution is quite complex and the densities are not well determined at the level of accuracy needed XUV column estimates. Some idea of the sensitivity of these predictions to the ISM density can be gained by varying the assumed average density. If the true ISM density is assumed to be a factor of 2 higher (i.e. $n_e = 0.14 \text{ cm}^{-3}$), this reduces the predicted source numbers typically by a factor of 2, at most by a factor of 4 (for the WFC S2 filter).

Conclusions

On the basis of these rather uncertain predictions, the WFC all-sky survey is expected to detect reasonable numbers of CVs. Of the order 50 - 200 polars should be detected together with a comparable number of dwarf novae in outburst (although this number is strongly dependent on spectrum). Dwarf novae in quiescence are unlikely to be detected in significant numbers unless their temperatures or luminosities have been seriously underestimated. The XRT survey, in comparison, is more sensitive for all but lowest temperatures. The XRT survey will typically detect 3-5 times as many polars, but similar numbers of dwarf novae.
Appendix D

Folded WFC survey light curves of polars

Here I present WFC survey light curves of a flux limited sample of AM Hers. The flux limit is set at 0.02 counts/sec, by which point the light curves have become dominated by counting statistics (see Fig. 4.6, Table 4.4 and Sect. 5.3).

For each system the raw light curve and exposure profile are presented, as well as the orbital-phase-folded light curves. The S1a and S2a raw light curves are plotted on the same axes; S1a points are represented by circles, S2a by crosses. The folded light curves are plotted twice for clarity. A reference to an ephemeris for each object is also provided.

The raw light curves are the simple ‘one-orbit binned’ light curves (Sect. 3.2), while the folded light curves make use of the full time resolution of the survey. The time axes for the raw light curves are labeled with modified Julian date less 48000 days, (i.e. JD–2448000.5). The count rate errors for all light curves are the 68% Bayesian confidence intervals (Sect. 3.2.2). The phase error on each point is also indicated, and the phase error due to the ephemeris is plotted as a separate error bar.

The light curves are presented in order of mean S1a count rate (brightest first), and are discussed in Sect. 5.3.
D.1 RE1938

The brightest CV in the WFC survey; RE1938 exhibits strong EUV modulation, with a constant filter ratio. The count rate does not drop to zero in the faint phase.

Ephemeris: $T(\text{MJD}) = 48476.9645(6) + 0.097235(16)E$ (optical maximum)

Reference: Buckley et al. (1993)
D.2 QQ Vul

The double peaked light curve and absorption dip of the normal mode QQ Vul light curve are visible in the S1a light curve (Osborne et al., 1987). However, there is considerable variation from the mean light curve and, of particularly importance, the S2a light curve has a different shape (see Sects. 5.3.2 & 5.3.2).

Ephemeris: $T(\text{MJD}) = 45234.5364(4) + 0.15452105(6)E$ (linear polarisation pulse)

Reference: Osborne et al. (1987) (from Cropper)
D.3 BL Hyi

Here it is more difficult to define a phase averaged light curve. Neither light curve is consistent with regular smooth modulation. The dominant emission in each filter is also out of phase with each other, suggesting the presence of two emitting poles. If the filter ratio in the S2a phase range is representative, then the emission from that pole must differ radically from that of a black body (Sect. 5.4.2).

Ephemeris: $T(\text{MJD}) = 44883.7178(6) + 0.07891518(4)E$ (steep rise to maximum)

D.4 EF Eri

Unfortunately the coverage here is rather poor, though the light curve is consistent with previous observations (e.g. Patterson, Williams & Hiltner, 1981). Once again there is evidence of much variability around the mean light curve (see Sect. 5.3.2).

Ephemeris: $T(MJD) = 43944.4522(4) + 0.05626586(8)E$ (absorption dip phase)

Reference: Bailey et al. (1981)
D.5 VV Pup

Very similar to the EXOSAT light curve. Patterson et al. (1984) report maxima occurring 0.03 cycles earlier than the predicted by the ephemeris. In this observation the lag is $\sim 0.1$ cycles. The low point in the S1a light curve at $\phi \sim 0.87$ is phased correctly to be due to the absorption dip seen in the Einstein light curves (Patterson et al., 1984), but I can not rule out the possibly that it is due to an attitude error (see Sect. 3.3.2).

Ephemeris: $T(\text{MJD}) = 27889.1474 + 0.0697468256E$ (optical maximum)

D.6 AN UMa

The light curves, though rather noisy, appear consistent with the EXOSAT LE light curve which was similar to that of QQ Vul.

Ephemeris: \( T(\text{MJD}) = 43190.4921(2) + 0.07975320(3)E \) (linear polarisation phase)

Reference: Liebert et al. (1982)
D.7 RE1149

This period is calculated from the most significant period in the S1a+S2a light curve. The error is the half width half maximum of the L-statistic peak. The detection of the beat allows an orbital period of 90 or 103 min. Mittaz et al. (1992) find a 90 min period in optical photometry.

Ephemeris: none \( P_{\text{orb}} = 5409 \pm 5 \text{ sec from these data} \)
D.8 RE1844

The extremely poor coverage prevents interpretation.

Ephemeris: \( T(\text{MJD}) = 48531.771(2) + 0.06244(6)E \) (optical minimum)

Reference: O'Donoghue et al. (1993)
D.9 RE0453

Again, poor coverage; though the S1a light curve indicates that there are counts at all phases, thus this can not be a 'two-pole system'.

Ephemeris: none \( P_{\text{orb}} = 95 \text{ min} \)

Reference: Beuermann & Schwope (1994)
D.10 RE1307

A fascinating system, showing evidence of emission from two poles (see Sect. 5.4.2), as well as being the most distant and the shortest period AM Her. It is also the first of the new AM Hers to have the WFC survey and optical observations phased. The strong S1a peak is at the same phase as the optical pulse centre (Osborne et al., 1994).

Ephemeris: \( T(\text{MJD}) = 48748.9421(5) + 0.05533838(26)E \) (optical pulse centre)

Reference: Osborne et al. (1994)
D.11 EK UMa

A weak detection, but there is clearly a peak in the S1a light curve, indicating that this is probably a ‘two-pole system’. Unfortunately the ephemeris is insufficiently precise to allow extrapolation to present epoch.

Ephemeris: \( T(\text{MJD}) = 46418.443(3) + 0.07948(14)E \) (optical maximum)

Reference: Simon et al. ()
**D.12 RE2107**

The light curves of this object, and of the remaining AM Hers, are dominated by counting statistics.

Ephemeris: $T(MJD) = 48773.19281(5) + 0.086757(7)E$ (eclipse centre)

Reference: Hakala et al. (1993)
Here I present figures showing the spectral constraints placed on polars by the ROSAT WFC survey.

For all sources I assume a black-body spectrum absorbed by interstellar material (Morrison & McCammon, 1983). A grid of spectra, in the \( kT - N_H \) plane, have been folded through the WFC response to give predicted count rates and S1:S2 ratios. A filter ratio defines a region in this plane with no further information. If the distance is known then emitting areas and luminosities can be calculated for each point in the grid.

Both emitting area and luminosity can be constrained by theory. I use a luminosity limit of \( 7.8 \times 10^{37} \text{ erg s}^{-1} \), which is the Eddington luminosity of a 0.6 \( M_\odot \) white dwarf. The emitting area is constrained by the size of the white dwarf, and by the observation that orbital binned light curves are strongly modulated; showing that the emitting region covers only a small fraction of the surface of the white dwarf. The limits I use are 10% of the surface area of a white dwarf, at a mass of 0.6\( M_\odot \) and at 1.0\( M_\odot \). Note that, as white dwarfs are degenerate, the radius decreases with mass.

We can also limit the temperature of the emission region by considering the local Eddington limit. This yields maximum temperature of 53 eV for a 0.6\( M_\odot \) white dwarf, and 76 eV at 1.0\( M_\odot \).

Finally, we can estimate the expected luminosity from the empirical relation of Patterson (1984) (see Sect. 5.4). These are marked on the following plots as dashed contours. All these constraints are discussed more fully in chapter 4.

The following figures show the \( kT - N_H \) plane for all polars brighter than 0.02 counts/sec that were detected in both filters; the same sample as in appendix D, except for EK UMAs and RE2107. The dark shaded region indicates the emitting area constraint, the width

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**Appendix E**

**WFC survey spectra of polars**

Here I present figures showing the spectral constraints placed on polars by the ROSAT WFC survey.

For all sources I assume a black-body spectrum absorbed by interstellar material (Morrison & McCammon, 1983). A grid of spectra, in the \( kT - N_H \) plane, have been folded through the WFC response to give predicted count rates and S1:S2 ratios. A filter ratio defines a region in this plane with no further information. If the distance is known then emitting areas and luminosities can be calculated for each point in the grid.

Both emitting area and luminosity can be constrained by theory. I use a luminosity limit of \( 7.8 \times 10^{37} \text{ erg s}^{-1} \), which is the Eddington luminosity of a 0.6 \( M_\odot \) white dwarf. The emitting area is constrained by the size of the white dwarf, and by the observation that orbital binned light curves are strongly modulated; showing that the emitting region covers only a small fraction of the surface of the white dwarf. The limits I use are 10% of the surface area of a white dwarf, at a mass of 0.6\( M_\odot \) and at 1.0\( M_\odot \). Note that, as white dwarfs are degenerate, the radius decreases with mass.

We can also limit the temperature of the emission region by considering the local Eddington limit. This yields maximum temperature of 53 eV for a 0.6\( M_\odot \) white dwarf, and 76 eV at 1.0\( M_\odot \).

Finally, we can estimate the expected luminosity from the empirical relation of Patterson (1984) (see Sect. 5.4). These are marked on the following plots as dashed contours. All these constraints are discussed more fully in chapter 4.

The following figures show the \( kT - N_H \) plane for all polars brighter than 0.02 counts/sec that were detected in both filters; the same sample as in appendix D, except for EK UMAs and RE2107. The dark shaded region indicates the emitting area constraint, the width
shows the difference between a white dwarf of mass $0.6 M_\odot$ and one of $1.0 M_\odot$, (the higher mass gives the tighter constraint). The dashed lines show the temperature limits (53 eV for $M_{\text{wd}} = 0.6 M_\odot$). The other shaded regions indicate the allowed spectra for each system; 68% and 95% regions are plotted. The associated contours extend into the disallowed regions, as these show the region of the $KT - N_H$ plane defined purely by the S1a:S2a filter ratio. The other contours are of luminosity; and are only plotted where there is a measure of the distance (taken from table 5.1. These are (from the left), $7.8 \times 10^{37}$ erg s$^{-1}$ the Eddington for a $0.6 M_\odot$ white dwarf, and $10^{35}$, $10^{34}$, $10^{33}$, $10^{32}$, $5 \times 10^{31}$, $3 \times 10^{31}$ and $1 \times 10^{31}$ erg s$^{-1}$.

The count rates used for these figures are taken from table 4.4, have been corrected for the drop in detector efficiency through the survey and have had 10% systematic errors added in quadrature to account for uncertainties in the efficiency drop and the spectral response of the WFC. In all cases the mean survey count rates have been used, so that no assumptions have to be made about the interpretation of the WFC light curves. For systems with unknown distances I have assumed a conservative value of 75 pc for the emitting area constraint, and have not plotted luminosity contours. In Sect. 5.4 I present phase resolved spectral constraints the sources which show orbital modulation of the filter ratio (QQ Vul, RE1307 and BL Hyi).
E.1 RE1938
E.2 QQ Vul
E.3 BL Hyi

\[ N_H [\text{cm}^{-2}] \]

Temperature [eV]
E.4 EF Eri
E.5 VV Pup
E.6 AN UMa
E.7 RE1149
E.8 RE1844
WFC spectra of polars

E.9 RE0453

Temperature [eV]

$N_H$ [cm$^{-2}$]

$10^{18}$  $10^{19}$  $10^{20}$  $10^{21}$
E.10  RE1307

WFC spectra of polars
Appendix F

WFC light curves of dwarf novae in outburst

Here I present WFC light curves of the non-magnetic cataclysmic variables discussed in Sect. 7.4.2. There are two bright nova-like variables, and nine dwarf novae known to have been in outburst during their survey observations.

Only one system, V3885 Sgr, is detected with confidence (2.6\( \sigma \) in S1a, 1.6\( \sigma \) in S2a), but several show low-significance short-term brightenings which may correspond to optical outburst. Optical outburst light curves are not yet available.

In all plots, solid lines represent 68\% confidence intervals and dotted lines are 95\% confidence. S2a points are marked as squares, S1a with circles. All have been binned with a program that adapts to the natural grouping of the survey scans.
Dwarf novae in outburst

![Graph of YZ Cnc](image)

![Graph of AQ Eri](image)
Dwarf novae in outburst

\[ V2051 \text{ Oph} \]

\[ \text{Time [MJD-48000]} \]

\[ \text{WFC counts/sec} \]

\[ \text{Exposure [min]} \]

\[ \text{RX And} \]

\[ \text{Time [MJD-48000]} \]
Dwarf novae in outburst

![Graph of AB Dra](image1)

![Graph of WX Hyi](image2)
Dwarf novae in outburst

**Graph 1:**
- **WW Cet**
- Exposure [min] on the y-axis, with values from 0 to 15.
- Time [MJD-48000] on the x-axis from 235 to 239.
- Data points indicate variability in exposure.

**Graph 2:**
- **V436 Cen**
- Exposure [min] on the y-axis, with values from 0 to 10.
- Time [MJD-48000] on the x-axis from 243 to 246.5.
- Data points indicate variability in exposure.
References


REFERENCES


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Over the years, I shared the top corridor happily with a total of more than fifteen other students: from the legendary Nandra-age, almost totally lost in the mists of time with only vague and painful memories of Tahir’s tape-recorder, to the modern age of squeaky-clean bright-young-things. Particular attention must be paid to Andy B, Simeski, Westy and Colin “no-nickname” Barber. I must also mention my brief dalliance with the sophisticated company of the Astronomy boys from the back passage. Good luck with the things.

Life in Leicester wouldn’t have been the same without the green kitchen and orange chairs of Tichborne St, and of course the wonderful people who have passed through, cooked in and sat on them. Thanks to all who shared their evenings with me down the Miller, or their Saturday afternoons drinking cheap bitter and watching U-boat movies. In particular I thank Debs for her loving attention and support over the last year, also for her boundless enthusiasm and energy, her emergency poetry readings and for showing me how to do things by the book. Cath and Dom must know how much I value their friendship, but I can take this opportunity to thank them for our innumerable jazz breakfasts and acknowledge that they were among the first to copulate on Chap. 2.

Life in Leicester wouldn’t have been the same either without my time outside it, notably in Glasgow. I happily thank than Lyndsay Fletcher for her years of love, friendship and fun.

Finally I reserve the warmest thanks to everyone who sat patiently in pubs listening to me explain how I “actually shouldn’t be here at all and really must go to work and write my thesis".