Observations of the extreme-ultraviolet transient RE J1255+266: a short outburst of a WZ Sge system?

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ABSTRACT

We present a previously unpublished ROSAT Wide Field Camera observation of the transient source RE J1255+266 made just 4 d before the discovery observations. The source is not detected, limiting the duration of the outburst to be less than expected for a superoutburst of a WZ Sge system.

We also present a marginal detection of X-ray emission from RE J1255+266 using ASCA. The most probable luminosity is $6 \times 10^{29}$ erg s$^{-1}$, which is very similar to WZ Sge itself.

We discuss the nature of the source in the light of these observations, and conclude that it is most probably a WZ Sge system, but that the observed outburst must have been a normal dwarf nova outburst.

Key words: accretion, accretion discs – binaries: close – stars: individual: RE J1255+266 – stars: low-mass, brown dwarfs – novae, cataclysmic variables – X-rays: stars.

1 INTRODUCTION

The remarkably bright transient source REJ1255+266 was discovered serendipitously in a ROSAT Wide Field Camera (WFC) observation (Dahlem & Kreysing 1994). Dahlem et al. (1995) report a peak WFC count rate of $14 \times 10^{-1}$ s$^{-1}$ in the S2 filter (62–110 eV; 112–200 Å) corresponding to an extreme-ultraviolet flux of about $7 \times 10^{-9}$ erg s$^{-1}$ cm$^{-2}$: this is twice as bright as the white dwarf HZ 43, which is the brightest persistent source in the extreme-ultraviolet sky (Pounds et al. 1993).

Dahlem et al. (1995) found that the WFC count rate decreased exponentially over a period of 3 d, with an e-folding time of about 1 d. The rise was not covered, and the source was not detected in another WFC observation eight days later (consistent with a continuing exponential decline).

A deep observation with the Extreme Ultraviolet Explorer (EUVE) in 1995 June also failed to detect the source. (Drake et al. 1998) derived a stringent upper limit to the quiescent extreme-ultraviolet flux, suggesting that the source brightened by a factor $>5 \times 10^3$ in outburst.

Watson et al. (1996) measured the optical spectrum of an object consistent with the WFC position ($V \sim 18$) and found a blue continuum with broad Balmer absorption lines, characteristic of a hot DA white dwarf. This spectrum was superimposed with strong narrow Balmer and He I emission lines. Watson et al. conclude that this object is very likely the optical counterpart of the extreme-ultraviolet transient, and they identified it as most likely a cataclysmic variable. However, they failed to find any direct evidence for the presence of a secondary star. The spectrum of the white dwarf was found to dominate the system even at 9300 Å, and sensitive radial velocity measurements did not reveal any orbital motion ($K \sim 5$ km s$^{-1}$). These observations show that any secondary star must be extremely low mass. Watson et al. conclude that RE J1255+266 is most likely a WZ Sge-type cataclysmic variable.

WZ Sge systems are a poorly defined subclass of dwarf novae. They are selected for their optical observational properties, which usually include short orbital periods, low accretion rates (indicated by the dominance of the white dwarf in the optical spectrum) and infrequent large-amplitude outbursts (Bailey 1979; O’Donoghue et al. 1991). The confusion over their definition stems from the current motivation for separating them from other dwarf novae, which is theoretical rather than observational. The aim is to identify the cataclysmic variables in which the secondary star has lost too much mass to sustain nuclear burning, and has become a brown dwarf. Such systems evolve more slowly than normal cataclysmic variables, and population synthesis models predict they should be very numerous (Kolb 1993). They also evolve gradually back to longer orbital periods, so it is impossible to distinguish them from normal cataclysmic variables by period alone. Without an unambiguous observational characteristic, there has been considerable disagreement as to which, if any, of the known cataclysmic variables are likely candidates (e.g. Howell, Szkody & Cannizzo 1995; Patterson 1998).

Recently Patterson (1998) has argued that it is possible to measure the mass ratio of a cataclysmic variable using the period of ‘superhumps’ detected in outburst light curves, and thus to

1 Howell and co-workers prefer the name ‘TOADs’ (tremendous outburst amplitude dwarf novae) to WZ Sge systems.
separate systems with red dwarf and brown dwarf companions at a given orbital period. This approach reveals only four WZ Sge candidates (WZ Sge, EG Cnc, AL Com and DI UMa), all of which lie close to the minimum observed orbital period. Throughout this paper we apply the label ‘WZ Sge system’ to these four objects only.

In this paper we present an unpublished WFC observation of REJ1255+266, made just four days before the discovery observations of Dahlem et al. No source is detected, limiting the duration of the outburst to much less than expected for a superoutburst of a WZ Sge system. We also present an upper limit to the X-ray emission of REJ1255+266, and discuss the nature of the source in the light of these observations.

2 OBSERVATIONS AND RESULTS

2.1 ROSAT Wide Field Camera

The ROSAT spacecraft carries two co-aligned telescopes: an X-ray telescope, and an extreme-ultraviolet telescope known as the UK Wide Field Camera (WFC; Sims et al. 1990). REJ1255+266 lies in the direction of the Coma cluster of galaxies, which has been observed many times with ROSAT. As a result, REJ1255+266 has been observed twenty times with the WFC, which has a large field of view (5° diameter). The field of view of the X-ray telescope is much smaller (2° or 0.6°, depending on detector) and it has covered the position of REJ1255+266 only once. On this occasion the source lay behind part of the window support structure of the X-ray detector, and no useful measurements were made.

Apart from the discovery observation, REJ1255+266 is not detected in any of the WFC observations. All yield similar upper limits, none of which approach that of (Drake et al. 1998) using EUVE. However, one WFC observation stands out because it was made just four days before the discovery observations (observation number 800242a04; see Table 1).

We have extracted both the discovery and pre-discovery WFC data sets from the ROSAT data archive at Leicester University and calculated light curves using the Bayesian method of Kraft, Burrows & Nousek (1991). This method yields appropriate count rates and upper limits in both the detection and non-detection regimes. We extracted source counts from a 6 arcmin radius circle centred on the position of the optical counterpart (Watson et al. 1996) and estimated the background using large annuli centred on the same position. We applied corrections for vignetting and for counts lost outside the accumulation region, but did not correct for the drop in detector efficiency caused by damage sustained when the spacecraft pointed at the Sun in 1991. This effect is a factor of 0.15 and 0.19 for filters S1a and S2b, respectively.

Our light curve is presented in Fig. 1, plotted on a logarithmic intensity scale. Error bars represent the 99 per cent confidence regions. The exponential decline of the outburst is clearly visible, and our new pre-discovery data show that the outburst cannot have started more than 4.5 d before the first observation of Dahlem et al. The 99 per cent confidence upper limit to the count rate of the last slot of the pre-discovery observations is 0.006 s⁻¹.

It may be argued that the outburst extends to earlier times, but that its spectrum is not detectable with the S1 filter (90–185 eV, in use during the pre-discovery observation). We regard this possibility as extremely unlikely. The bandpasses of the S1 and S2 filters are very close and the implied filter ratio is enormous. Even if we assume that the discovery count rate of 14 s⁻¹ is the outburst maximum, the implied filter ratio at the end of the pre-discovery observations is > 2 × 10⁷. For comparison, a blackbody spectrum can satisfy this lower limit only with temperatures less than 30 000 K (and would require an unreasonably high ultraviolet flux). While we cannot rule out a bizarre spectral form, perhaps dominated by very intense line emission in the S2 bandpass, we regard this possibility as unlikely and conclude that the outburst began on or after 1994 June 21 (MJD 49524).

2.2 ASCA

The ASCA spacecraft carries four co-aligned X-ray telescopes, two with CCD detectors and two with gas-scintillation proportional counter detectors (Tanaka, Inoue & Holt 1994). ASCA was used to observe REJ1255+266 for 21 ks on 1996 January 8. Using the standard screened data, we find an enhancement of counts at the source position in all four telescopes, but each...

Table 1. All public ROSAT WFC observations of REJ1255+266.

<table>
<thead>
<tr>
<th>Obs. No.</th>
<th>Target</th>
<th>Start Date</th>
<th>End Date</th>
<th>Exposure (ks)</th>
<th>Filter</th>
<th>Detection?</th>
</tr>
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<tr>
<td>170027</td>
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<td>91-Jun-16</td>
<td>91-Jun-16</td>
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<tr>
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<td>91-Jun-18</td>
<td>31.6/17.4</td>
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<tr>
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<td>91-Jun-19</td>
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<td>S1a/S2b</td>
<td>No</td>
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<td>No</td>
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<td>Yes</td>
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<td>S1a</td>
<td>No</td>
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individually does not exceed fluctuations that may be expected in the background (none represents an enhancement of the background above $3\sigma$). Nevertheless, the presence of a fluctuation at the source position in all four telescopes suggests that the source lies a little below the formal detection limit of our observations. Thus we present a most probable count rate, as well as a formal upper limit.

We extracted source counts from a 3-arcmin radius circle in both of the gas-scintillation proportional counter detectors (GIS2 and GIS3), and measured the background count rates using annuli with outer radii 7.4 arcmin. We did not use the CCD detectors because the area available for background determination is limited. In Fig. 2 we plot the radial distribution of GIS2+3 counts around the position of REJ1255+266. We found total source-region counts of 146 and 147 for the GIS2 and GIS3 detectors respectively, and estimated normalized background counts of $116^{+5}_{-5}$ and $122^{+5}_{-5}$.

The exposure in each instrument is 20 642 s, thus the measured source count rates are $1.45^{+0.79}_{-0.79}$ and $1.23^{+0.79}_{-0.79}$, combining these count rates we find a mean rate of $1.74^{+0.56}_{-0.56}$ and a 3$\sigma$ upper limit to the mean count rate of $3\times10^{-3}$ s$^{-1}$.

We estimate the corresponding X-ray flux using the spectral-fitting program XSPEC (Arnaud 1996). We extracted a spectrum from the GIS2 data, and created an appropriate instrument response file using the FTOOL ASCAARF. This includes corrections for vignetting, point spread function and window transmission, all as a function of energy. We have assumed an optically thin spectrum with $kT = 5$ keV, which is fairly typical of the X-ray spectra of non-magnetic cataclysmic variables, and we assumed negligible interstellar absorption. For a count rate of $1.34\times10^{-3}$ s$^{-1}$ this corresponds to a 1–10 keV flux of $1.1\times10^{-13}$ erg cm$^{-2}$ s$^{-1}$. This result is not very sensitive to temperature: at 1 keV the flux would be $0.5\times10^{-13}$ erg cm$^{-2}$ s$^{-1}$ and at 30 keV it would be $1.4\times10^{-13}$ erg cm$^{-2}$ s$^{-1}$. Corrections for X-ray flux lost outside the bandpass of ASCA are also quite small: factors of 2.9 at 1 keV; 1.5 at 5 keV; 1.7 at 10 keV; and 2.5 at 30 keV.

(Watson et al. 1996) fitted the optical spectrum of the white dwarf in REJ1255+266 and found a distance of $180^{\pm80}_{\pm55}$ pc. We adopt this value, but note that it is sensitive to their assumption of negligible dilution of the spectrum by other spectral components.
At 180 pc, taking our most probable count rate, and the 5-keV spectrum, we find a most probable X-ray luminosity of $6 \times 10^{29}$ erg s$^{-1}$. At 260 pc and taking our upper limit to the count rate, we find an upper limit to the X-ray luminosity of $3 \times 10^{30}$ erg s$^{-1}$.

3 DISCUSSION

3.1 Outburst duration

Watson et al. (1996) identified RE J1255 + 266 as a probable member of the WZ Sge subclass of cataclysmic variable, based on the dominance of the white dwarf in the optical spectrum and the lack of radial velocity variations. WZ Sge systems show a strong preference for superoutbursts (lasting weeks) rather than normal outbursts (lasting days) (e.g. Warner 1995), so our limit of just a few days on the duration of the outburst is somewhat surprising.

Clearly we must be careful in comparing our extreme-ultraviolet light curve with the optical light curves of other systems, but the few cases where both wavebands have been observed simultaneously have shown that the extreme-ultraviolet does provide a good estimate of the optical outburst duration (Van der Woerdt & Heise 1987; Ponman et al. 1995; Wheatley et al. 1996b; Long et al. 1996). In each case the extreme-ultraviolet flux remains well above the quiescent level during the plateau phase of the outburst, then drops steeply in the fast-decline phase. The discovery observations of RE J1255 + 266 apparently show it already in fast decline, so any plateau phase cannot have lasted more than 4.5 d. For comparison, the superoutburst plateau-phase durations of the known WZ Sge systems (as defined by Patterson 1998) are 26 d (WZ Sge, Patterson et al. 1981), >25 d (AL Com, Patterson et al. 1996) and >15 d (EG Cnc, Patterson et al. 1998). The shortest plateau for any dwarf nova superoutburst is 7 d (Warner 1995).

The optical light curves of WZ Sge systems are relatively poorly observed, largely because their quiescent magnitudes tend to be beyond the reach of amateur observers. The only well-studied system is WZ Sge itself, with a visual magnitude in quiescence around 15. No normal outbursts have ever been observed in WZ Sge, giving the impression that the entire class exhibits only superoutbursts. In fact, other candidate WZ Sge systems have apparently shown short outbursts (e.g. AL Com, Howell et al. 1996; and possibly EG Cnc, Patterson et al. 1998). The poor optical coverage of these systems allows such outbursts to be easily as numerous as superoutbursts. Given the evidence presented by Watson et al. (1996), we conclude that the observed outburst of RE J1255 + 266 is most likely a normal dwarf-nova outburst of a WZ Sge system.

3.2 Outburst luminosity

The observed extreme-ultraviolet flux during the outburst of RE J1255 + 266 is enormous, but we must be cautious before deciding that this represents an unusually high luminosity.

A simple consideration of Kepler’s laws leads one to expect that an accretion disc will radiate one half of the available gravitational energy, and that half must be released very close to the central object. However, observations of dwarf novae in outburst have shown that the extreme-ultraviolet emission attributed to the boundary layer is substantially less luminous than the ultraviolet and optical emission attributed to the disc (Ferland et al. 1982; Van Teeseling & Verbunt 1994; Wheatley et al. 1996b). A possible solution to this problem, that the central objects are rapidly rotating, has been ruled out in at least seven cases by Hubble Space Telescope and EUVE observations (Mauche 1997; Livio & Pringle 1998 and references therein). The ultraviolet luminosity of dwarf novae in outburst is around $10^{34}$ - $10^{35}$ erg s$^{-1}$ (Ponman et al. 1995; Mauche, Raymond & Mattei 1995; Wheatley et al. 1996a,b; Long et al. 1996), which is similar to the observed extreme-ultraviolet luminosity of RE J1255 + 266. Perhaps we should think of this system as the first dwarf nova to show sufficient boundary layer emission, rather than excess emission.

Two unusual features may combine to make the extreme-ultraviolet emission of RE J1255 + 266 so striking. First, it probably has a high-mass white dwarf ($M_{\text{wd}} \sim 1 M_{\odot}$; Watson et al. 1996). The only other dwarf nova with a soft component easily detected with ROSAT is SS Cyg (Ponman et al. 1995) which probably also has a massive white dwarf (Friend et al. 1990). The deep potential well and small radius of a high-mass white dwarf will force the boundary layer to be smaller and more luminous, perhaps resulting in a temperature high enough to be detectable with the WFC. The second unusual feature of RE J1255 + 266 is that we view it at low inclination (probably $i \approx 5^\circ$; Watson et al. 1996). We may speculate that this low inclination allows an unobserved view of the entire boundary layer, providing the first measurement of the total extreme-ultraviolet luminosity of any dwarf-nova outburst.

3.3 Outburst decline

Dahlem et al. (1995) measure a half-light decline time-scale for RE J1255 + 266 of 0.86 ± 0.04 d, and claim that this is faster than the optical decline of dwarf novae. We point out there is a known correlation between orbital period and decline time-scales in dwarf novae (e.g. Warner 1995) with short-period systems declining more quickly. If RE J1255 + 266 is a short-period cataclysmic variable, as we suspect, then one would expect optical decline time-scales in the range 0.6 – 1.5 d mag$^{-1}$.

We also point out that the extreme-ultraviolet decline of dwarf novae is faster than their optical decline. In SS Cyg, for instance, the e-folding time-scale of the optical decline is ~3 d while the extreme-ultraviolet time-scale is just 1 d (Ponman et al. 1995). If anything, the extreme-ultraviolet decline of RE J1255 + 266 is rather slower than one would expect.

3.4 X-ray luminosity

Our tentative detection of X-ray emission from RE J1255 + 266 (Section 2.2, Fig. 2) provides further evidence that the system is a binary. Photospheric emission from isolated white dwarfs is too soft to be detected with ASCA, so the X-rays must originate from a binary companion: either as an X-ray source in its own right, or as a mass donor fuelling accretion on to the white dwarf. Our most probable X-ray luminosity, $6 \times 10^{29}$ erg s$^{-1}$, is fairly typical of rapidly rotating late-type main-sequence stars, though it is a little high for the latest M dwarfs (Stauffer et al. 1994). The level of X-ray emission from brown dwarfs is unknown, but Stauffer et al. (1994) show that the X-ray emission of late-type stars scales with surface area. Secondary stars in short-period cataclysmic variables are expected to be significantly oversized for their mass, so it is conceivable that even extremely low-mass secondaries maintain X-ray emission appropriate to the lower main sequence.
Such luminosities, even our formal upper limit of $3 \times 10^{30} \text{erg s}^{-1}$, are low for a cataclysmic variable. In most cases the accretion-driven X-ray emission far exceeds the level attributable to the secondary star. Verbunt et al. (1997) present the full set of observations of cataclysmic variables in the ROSAT All-Sky Survey. They find X-ray luminosities of cataclysmic variables in the range $10^{29} - 10^{32} \text{erg s}^{-1}$, with all the systems below $10^{30} \text{erg s}^{-1}$ being short-period dwarf novae (or low-state magnetic systems). Thus our most probable and limiting X-ray luminosities for REJ1255+266 are consistent with emission from a short-period cataclysmic variable. In fact, our flux limit is somewhat tighter than appears at first sight, since the luminosities of Verbunt et al. apply only to the 0.5–2.5 keV band, and because REJ1255+266 probably has a massive white dwarf ($\sim 1 M_\odot$; Watson et al. 1996). Using this mass, our luminosity upper limit corresponds to an upper limit to the accretion rate on to the white dwarf of $10^{13} \text{g s}^{-1}$ (and a most probable rate of $2 \times 10^{12} \text{g s}^{-1}$).

Verbunt et al. (1997) measure a ROSAT count rate for WZ Sge itself, but not a luminosity. At a distance of 48 pc (Smak 1993; Spruit & Rutten 1998) we find a 0.5–2.5 keV X-ray luminosity of $4 \times 10^{30} \text{erg s}^{-1}$. This is essentially the same as our most probable luminosity for REJ1255+266. There has been much debate over the mass of the white dwarf in WZ Sge (summarized by Patterson 1998): however, if we accept the high mass favoured by the careful analysis of Spruit & Rutten (1998) we find that WZ Sge and REJ1255+266 also have similar quiescent accretion rates.

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