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EUVE J1429 – 38.0: an eclipsing polar

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ABSTRACT

Photometric, polarimetric and spectroscopic observations are presented for EUVE J1429 – 38.0. Spectroscopically, the system is dominated by the M2 secondary star but with the emission lines characteristic of a polar in its low state. The photometric data reveal the system to be an eclipsing binary, $P_{\mathrm{orb}} = 4.765$ h, with a strong ellipsoidal variation. The eclipse of the hot compact source occurs substantially before inferior conjunction as determined by the ellipsoidal variation. This, together with the eclipse ingress and egress detail, leads to the conclusion that the compact light source eclipsed is not coincident with the white dwarf, but may be associated with the accretion stream.

Key words: accretion, accretion discs – binaries: eclipsing – stars: individual: EUVE J1429 – 38.0 – novae, cataclysmic variables.

1 INTRODUCTION

This paper presents photometry, polarimetry and spectroscopy of a newly identified eclipsing polar (AM Herculis system), EUVE J1429 – 38.0. Polars are a class of magnetic cataclysmic variables where the magnetic field of the white dwarf controls the accretion flow, prevents disc formation, and is sufficiently strong to synchronize the system (see recent reviews by Cropper 1990, Bailey 1995 and Warner 1995). Furthermore, they are strong sources of soft X-ray and extreme UV emission.

EUVE J1429 – 38.0 was announced to be a magnetic cataclysmic variable (Craig et al. 1996), discovered serendipitously by the *Extreme Ultraviolet Explorer* (*EUVE*) satellite during Right Angle Program (RAP) observations. The optical spectrum showed intense broad Balmer, He I and He II emission lines superimposed on a very hot (i.e. blue) continuum with a Balmer jump in emission, characteristic of a polar in its high state. This, together with the bright/faint phases in the *EUVE* light curve, is convincing evidence that the system is a polar.

Our observations (in 1996 March) of EUVE J1429 – 38.0 were taken when it was ~1 mag fainter than at discovery, indicating that it was in a lower accretion state. These data clearly establish EUVE J1429 – 38.0 as an eclipsing polar with orbital period $P_{\mathrm{orb}} = 4.765$ h. The light curve shows a strong ellipsoidal modulation caused by the varying aspect of the M2 star. The eclipse is of a hot compact light source which appears to be distinct from the white dwarf. Spectroscopic observations in and out of eclipse are dominated by the light of the M2 star with the characteristic emission lines of a polar. The properties of this system in its low state are different from those of any of the eight previously known eclipsing polars.

2 OBSERVATIONS

2.1 Photometry

The photometric data were obtained with the 1.9-m telescope of the South African Astronomical Observatory at Sutherland. High-speed CCD photometry was obtained in 1996 March and May with the University of Cape Town (UCT) CCD camera developed by one of us (DO'D). This uses a Wright Instruments blue-sensitive CCD chip in frame transfer mode, thus eliminating dead time. The size in frame transfer mode is 289 × 430 pixels, corresponding to a field of view of 38 × 56 arcsec^2 at the Cassegrain focus of the 1.9-m telescope.

Batch mode DoPHOT routines (Mateo & Schechter 1989) were used for the reductions to give aperture and profile-fitted magnitudes. The profile-fitted magnitudes gave higher precision photometry by deriving differential magnitudes of the programme star relative to brighter comparison stars.

For the first three nights of observations the camera was used with no filter, at 10-s time resolution, and the Shara focal reducer was employed. This increased the field of view to 2.0×1.4 arcmin^2, although the blue response was diminished by the focal reducer. The CCD chip was used in pre-binning mode, giving an effective scale of 0.26 arcsec pixel^{-1}, to improve the signal-to-noise ratio of the profile-fitted magnitudes. Twilight sky frames were obtained to determine the flat-field response. The no-filter observations on the first three nights are illustrated in Fig. 1. The quality of the photometry on the first night is not as good as on the other two nights because the seeing was much worse. The light curve shows a strong ellipsoidal variation with an eclipse of a compact light source lasting 26 min.

In order to obtain more wavelength-dependent information on the system, *BVRI* observations were obtained on the last two nights. Cyclic *BVRI* data (with a cycle time of ~ 100 s) were obtained with the Shara focal reducer removed to increase the blue response. On the first night the integration times were 20 s in all filters, while on the second night the integration times were 40 s (B), 20 s (V) and 10 s (R,I), in order to equalize the signal-to-noise ratios. Fig. 2 illustrates the *BVRI* data for the first night. The depth of the eclipse varies as a function of wavelength from 0.78 mag in B, 0.19 mag in V and 0.08 mag in R to <0.01 mag in I, which clearly demonstrates that it is a hot, compact light source that is eclipsed. An important point to note is that the eclipse occurs prior to secondary inferior conjunction, as judged by the minimum of the ellipsoidal variation (see Section 3.3).

The time resolution (10 s) in Fig. 1 is inadequate to resolve the details of the eclipse ingress and egress. Subsequently, however, 3- and 5-s time resolution data of the eclipse were obtained (in 1996 May). These data show that the eclipse ingress is on average longer in duration (~ 60 s) in comparison with the eclipse egress ($\lesssim 30$ s). Thus the eclipse cannot be simply of a white dwarf but is more likely to be of an elongated source that has different foreshortening factors on ingress and egress. There is also evidence that the durations of ingress and egress are not completely constant from cycle to cycle.

2.2 Polarimetry

Photopolarimetry of EUVE J1429 $-$ 38.0 was carried out using the UCT Polarimeter (Cropper 1985), with a GaAs photomultiplier, on the SAAO 1.9-m telescope in 1996 March. A short 'white-light' observation on March 20/21 failed to show any circular polarization. A more extended (48 min) observation using a red OG570 filter (which transmits light longwards of ~ 5700 Å) was undertaken on March 25/26. Thirteen 100-s integrations were obtained, with no convincing polarization detected ($\langle V/I \rangle = -0.07$ per cent, s.d. $= 1.16$ per cent). Attempts to measure polarization using a blue BG38 filter were unsuccessful, as the count rate was too low for a meaningful result.

2.3 The low-state spectrum

Spectroscopic observations were obtained on 1996 April 20 using the Double Beam Spectrograph on the Australian National University (ANU) 2.3-m telescope. The 'blue' and

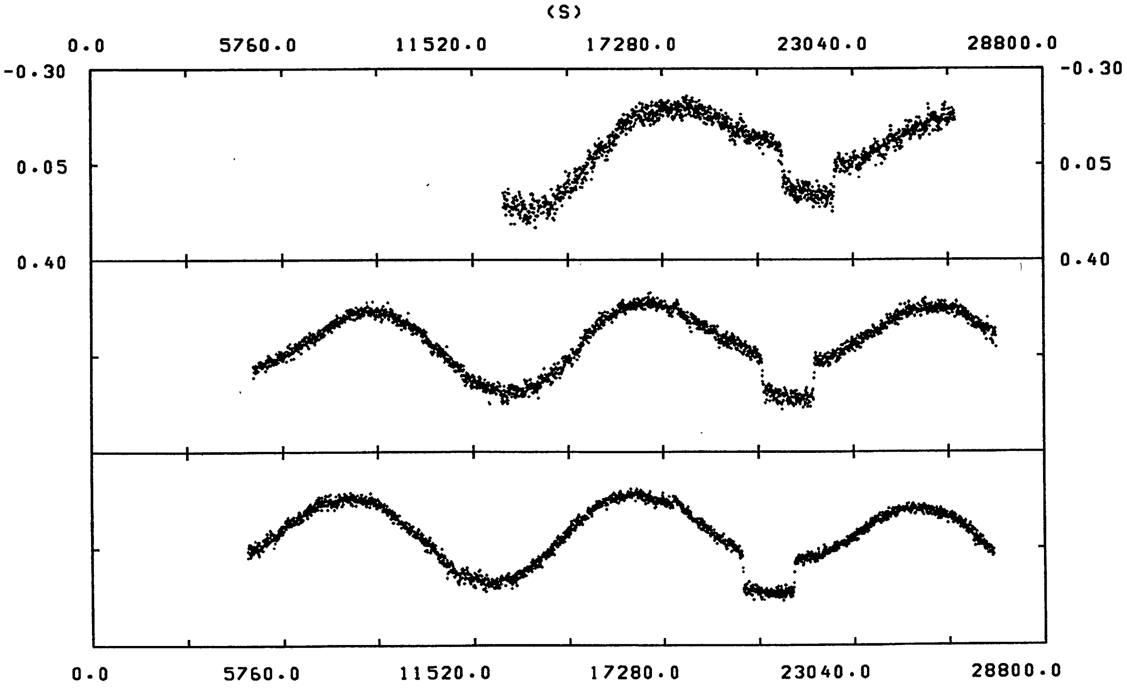

Figure 1. Three successive nights of white light observations of EUVE J1429 $-$ 38.0 with 10-s time resolution. The abscissa of each panel corresponds to exactly one-third of a day (28 800 s) and starts at the same fractional Julian date. The eclipse (of duration 26 min) of the compact light source can be seen to occur successively earlier each night by 10.4 min. Note that the eclipse is not centred exactly on a minimum of the ellipsoidal variation, and that there is no evidence of flickering in the light curve.

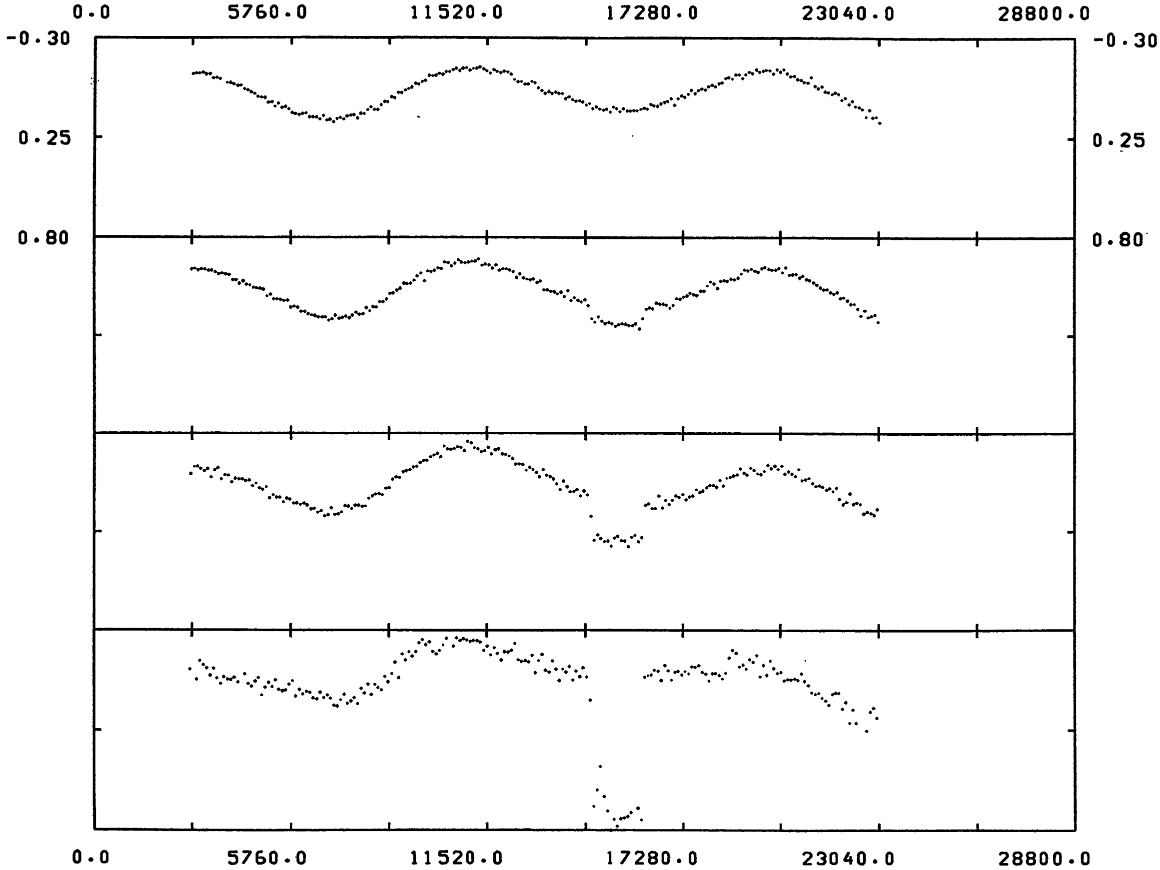

Figure 2. Four colour light curves of EUVE J1429 − 38.0 in order, from top to bottom, *I* band, *R* band, *V* band and *B* band. The eclipse varies in depth as a function of wavelength from 0.78 mag in *B* to < 0.01 mag in *I*.

'red' arms of the spectrograph covered the range 3400–6000 and 5800–9100 Å, respectively, at a reciprocal dispersion of 2 Å pixel^{-1}. In Fig. 3 we show the mean spectra for outside and inside eclipse. Apart from the emission lines, and the Balmer jump in emission, the spectrum is dominated by the late-type secondary star. Many features typical of an M star are seen (TiO, VO and MgF bands), and we used the TiO band near 7120 Å as a spectral type diagnostic (Bessell 1991). The depth of this feature with respect to the continuum indicates a spectral type of M2 for the in-eclipse spectrum. We convolved our spectra with the *UBVRI* (Cousins system) bandpasses, to obtain the following magnitudes and colours. Eclipse: $V = 18.10$, $B - V = 1.32$, $R - I = 1.18$; outside eclipse: $V = 17.54$, $U - B = -0.86$, $B - V = 0.78$, $R - I = 1.05$. The eclipse $(R - I)$ colour is consistent with the M2 spectral type, which has a canonical value of 1.16 (Bessell 1991).

The appearance of this spectrum is typical of a low-state polar, showing reduced excitation, strength and width of the emission lines. The He II 4686-Å line is markedly weaker than in the discovery spectrum (Craig et al. 1996). The spectral variation at longer wavelength (by ~0.3 mag at *I*) is clearly due to the ellipsoidal variations of the secondary. This is confirmed from looking at the TiO line depth ratio, which remains essentially unchanged. Subtracting a scaled M2 spectrum (i.e. the eclipse spectrum) from the outside-eclipse spectrum shows the contribution from the white dwarf and accretion spot/stream. The only features seen in this spectrum, other than the strong emission lines, are residual absorption band features from the M dwarf. These are probably due to temperature variation over the surface of the distorted secondary. We conclude, therefore, that there is no evidence for cyclotron lines in the spectrum, and suggest that the features tentatively identified as such by Craig et al. are due to TiO bands instead. Neither is there any indication of Zeeman features in the spectrum.

3 BINARY SYSTEM PARAMETERS

3.1 Orbital period

The orbital period and the eclipse parameters can be derived most accurately from the white light observations. From an analysis of the eclipse detail, the heliocentric Julian dates of the first, second, third and fourth contacts and the times of mid-ingress and mid-egress were derived. From these data the ephemeris for mid-eclipse (defined as the mean of mid-ingress and mid-egress times) is

$$T(\mathrm{HJD}) = 245\,0155.591\,15(14) + 0.198\,5598(3)E. \qquad (1)$$

Within the errors, the times of mid-ingress and mid-egress appear to be constant in phase. The ellipsoidal variation was also analysed for the frequencies present by combining the white light observations (excluding the eclipse) for the first

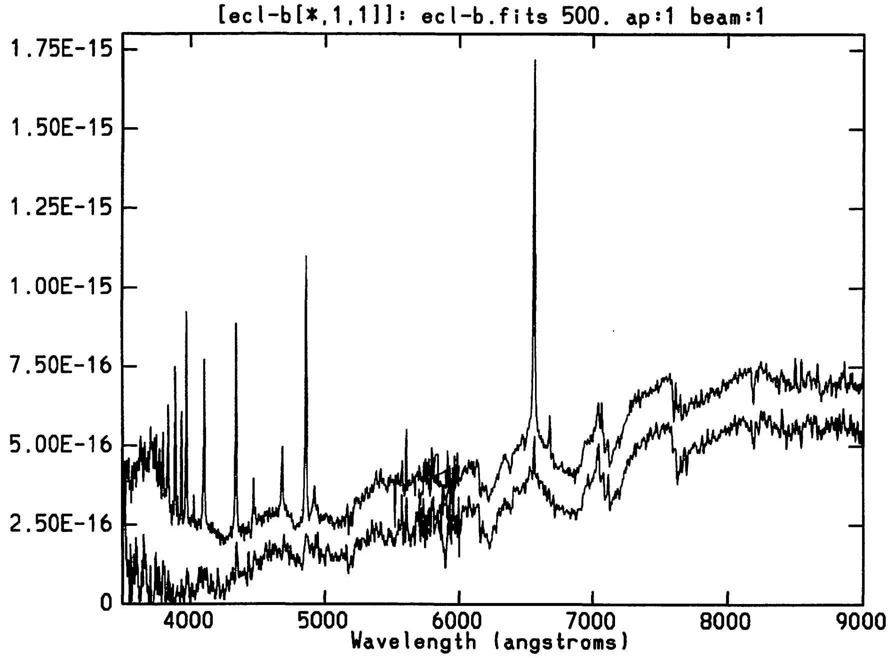

Figure 3. Mean spectra of EUVE J1429 – 38.0 in the low state, outside eclipse (upper spectrum) and inside eclipse (lower spectrum).

three nights. No periodic signals other than those related to the orbital modulation were detected.

The ellipsoidal modulation shows unequal minima similar to the infrared light curve of the low-mass X-ray binary system Centaurus X-4 (Shahbaz, Naylor & Charles 1993). Detailed modelling of the ellipsoidal modulation can be used to determine the mass ratio q $(=M_2/M_1)$ and the inclination i. The deeper minimum at superior conjunction is caused by the gravity-darkening and limb-darkening effects on the Roche-lobe-filling secondary, which are more severe on the side of the secondary containing the L_1 point. This in itself shows that the irradiation of the secondary by the hot compact source has a minor effect on the continuum light distribution over the surface of the secondary, otherwise the deeper minimum would not occur at inferior conjunction of the secondary.

3.2 Masses, radii and separation

There is good evidence that EUVE J1429 – 38.0 contains a Roche-lobe-filling secondary. We know that *EUVE* observations of the system (Craig et al. 1996) showed it to be in a high state during 1993 March and to be in a low state during 1995 March/April. Recent *EUVE* observations in 1996 May also show it to be in a low state (Stroozas 1996). Although there is no evidence of flickering in the light curve, indicative of mass transfer, the spectroscopic evidence during our observations (Fig. 3) is characteristic of a polar in a low state, namely the secondary is filling its Roche lobe but transferring mass at a low rate.

Approximate binary system parameters can be derived following Warner (1995). The separation between the centres of mass of the binary components is given by

$$a=3.53\times10^{10}(M_1/\mathrm{M}_\odot)^{1/3}(1+q)^{1/3}P_{\mathrm{orb}}^{2/3}(\mathrm{h})\ \mathrm{cm}, \qquad (2)$$

where M_1 is the mass of the primary, M_2 is the mass of the secondary, $q=M_2/M_1$ and P_{orb} is the orbital period in hours. With $P_{\mathrm{orb}}=4.765$ h and adopting $q=1$ and $M_1/\mathrm{M}_\odot=0.6$, the mean mass of white dwarfs (Bergeron, Saffer & Liebert 1992), we derive $a=1.06\times10^{11}$ cm.

For the secondaries of cataclysmic variables, the mean empirical mass–period and radius–period relationships (Warner 1995) lead to $M_2/\mathrm{M}_\odot=0.46$ and $R_2/\mathrm{R}_\odot=0.51$, respectively, for EUVE J1429 – 38.0. The resultant mean density of the secondary, $\bar{\rho}_2=4.71$ g cm^{-3}, corresponds to the mean density of a lower main-sequence star of spectral class M2, consistent with the spectroscopic evidence in Section 2.3.

With $R_2/\mathrm{R}_\odot=0.51$ and $a=1.06\times10^{11}$ cm, we derive $R_2/a=0.33$. If we equate R_2 with the volume radius of the Roche lobe R_{L2} given by Paczynski's (1971) relation

$$R_{\mathrm{L2}}/a=0.38+0.20\log q, \qquad 0.3<q<20, \qquad (3)$$

then we derive $q=0.56$. This leads to $M_1/\mathrm{M}_\odot=0.82$ and hence, using the revised values for q and M_1 in equation (2), we derive a revised value of $a=1.08\times10^{11}$ cm.

3.3 The hot compact light source

At first sight the light curves (Fig. 1) show an eclipse that looks very similar to an eclipse of a white dwarf. However, two points argue against this. First, the hot compact light source that is eclipsed cannot be solely a white dwarf because the ingress time is on average a factor of 2 greater than the egress time (Section 2.1). Secondly, the timing of the eclipse is not centred on the minimum of the ellipsoidal modulation. Thus, if we were to claim that the eclipse is of the white dwarf and hence defines inferior conjunction, some other mechanism would need to be invoked to explain the non-symmetric distribution of light on the M2 star. The ellipsoidal effect appears to be so classical that it is deemed more likely that this can be used to define the time of inferior conjunction.

We have defined the time of inferior conjunction as follows. Using the white light high-speed photometry on the first three nights (excluding the eclipse data), we find the best-fitting Fourier series to the half-orbital period, 0.099 280 d, and determine the times of secondary inferior conjunction. From these data we then derive, relative to phase $\phi=0.00$ at secondary inferior conjunction, the following mean values of phase: ϕ(mid-ingress) $= -0.0757 \pm 0.002$, ϕ(mid-egress) $= 0.0149 \pm 0.002$, ϕ(mid-eclipse) $= -0.0304$; and the duration of eclipse $\Delta\phi = 0.0906 \pm 0.0005$.

The geometry of the eclipse of a point-like star by a Roche-lobe-filling secondary companion has been determined by Chanan, Middleditch & Nelson (1976). They demonstrated that the eclipse half-width $\pm\phi_{\mathrm{p}}$ is a function only of the mass ratio, q, and the inclination, i. Horne (1985) has illustrated this relationship between q and i graphically. Although we have concluded that the compact light source is not the white dwarf, provided that the light source is proximate to the white dwarf, these results can still be used to estimate the inclination, i. With $\Delta\phi = 0.0906$ we find from fig. 2 of Horne that $76° < i < 90°$ for $1 > q > 0.3$ (i.e. covering the range of white dwarf masses from $M_1/\mathrm{M}_{\odot} = 0.46$ to 1.4). If $q = 0.56$, as deduced above, then $i = 81°$.

The location of this hot compact light source in the system can be determined from the phases of mid-ingress and mid-egress. For $q = 0.56$ and $i = 81°$, the shadowing of the secondary in the orbital plane at phases ϕ(mid-ingress) $= -0.0757$ and ϕ(mid-egress) $= 0.0149$ leads to the conclusion that the light source is at an azimuth $\psi \approx -90°$ (in the convention of Cropper 1988) and at a distance, d, from the white dwarf of $d/a \approx 0.2$. With $a = 1.08 \times 10^{11}$ cm then the compact light source is at $d \approx 2 \times 10^{10}$ cm from the white dwarf (i.e. ~30 white dwarf radii distant). Consideration of these factors makes it likely that the hot compact light source is associated with the accretion stream and not the white dwarf itself. The above deductions are based on the assumption that the compact light source lies in the orbital plane and will need modification if the compact source is substantially out of the plane.

4 DISCUSSION

The optical light curves in Fig. 1 are quite unlike those of any known eclipsing polar, whether in the high or low state. In addition, there is no evidence of flickering in the light curve. However, our optical light curves do resemble the low-state IR (J) light curve of UZ For (Ferrario et al. 1989), which was also dominated by an ellipsoidal variation. Optical light curves of other eclipsing polars (Biermann et al. 1985; Remillard et al. 1991; Schwope, Thomas & Beuermann 1993; Barwig, Ritter & Bärnbanter 1994; Sohl, Watson & Rosen 1995; Shafter et al. 1995) tend to show much more irregular variations, and in the high state are dominated by the light from the accretion stream and accretion shock. The system RX J0515.6 + 0.105 also shows two out-of-eclipse light curve maxima (Shafter et al. 1995), but the amplitude in this case is much too large to be attributed solely to an ellipsoidal variation. In no case is the ellipsoidal variation in the optical so clearly shown as in EUVE J1429 − 38.0.

Our model of the system makes specific predictions about the azimuth, ψ, of the magnetic pole on which matter is accreting. Because the eclipse occurs before inferior conjunction, this magnetic pole must have negative ψ. In a study of the orientations of the magnetic pole in AM Her systems, Cropper (1988) found that the azimuths were clustered in a range of ψ from $-14°$ to $+49°$, with only one out of eight systems having negative ψ (DP Leo – see Biermann et al. 1985). The azimuth of the magnetic pole is usually determined by the phase at which the accretion column is seen closest to the line of sight on the visible hemisphere relative to the phase of secondary inferior conjunction. Once the ephemeris of EUVE J1429 − 38.0 is sufficiently accurately determined to tie in with the earlier *EUVE* observations when the system was in a high state, it will be interesting to see if our phasing prediction is confirmed. The absence of detectable polarization is consistent with an emission region at some distance from the white dwarf, as deduced from the eclipse geometry.

In a future paper we will present a detailed analysis of the orbital spectroscopic behaviour, the modelling of the ellipsoidal variation and the phasing of the high-state *EUVE* observations.

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