ULTRACAM photometry of the eclipsing cataclysmic variables XZ Eri and DV UMa

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ABSTRACT

We present high-speed, three-colour photometry of the faint eclipsing cataclysmic variables XZ Eri and DV UMa. We determine the system parameters through two techniques: first, timings of the eclipse contact phases of the white dwarf and bright-spot using the derivative of the light curve; and secondly, a parameterized model of the eclipse fitted to the observed light curve by $\chi^2$ minimisation. For both objects, we prefer the latter method, as it is less affected by photon noise and rapid flickering. For XZ Eri we obtain a mass ratio $q = 0.1098 \pm 0.0017$ and an orbital inclination $i = 80.16 \pm 0.09$. For DV UMa we derive figures of $q = 0.1506 \pm 0.0009$ and $i = 84.24 \pm 0.07$. The secondary star in XZ Eri has a very low mass $M_r / M_\odot = 0.0842 \pm 0.0024$, placing it close to the upper limit on the mass of a brown dwarf.

Key words: binaries: close – binaries: eclipsing – stars: dwarf novae – stars: individual: DV UMa – novae: cataclysmic variables – stars: individual: XZ Eri

1 INTRODUCTION

Cataclysmic variable stars (CVs) are a class of interacting binary system undergoing mass transfer via a gas stream and accretion disc from a Roche-lobe filling secondary to a white dwarf primary. A bright spot is formed at the intersection of the disc and gas stream, giving rise to an ‘orbital hump’ in the light curve at phases 0.6–1.0 due to foreshortening of the bright-spot. The light curves of eclipsing CVs can be quite complex, with the accretion disc, white dwarf and bright-spot all being eclipsed in rapid succession. With sufficient time-resolution, however, this eclipse structure allows the system parameters to be determined to a high degree of accuracy. Warner (1995) gives a comprehensive review of CVs.

XZ Eri was first noted to be variable by Shapley & Hughes (1934). Until recently (Howell et al. 1991; Szkody & Howell 1992), however, XZ Eri had been rather poorly studied. The presence of eclipses in the lightcurve of XZ Eri was discovered by Woudt & Warner (2001). More recently, Uemura et al. (2004) observed superhumps in the outburst lightcurve of XZ Eri, confirming its classification as an SU UMa star.

Previous observations of DV UMa are summarized by Nogami et al. (2001), who also present light curves obtained during the 1995 outburst and the 1997 superoutburst. Patterson et al. (2000) present superoutburst and quiescent photometry from which they derive the system parameters. Mukai et al. (1990) estimated the spectral type of the secondary star to be $\sim M4.5$ from spectroscopic observations.

In this paper we present simultaneous three-colour, high-speed photometry of XZ Eri and DV UMa. We derive the system parameters via two separate methods – timings of the eclipse contact phases and fitting a parameterized model of the eclipse – and discuss the relative merits of each.

2 OBSERVATIONS

XZ Eri and DV UMa were observed simultaneously in three colour bands using ULTRACAM (Dhillon & Marsh 2001; Dhillon et al., in preparation) on the 4.2-m William Herschel Telescope (WHT) at the Isaac Newton Group of Telescopes, La Palma. The observations are summarized in Table 1.

Data reduction was carried out as described in Feline et al.
Figure 1. The light curve of XZ Eri. The data are contiguous. The $r'$ data are offset vertically upwards and the $u'$ data are offset vertically downwards.

2004 using the ULTRACAM pipeline data reduction software. The resulting light curves of XZ Eri and DV UMa are shown in Figs 1 and 2 respectively. The observations of XZ Eri began at high airmass (1.8) – this is evident in the improved quality of the second cycle. Note also that the XZ Eri data of 2003 November 13 have significantly worse time-resolution than those of DV UMa, despite both objects being of similar magnitude. This is due to the higher brightness of the sky on 2003 November 13.

3 LIGHT-CURVE MORPHOLOGY

The light curve of XZ Eri shown in Fig. 1 is a classic example of an eclipsing dwarf nova. Between phase $-0.4$ and the start of eclipse, the orbital hump is clearly visible, with a brightening in $g'$ flux of 0.025 mJy (0.5 mag). The light curve clearly shows separate eclipses of the white dwarf and bright-spot in all three colour bands.

During our observations XZ Eri had $g' \sim 19.5$, falling to $g' \sim 21.5$ in mid-eclipse. Comparing this to the previous (quiescent) observations of Woudt & Warner (2001), who observed the system at $V \sim 19.2$, confirms that XZ Eri was in quiescence at the time of our observations.

The light curve of DV UMa is presented in Fig. 2. Although the phase coverage is less complete than for XZ Eri, the eclipse morphology is again typical of eclipsing short-period dwarf novae. The white dwarf and bright-spot ingress and egress are both clear and distinct. The orbital hump in DV UMa is much less pronounced than in XZ Eri.

Howell et al. (1988) quoted $V \sim 19.2$ in quiescence for DV UMa. This compares to $g' \sim 19$ at the time of our observations, which fell to $g' \sim 22$ during eclipse. DV UMa was therefore in quiescence over the course of our observations.

4 ORBITAL EPHEMERIDES

The times of white dwarf mid-ingress $T_{wi}$ and mid-egress $T_{we}$ were determined by locating the times when the minimum and maximum values, respectively, of the light curve derivative occurred (Wood, Irwin & Pringle 1985). The times of mid-eclipse $T_{mid}$ given in Table 2 were determined by assuming the white dwarf eclipse to be symmetric around phase zero and taking $T_{mid} = (T_{we} + T_{wi})/2$.

To determine the orbital ephemeris of XZ Eri we used the one mid-eclipse time of Woudt & Warner (2001), the 25
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Table 1. Journal of observations. Observing conditions were clear except for 2003 May 20, when thin cirrus was present. The dead-time between exposures was 0.025 s for all the DV UMa observations, and 0.024 s for the XZ Eri observations.

| Date         | Cycle | Target       | Filters | Exposure time (s) | Data points | Eclipses | Seeing (arcsec) | Airmass |
|--------------|-------|--------------|---------|-------------------|-------------|----------|----------------|---------|
| 2003 May 20  | 69023 | DV UMa       | u'g'i' | 5.921             | 339         | 1        | 1.3–2.0        | 1.5–1.8 |
| 2003 May 22  | 69046 | DV UMa       | u'g'i' | 4.921             | 345         | 1        | 1.2            | 1.4–1.5 |
| 2003 May 23  | 69058 | DV UMa       | u'g'i' | 4.921             | 60          | 0        | 1.0            | 1.6–1.9 |
| 2003 May 23  | 69058 | DV UMa       | u'g'i' | 3.921             | 540         | 1        |                |         |
| 2003 Nov. 13 | 4733/4734 | XZ Eri | u'g'i' | 6.997             | 1225        | 2        | 1.0–2.0        | 1.4–1.8 |

Table 2. Mid-eclipse timings (HJD + 2452000).

| XZ Eri cycle | u' | g' | i' |
|--------------|----|----|----|
| 4733         | 957.508910 | 957.508789 | 957.508870 |
| 4734         | 957.570081 | 957.570090 | 957.570000 |

| DV UMa cycle | u' | g' | i' |
|--------------|----|----|----|
| 69023        | 780.469225 | 780.469225 | 780.469225 |
| 69046        | 782.443801 | 782.443829 | 782.443801 |
| 69058        | 783.474062 | 783.474040 | 783.474040 |

The mass ratio – and hence the inclination – may be determined by comparing the bright-spot light centres corresponding to the measured eclipse contact phases φw and φe with the theoretical stream trajectories for different mass ratios. As illustrated in Fig. 3, the assumption that the gas stream (originating from the inner Lagrangian point L1) passes directly through the light centre of the bright-spot at the edge of the disc allows the determination of the mass ratio, orbital inclination and relative outer disc radius $R_d/a$ (where $a$ is the orbital separation).

For the mean eclipse phase width of $\Delta \phi = 0.035889$, the eclipse timings of XZ Eri (Tables 3 and 4) yield the mass ratio, inclination and relative disc radius given in Table 5. The results for DV UMa for the mean eclipse phase width of $\Delta \phi = 0.063604$ are also given in Table 5. The errors on these parameters are determined by the rms variations in the measured contact phases. We use the bright-spot eclipse timings to determine upper limits on the angular size and the radial and vertical extent of the bright-spots, defining $\Delta \phi$, $\Delta R_d$, $\Delta Z$ and $\Delta Z_d$ as in Feline et al. (2004). The mean position and extent of the bright spots thus derived are given in Table 6.

These ephemerides were used to phase all of our data.

5 LIGHT-CURVE DECOMPOSITION

5.1 The derivative method

This method of determining the system parameters of an eclipsing dwarf nova was originally developed by Wood et al. (1986). It relies upon the fact that there is a unique relationship between the mass ratio $q = M_i/M_e$ and orbital inclination $i$ for a given eclipse phase width $\Delta \phi$ (Bailey 1973).

The eclipse contact phases given in Tables 3 and 4 were determined using the derivative of the light curve, as described by Feline et al. (2004) and references therein. The midpoints of ingress and egress are denoted by $\phi_i$ and $\phi_e$, respectively. The eclipse contact phases corresponding to the start and end of the ingress are denoted $\phi_1$ and $\phi_2$, and the start and end of the egress by $\phi_3$ and $\phi_4$. In the discussion that follows, we use the suffixes ‘w’ and ‘b’ to denote white dwarf and bright-spot contact phases, respectively (e.g. $\phi_{wi}$ means the mid-point of the white dwarf ingress). The eclipse phase full width at half-depth is $\Delta \phi = \phi_{wi} - \phi_{wi}$. In the following analysis we have combined the timings of all three colour bands for each target in order to increase the accuracy of our results.

Using the mass ratio and orbital inclination given in Table 5, and the eclipse constraints on the radius of the white dwarf (Table 6), we find that the white dwarf in XZ Eri has a radius of $R_w/a = 0.012 \pm 0.002$. For DV UMa we obtain $R_w/a = 0.0075 \pm 0.0020$. We will continue under the assumption that the eclipsed central object is a bare white dwarf. This assumption and its consequences are discussed in more detail in Feline et al. (2004).

The white dwarf temperatures $T_w$, thus calculated are given in Table 6.

To determine the remaining system parameters of XZ Eri and DV UMa we have used the Nauenberg...
mass-radius relation for a cold, non-rotating white dwarf (Nauenberg 1972, Cook & Warner 1984), which gives an analytical approximation to the Hamada–Salpeter mass–radius relation (Hamada & Salpeter 1961). This relation, together with Kepler’s third law and the relative white dwarf radius, allows the analytical determination of the absolute system parameters, given in Table 7. The secondary radius has been calculated by approximating it to the volume radius of the Roche lobe (Eggleton 1983), which is accurate to better than 1 per cent. Because the Nauenberg mass-radius relation assumes a cold white dwarf, we have attempted to correct this to a temperature of $T_w \sim 15000$ K for XZ Eri and to $T_w \sim 20000$ K for DV UMa, the approximate temperatures given by the model atmosphere fit. The radius of the white dwarf at 10000 K is about 5 per cent larger than for a cold (0 K) white dwarf (Koester & Schönberner 1984). To correct from 10000 K to the appropriate temperature, the white dwarf cooling curves of Wood (1995) for $M_w/M_\odot = 1.0$, the approximate masses given by the Nauenberg relation, were used. This gave total radial corrections of 6.0 and 7.0 per cent for XZ Eri and DV UMa, respectively.

5.2 A parameterized model of the eclipse

Another way of determining the system parameters is to use a physical model of the binary system to calculate eclipse
light curves for each of the various components. We used the technique developed by Horne et al. (1994) and described in detail therein. This model assumes that the eclipse is caused by the secondary star, which completely fills its Roche lobe. A few changes were necessary in order to make the model of Horne et al. (1994) suitable for our data. The most important of these was the fitting of the secondary flux, prompted by the detection of a significant amount of flux from the secondary in the $i'$ band of DV UMa. The secondary flux is very small in all the other bands. Fitting of ellipsoidal variations made no significant improvement to the overall fit, so we have assumed the flux from the secondary star to be constant. For both XZ Eri and DV UMa we fitted this model to all the cycles, which were phase-folded and binned by 2 data points. Examination of the light curves shown in Figs 1 and 2 shows that cycle-to-cycle variations for both targets were minimal.

Table 3. White dwarf contact phases and out-of-eclipse white dwarf fluxes. We estimate that the errors on the fluxes are ±0.001mJy.

| Cycle | Band | $\phi_{w1}$ | $\phi_{w2}$ | $\phi_{w3}$ | $\phi_{w4}$ | $\phi_{wi}$ | $\phi_{we}$ | Flux (mJy) |
|-------|------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| XZ Eri | $u'$ | -0.20996 | -0.01625 | 0.01613 | 0.02246 | -0.01855 | 0.01855 | 0.0434 |
| 4733  | $g'$ | -0.02246 | -0.01119 | 0.01220 | 0.02002 | -0.01855 | 0.01758 | 0.0466 |
| 5806  | $r'$ | -0.01806 | -0.01316 | 0.01316 | 0.02002 | -0.00155 | 0.01613 | 0.0441 |
| RV UMa | $u'$ | -0.03346 | -0.03096 | 0.03061 | 0.03221 | -0.03132 | 0.03221 | 0.0351 |
| 4734  | $g'$ | -0.02246 | -0.01316 | 0.01367 | 0.02145 | -0.01312 | 0.03221 | 0.0375 |
| 5806  | $r'$ | -0.02246 | -0.01316 | 0.01513 | 0.02002 | -0.01709 | 0.01758 | 0.0435 |

| Cycle | Band | $\phi_{b1}$ | $\phi_{b2}$ | $\phi_{b3}$ | $\phi_{b4}$ | $\phi_{b5}$ | $\phi_{we}$ |
|-------|------|-------------|-------------|-------------|-------------|-------------|-------------|
| XZ Eri | $u'$ | -0.00097 | 0.00638 | 0.06494 | 0.06781 | 0.00290 | 0.06640 |
| 4733  | $g'$ | 0.00000 | 0.00638 | 0.06936 | 0.07421 | 0.00306 | 0.07242 |
| 5806  | $r'$ | -0.00097 | 0.00638 | 0.06936 | 0.07320 | 0.00145 | 0.07031 |
| RV UMa | $u'$ | -0.03279 | -0.03013 | 0.03321 | 0.03145 | 0.00290 | 0.03879 |
| 4734  | $g'$ | -0.03346 | -0.03013 | 0.03321 | 0.03145 | 0.00290 | 0.03879 |
| 5806  | $r'$ | -0.03279 | -0.03013 | 0.03321 | 0.03145 | 0.00290 | 0.03879 |

The 10 parameters that control the shape of the light curve are as follows:

(i) The mass ratio, $q$.
(ii) The eclipse phase full-width at half-depth, $\Delta \phi$.
(iii) The outer disc radius, $R_d/a$.
(iv) The white dwarf limb darkening coefficient, $U_w$.
(v) The white dwarf radius, $R_w/a$.
(vi) The bright-spot scale, $S/a$. The bright-spot is modelled as a linear strip passing through the intersection of the gas stream and disc. The intensity distribution along this strip is given by $(X/S)^{e^{-X/S}}$, where $X$ is the distance along the strip.

(vii) The bright-spot tilt angle, $\theta_B$, measured relative to the line joining the white dwarf and the secondary star. This allows adjustment of the phase of the orbital hump.

(viii) The fraction of bright-spot light which is isotropic, $f_{iso}$. 

Table 4. Bright-spot contact phases.
(ix) The disc exponent, $b$, describing the power law of the radial intensity distribution of the disc.

(x) A phase offset, $\phi_0$.

The AMOEBA algorithm (downhill simplex, Press et al. 1986) was used to adjust selected parameters to find the best fit. A linear regression was then used to scale the four light curves (for the white dwarf, bright-spot, accretion disc and secondary) to fit the observed light curves in each passband. The data were not good enough to determine the limb-darkening coefficient $U_w$ accurately, so this was held at a typical value of 0.5 for each fit. The disc parameter for DV UMa was held fixed at $b = 1.0$ as it was too faint to be well constrained.

In order to estimate the errors on each parameter once the best fit had been found, we perturbed one parameter from its best fit value by an arbitrary amount (initially 5 per cent) and re-optimised the rest of them (holding the parameter of interest, and any others originally kept constant, fixed). We then used a bisection method to determine the perturbation necessary to increase $\chi^2$ by 1, i.e. $\chi^2 - \chi_{\text{min}}^2 = \Delta \chi^2 = 1$. The difference between the perturbed and best-fit values of the parameter gave the relevant 1σ error (Lampton, Margon & Bowyer 1976). This procedure failed to find the likely error for the disc exponent $b$ of the $u'$ band of XZ Eri, as the disc flux is small in this case and the light curve noisy, so perturbation of the parameter made virtually no difference to the $\chi^2$ of the fit.

The results of the model fitting are given in Table 6 and shown in Fig. 3. Each colour band was fitted independently, as there were found to be significant differences between many of the optimum parameters for each band. This is to be expected for parameters such as the bright-spot scale $S$, where one would anticipate that the cooler regions are more extended than the hotter ones (as seen for DV UMa). We would of course expect the mass ratio to remain constant in all three colour bands for each object, which it indeed does.

The results of a white dwarf model atmosphere fit (Bergeron et al. 1993) to the fluxes in each passband are given in Table 7. We have used the white dwarf cooling curves of Wood (1993) for $M_w/M_\odot = 0.75$ (interpolating between 0.7 and 0.8) and $M_w/M_\odot = 1.0$, the approximate masses found using the Nauenberg relation for XZ Eri and DV UMa, to give radial corrections of 7.6 and 7.0 per cent, respectively. These were used to determine the absolute system parameters given in Table 4.

We note that the higher signal-to-noise light curves of the $i'$, $i''$ and $g'$ bands have $\chi^2/\nu \gg 1$ (see Table 5). This is because these data are dominated by flickering, not photon noise, unlike the $u'$ data. If we had enough cycles to completely remove the effects of flickering we would expect, for an accurate model, to achieve $\chi^2/\nu = 1$.

Table 5. Mean position and extent of the bright-spot as defined in Feline et al. (2004).

| Parameter | XZ Eri | DV UMa |
|-----------|--------|--------|
| $\Delta R/w/a$ | 0.0378 | 0.0258 |
| $\Delta \theta$ | $8^\circ 73$ | $7^\circ 57$ |
| $\Delta Z/w/a$ | 0.0174 | 0.0399 |
| $R_1/a$ | 0.300 | 0.322 |
| $\theta$ | 34$^d$53 | 27$^d$47 |

5.3 Comparison of methods

We have determined the system parameters of the eclipsing dwarf novae XZ Eri and DV UMa through two methods: the derivative method of Wood et al. (1986) and the parameterized model technique of Horne et al. (1994). We proceed to compare these two techniques, first noting that the system parameters determined by each (given in Table 4) are reassuringly in good agreement for the most part.

Given data with an excellent signal-to-noise ratio (S/N) and covering many phase-folded cycles, the measurement of the contact phases from the light-curve derivative is capable of producing accurate and reliable results (e.g. Wood et al. 1986). It is less dependable with only a few cycles, however, even if they are individually of high S/N. This is due to flickering having the effect of partially masking the exact location of the contact phases $\phi_1, \ldots, \phi_4$. This problem will affect the values for the deconvolved fluxes of each component and the constraints on the size of the white dwarf and bright-spot, which are used to determine the individual component masses. The mid-points of ingress and egress, especially those of the white dwarf, are generally still well determined though, since the signal (a peak in the derivative of the light curve) is large due to the rapid ingress and egress of the eclipsed body. This makes the determination of the mass ratio and the orbital inclination relatively simple and reliable. It also means that this technique is well suited to determining the times of mid-eclipse in order to calculate the ephemeris.

We believe that the differences between the component masses and radii of XZ Eri determined by each technique (Table 4) are due to the above effect of flickering. The mass ratios quoted are consistent with each other, but the relative white dwarf radius estimated from the derivative method is somewhat smaller than that determined from the parameterized model ($R_w/a = 0.012 \pm 0.002$ and $R_w/a = 0.0181 \pm 0.0005$, respectively). This also affects the estimates of the component radii and masses.

For the purpose of determining the system parameters we prefer the parameterized model technique over the derivative method. This is because the former constrains the parameters using all the points in the light curve to minimise $\chi^2$. This procedure has several advantages:

(i) The value of $\chi^2$ provides a reliable estimate of the goodness of fit which is used to optimise the parameter estimates. The measurement of the contact phases and subsequent deconvolution of the light curves in the derivative method is not unique (it is affected by the choice of box-car
Figure 4. Left: the phase-folded $u'$, $g'$ and $r'$ light curves of XZ Eri, fitted separately using the model described in Section 5.2. Right: the phase-folded $u'$, $g'$ and $i'$ light curves of DV UMa. The data (black) are shown with the fit (red) overlaid and the residuals plotted below (black). Below are the separate light curves of the white dwarf (blue), bright spot (green), accretion disc (purple) and the secondary star (orange). Note that the disc in both objects is very faint, as is the secondary (except for the $i'$ band of DV UMa).

and median filters, for instance), and this technique lacks a comparable merit function.

(ii) Rapid flickering and photon noise during the ingress and/or egress phases are less problematic for the parameterized model as the light curves are evaluated using all the data points, not just the few during ingress and egress.

(iii) The above points indicate that the parameterized model technique requires fewer cycles to obtain accurate results. This is indeed what we found in practice, meaning that this method could be applied to each passband separately to investigate the temperature dependence of each parameter, if any.

(iv) The bright-spot egress in particular is often faint (due to foreshortening) and difficult to reconstruct using the derivative method. The parameterized model method is also likely to be easier to apply to cases where the ingress of the white dwarf and bright-spot are merged, as seen in IP Peg (Wood et al. 1986) and EX Dra (Baptista et al. 2000).

For these reasons, we believe that the results given by the parameterized model of the eclipse are better determined than those of the derivative technique. However, the former method does have some disadvantages. Ideally, it requires observations of most of the orbital cycle, as the orbital hump is needed to fit some parameters reliably. Longer time-scale flickering can also cause some problems if only a few cycles are available. As with any such technique, the key weakness of the parameterized model method is the need for an accurate model. As Fig. 4 shows, apart from the $i'$ band
DV UMa the residual from the fit shows no large peaks in areas such as the ingress and egress of the white dwarf or bright-spot. Such peaks would be expected if the model were not adequately fitting the data.

### 6 DISCUSSION

We have presented an analysis of two quiescent eclipses of XZ Eri and three quiescent eclipses of DV UMa. For both objects, separate eclipses of the white dwarf and bright-spot were observed. The identification of the bright-spot ingress and egress is unambiguous in each case. These eclipses have been used to determine the system parameters, given in Table 4, via two independent methods. The first of these is through analysis of the light-curve derivative (Wood et al. 1982, 1988) and the second by fitting a parameterized model of the eclipse (Horne et al. 1994).

The system parameters of DV UMa have also been estimated by Patterson et al. (2000) using eclipse deconvolution. Our analysis is consistent with their findings, but the parameterized model of the eclipse provides much more accurate results. The value we obtain for the mass ratio, for instance, is a factor of ~17 more accurate than that obtained by Patterson et al. (2000). As Patterson et al. (2000) note, the spectral type of the secondary star in DV UMa (M4.5, Mukai et al. 1990) implies $M_2/M_1 = 0.12 \pm 0.18$ for a main-sequence star of solar metallicity (Chabrier & Baraffe 1997; Henry et al. 1996), consistent with our results (Table 4). Mukai et al. (1990) derive the primary temperature and radius of DV UMa from spectroscopic observations by assuming that the white dwarf emits a blackbody spectrum. The temperature they derive, $T_w = 22000 \pm 1500$ K, is consistent with our results (Table 4). The primary radius ($R_w = 26000 - 7700$ km) (Mukai et al. 1990) calculate is only marginally consistent with our results for the derivative technique and not consistent with the results of the parameterized model. This is probably due to the limitation of assuming a blackbody spectrum (Mukai et al. 1990).

The two quiescent eclipses of XZ Eri have been used to make the first determination of the system parameters for this object, given in Table 4. The mass ratio we derive, $q = 0.1098 \pm 0.0017$, is consistent with XZ Eri being an SU UMa star (Whitehurst 1988; Whitehurst & King 1990), as indicated by its (super)outburst history (Woudt & Warner 2001; Uemura et al. 2004). We also note that the orbital period and mass ratio of XZ Eri are similar to those of OY Car (Wood et al. 1989).

The bright-spot scale $S$ of XZ Eri is constant over all three colour bands. In DV UMa, however, it increases in size as the colour becomes redder. This is easily interpretable:
the material cools as it moves farther from the impact region between the accretion disc and the gas stream.

The results from the parameterised model of XZ Eri give a very low secondary star mass of $M_2/M_\odot = 0.0842 \pm 0.0024$. This is close to the upper limit on the mass of a brown dwarf, which is 0.072$M_\odot$ for objects with solar composition, but can be up to 0.086$M_\odot$ for objects with zero metallicity (Basri 2000).

The empirical mass-radius and mass-period relations for the secondary stars of CVs of Smith & Dhillon (1998) are in good agreement with the values determined here. The mass of the white dwarf in XZ Eri is consistent with the mean mass of white dwarfs in dwarf novae below the period gap derived by Smith & Dhillon (1998). The white dwarf in DV UMa, however, is unusually massive. Our assumption that we are observing a bare white dwarf and not a boundary layer around the primary cannot explain this, as the white dwarf mass derived would be in this case a lower limit (e.g. Feline et al. 2004, Bisikalo et al. 1998) found from numerical simulations that ‘bright-spot’ eclipse features in CVs may be due to an extended shock wave located on the edge of the stream. Our results do not show any evidence for this. If the bright-spot emission were coming from a region of shocked gas in the stream then we might expect the bright-spot orientation $\phi_0$ to coincide with the flow direction of the stream, which is approximately 169$^\circ$ for XZ Eri and 167$^\circ$ for DV UMa. In fact, apart from the less reliable $i$ band measurement of DV UMa, the results in Table 8 show that the orientation is half-way between the direction of the stream and disc (approximately 125$^\circ$ for XZ Eri and 118$^\circ$ for DV UMa) flows. The eclipse timings of the bright-spot also show the bright-spot to be extended along the line between the stream and disc trajectories (Fig. 5).

Finally, we note that the system parameters we derive for DV UMa are consistent with the superhump period-mass ratio relation of Patterson (1998). XZ Eri, however, lies 5$\sigma$ off this relation. We use here the superhump periods $P_{sh} = 0.062808 \pm 0.000017$ days for XZ Eri (Uemura et al. 2004) and $P_{sh} = 0.08870 \pm 0.00008$ days for DV UMa (Patterson et al. 2004).

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