UBVRI photopolarimetry of the long-period eclipsing AM Herculis binary V1309 Ori

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ABSTRACT
We report simultaneous UBVRI photopolarimetric observations of the long-period (7.98 h) AM Her binary V1309 Ori. The length and shape of the eclipse ingress and egress vary from night to night. We suggest that this is a result of the variation in the brightness of the accretion stream. By comparing the phases of circular polarization zero-crossovers with previous observations, we confirm that V1309 Ori is well synchronized, and find an upper limit of 0.002 per cent for the difference between the spin and orbital periods. We model the polarimetry data using a model consisting of two cyclotron emission regions at almost diametrically opposite locations, and centred at colatitude $\beta = 35^\circ$ and $145^\circ$ on the surface of the white dwarf. We also present archive X-ray observations which show that the negatively polarized accretion region is X-ray bright.

Key words: binaries: eclipsing – stars: individual: V1309 Ori – stars: magnetic fields – novae, cataclysmic variables – white dwarfs.

1 INTRODUCTION
The X-ray source RX J0515.6+0105 (V1309 Ori) was preliminarily identified in the ROSAT All-sky Survey as a cataclysmic variable (CV) with an orbital period of $\sim 8$ h (Beuermann & Thomas 1993). Garnavich et al. (1994) showed that V1309 Ori has properties that are typical of magnetic CVs (mCVs). They also found a deep total eclipse in the light curves. Pointed X-ray observations made using ROSAT (Walter, Wolk & Adams 1995) showed extremely variable X-ray emission in short bursts (up to few seconds), suggesting inhomogeneous accretion of dense blobs. Detection of variable circular polarization in white light by Buckley & Shafter (1995) confirmed the classification of V1309 Ori as an AM Her star (synchronized mCVs).

The orbital period of V1309 Ori 7.98 h is $\sim 3$ h longer than in any other known AM Her system. Only three AM Hers are known to have periods over 4 h (RX J1313–32: 4.25 h; AI Tri: 4.59 h; V895 Cen: 4.77 h; Ritter & Kolb 1998). The exceptionally long orbital period indicates that the separation between the primary and the secondary is large for mCV. According to Patterson’s (1994) scaling law, magnetic field strengths up to 150–730 MG should be required to synchronize the spin of the white dwarf with the rotation of the binary system, assuming a mass for the white dwarf $M_{WD} = 0.6$–1.0 $M_\odot$ (Shafter et al. 1995). However, spectroscopic studies have given significantly lower magnetic field values: 33–55 MG, Garnavich et al. (1994); 61 MG, Shafter et al. (1995); <70 MG, de Martino et al. (1998). Frank, Lasota & Chanmugam (1995) have proposed that these low magnetic field values can be understood in terms of the standard evolutionary model, if the system is in a low accretion state for a long enough time or if the magnetic field of the secondary is strong enough ($> 1$ kG) to maintain synchronism. For these reasons, V1309 Ori is one of the most important objects for studying synchronization and accretion processes in mCVs and their evolution. In this paper we present the results and analysis of our polarimetric, photometric and spectroscopic observations of this system.

2 OBSERVATIONS
Photopolarimetric observations were made at the Nordic Optical Telescope, La Palma (NOT) using the Turpol-photo-polarimeter in 1997 October and November (see Table 1 for the log of observations). Observations were also made on 1997 December and 1998 January with the 2.15-m CASLEO telescope (Argentina) using

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the Turin-photo-polarimeter. This instrument at CASLEO is almost identical to the Turpol at NOT.

The polarimeters have four dichroic filters, splitting the light into $UBVRI$ bands. The time resolution for photometric data is 24 s. One polarization measurement consists of eight integrations and takes $\sim$3 min. In the simultaneous circular and linear mode with the $\lambda/4$-retarder the efficiency for circular polarization is approximately 70 per cent and for linear polarization approximately 50 per cent. With the $\lambda/2$-retarder $\sim$100 per cent efficiency for linear polarization is achieved. The seeing was between 0.6 and 1.5 arcsec during all the nights at NOT and the 7.5-arcsec diaphragm was used. At CASLEO, average seeing was between 2 and 3 arcsec and the diaphragm was 11 arcsec.

Sky background polarization was eliminated by using a calcite plate as a beamsplitter. Sky intensity was measured at 15–30 min intervals. Instrumental polarization and the zero-point of position angle were determined from observations of standard stars BD+32°3739, HD 204827, BD+64°106, HD161056 and HD155197 (Schmidt, Elston & Lupie 1992). Photometric $UBVRI$ standard stars 92282, 94242, 97351, 110340 and 114750 (Landolt 1992) were used to calibrate the photometry.

Spectroscopic observations of V1309 Ori were carried out on three nights, starting on 1998 December 25, using the Australian National University (ANU) 2.3-m telescope at Siding Spring Observatory (SSO), Australia. Spectra were obtained with the double-beam spectrograph using 600 line mm$^{-1}$ gratings. The effective wavelength coverage was 3800–5000 and 6200–7500 Å in the blue and red arms of the spectrograph, respectively. The conditions were photometric throughout the observations, and the effective resolution as measured from the FWHM of the arc lines was 2.1 Å. The exposure time was 300 s for both blue and red spectra. Wavelength calibration of the flat-fielded and bias-subtracted two-dimensional images was performed using He–Ar arc spectra taken at various points during the night.

The photometric ephemeris of Staude, Schwope & Schwarz (2001) (their equation 1) is used to phase the data throughout the paper.

3 PHOTOMETRY

During our observations V1309 Ori was in a high accretion state ($V = 16$), as also found in earlier photometric studies (Garnavich et al. 1994; Shafter et al. 1995). In Fig. 1 we present simultaneous $UBVRI$ light curves covering nearly the full orbital cycle, obtained on 1997 November 24/25, at NOT. Our observations made in 1997 October (NOT) and in 1998 January (CASLEO) do not cover the complete orbital cycle (and are not shown here) show that V1309 Ori was in the same brightness level ($V = 16$) as in 1997 November. We show the circular polarization data in Fig. 2 and the linear polarization data in Fig. 3.

The most distinctive feature of the intensity curves (Fig. 1) is the well-known deep eclipse that has a duration of $\sim$0.1 orbital phase and also a strong colour dependence (up to $\sim$4 mag in $U$ and less than 1 mag in $I$). Flux variations outside the eclipse are approximately 1.5 mag in the $U$ and approximately one magnitude in the $BVRi$ bands. Light curves show two local brightness maxima, at orbital phases $\Phi = 0.2$ and 0.7. There is a clear asymmetry between these two maxima: in the $U$ band the first peak near $\Phi = 0.2$ is approximately 0.5 mag brighter than observed at $\Phi = 0.7$, whereas in the $B$ and $V$ bands this difference is approximately 0.3 mag and in the $I$ band typically approximately 0.2 mag.

The colour indices in Fig. 4 show V1309 Ori bluer after the eclipse, where the system is also brighter than before the eclipse (Fig. 1). Significant colour changes take place over the whole orbital period, when different parts of the stream are viewed at different angles. Eclipsing of the secondary star by the stream also contributes, noticeably in the $R$ and $I$ bands in the phase interval 0.4–0.7.

3.1 The eclipse

The eclipse profiles of V1309 Ori are unusual compared with other eclipsing AM Her stars such as HU Aqr or UZ For: the ingress and egress of the eclipse are very shallow and have large night to night variations (Fig. 5). This suggests that there is an unusually prominent stream component. We have analysed the colours of the 'extra' emission defined as the flux difference between the shallowest (most disturbed) eclipse and the widest (cleanest) flat-bottom light curve (Fig. 5). The resulting colour indices for the additional flux $(U-B)_o = -1.0$, $(B-V)_o = 0.1$ and $(V-R)_o = 0.5$, match the (stream-dominated) colours of V1309 Ori outside the eclipse. This supports the view that eclipse shape variations are caused by variations in the brightness or trajectory of the accretion stream.

Since the eclipse is composed of an eclipse of the white dwarf and stream, the mid-point of the eclipse may not be a good marker.
Figure 1. Simultaneous UBVRI light curves of V1309 Ori observed at NOT on 1997 November 24/25. Each point presents a single photometric measurement, with a 24-s time resolution. Data have been plotted twice to clarify brightness variations over a complete orbital cycle. The short gap (15 min) near the phase of $\Phi = 0.6$ is caused by cloud. Note the different scale in the U/B and the V/R bands.

of the inferior conjunction of the secondary. This is clearly shown by Staude et al. (2001), who found that mid-eclipse of the white dwarf occurs $172 \pm 20$ s earlier than the observed mid-eclipse seen in the light curves.

A more detailed examination of the eclipse profiles (Fig. 6) reveals a rapid eclipse ingress of the white dwarf and accretion region between $\Phi = 0.951$ and 0.952, seen for the first time in the optical range. This drop is most prominent in data obtained in 1997 October 7/8, while on the other observing nights in October this phenomenon was not as prominent. With a time resolution of 24 s, we cannot determine whether this rapid drop is caused by the eclipse of the hotspot, or the whole white dwarf. The corresponding ingress of the white dwarf should take place at $\Phi = 1.036$ according to Staude et al. (2001). Our data (e.g. Fig. 5), hints at a rise at orbital phase 1.04, although it is far from clear.

Interestingly, time resolved Hubble Space Telescope (HST) UV spectroscopy by Schmidt & Stockman (2001) revealed a sharp drop in brightness, with duration of $6 \pm 2$ s at an orbital phase of $\Phi = 0.952$, which they identified as the eclipse ingress of the hot accretion spot on the surface of the white dwarf. Staude et al. (2001) did not detect the ingress and egress of the white dwarf in their broadband optical photometry, but they re-analysed the same HST data on V1309 Ori and concluded that the ingress (duration of $45 \pm 30$ s), which occurs at orbital phase $\Phi = 0.952$ is actually caused by the eclipse of the whole white dwarf.

The observed brightness of V1309 Ori during the mid-eclipse in the V band is 17.3 mag and colours: $U - B = 1.3$, $B - V = 0.9$, $V - R = 1.1$ and $R - I = 0.7$. The observed $B - V$ value corresponds to that of a K2 dwarf, whereas other colours ($U - B$, $V - R$, $R - I$) fit better with K5, K7 or M0 dwarf (Cox 2000). The orbital period–secondary star relation given by Smith & Dhillon (1998) gives a much earlier spectral type for the secondary (K2–K3). The observed $B - V = 0.9$ shows that there is $\sim 50$ per cent more flux in the B band compared with that expected from a K7 spectral-type dwarf. This extra flux might be emitted by an accretion stream that was not completely eclipsed even during the mid-eclipse. However, HST spectroscopy analysed by Staude et al. (2001), showed that the eclipse of the stream and the white dwarf was total in UV during their observations, implying that this was unlikely.

3.2 Quasi-period oscillations

We have studied this phenomenon by performing wavelet time-series analysis of our photometric data. The main difference of using this method instead of standard Fourier analysis is that the shape of
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Figure 3. Linear polarization and position angle curves for V1309 Ori. Data have been combined from four nights in 1997 October and November at NOT and on five nights in 1998 January at CASLEO. Polarization has been computed by vectorially averaging individual observations in the UBVRI bands into 40 phase bins.

The (mother) wavelet can easily be adjusted to better correspond to the shape of the flares in flickering (for example, more triangular).

The moderate time resolution of 24 s of photometry does not allow us to search for variations on time-scales much less than 1 min. CASLEO observations (1998 January) are not included in this analysis because of their higher noise level. In our analysis we used Morelet wavelets (for more details, see Lehto, Katajainen & Piirola 1999). Flickering up to 0.2 mag occurs in the V1309 Ori light curves from night to night. This is most prominent between the orbital phases $\Phi_1 = 0.20 - 0.25$.

Our results show evidence for variability on time-scales of $\sim 10$ min (NOT observations on 1997 October 6/7; Fig. 7), mostly in UBV. Other nights also show similar variability. The quasi-periodic objects (QPOs) and flickering in the light curves have largest amplitudes near orbital phases $\Phi = 0.20 - 0.25$ when the accreting pole emitting positive circular polarization is seen face-on.

4 POLARIMETRY

4.1 Circular polarization

Our UBVRI circular polarimetry, obtained on 1997 November 24/25, over one complete orbital cycle (Fig. 2) shows both negative and positive polarization. Positive circular polarization is observed between phases of $\Phi = 0.0$ and 0.4, while negative circular polarization is observed between phases of $\Phi = 0.5$ and 0.9. The circular polarization shows a strong colour dependence: polarization is strongest in $B$ and $V$, and is fairly modest in $U$ and $I$. This can be explained by the combined effects from cyclotron emission and dilution by the stream.

The circular polarization variations indicate that accretion occurs on to two separate regions. A single accreting pole can only give brief sign reversal when the accreting region is near the limb of the white dwarf, if the geometry is such that the angle between the line of sight and the magnetic field can go through 90°.

The circular polarization sign is reversed at the same orbital phases (at $\Phi = 0.0$ and 0.4) both in our 1997 October and November data, setting tight constraints on the degree of synchronism of the spin of the white dwarf and the binary orbital period. This high degree of synchronism is strengthened when we compare our observations with the white light circular polarization data taken in 1994 December and 1995 January by Buckley & Shafter (1995): the sign

Figure 4. Colour indices $U - B$, $B - V$, $V - R$, and $V - I$ of V1309 Ori (1997 November 24/25), plotted over the orbital cycle.
Figure 5. V1309 Ori eclipse profiles (UBVRI), between $\Phi_1 = 0.92$ and 1.08. Observations are plotted for two nights showing the largest difference in eclipse width: the 1997 October 6/7 (black circles) with the narrowest (most disturbed) eclipse is compared with the widest (flat-bottom) light curve obtained on November 24/25 (crosses). Variations in the ingress and egress shape indicate different contributions from the extended accretion stream. Dashed lines show the start and end of the white dwarf eclipse according to Staudt et al. (2001).

Figure 6. The ingress in UBVR, observed at 1997 October 7/8, with the time resolution of 24 s. The two dashed lines shows the place of the ingress between phases of $\Phi = 0.951$ and 0.952. This is the same phase as observed by Schmidt & Stockman (2001) and Staudt et al. (2001) in HST far-UV data.

of the circular polarization changes at the same orbital phases ($\Phi = 0.0$ and 0.4) in their observations. An uncertainty of approximately 0.05 of the phase difference of the zero crossovers over more than 3000 orbital cycles corresponds to the white dwarf spin and orbital periods being equal to better than $\sim 10^{-5}$.

4.2 Linear polarization

Fig. 3 (upper panel) combines our linear polarization data obtained in 1997 October, November (NOT) and in 1998 January (CASLEO). These data have been vectorially averaged from individual observations in the UBVR bands into 40 phase bins, in order to increase the signal-to-noise ratio. Our linear polarization data cover a complete orbital cycle, in contrast with previous studies that were incomplete (Shafter et al. 1995; Buckley & Shafter 1995). However, the
observed linear polarization in V1309 Ori is very low, less than 0.3–1.0 per cent during the orbital cycle, with no evidence for peaks near the orbital phases where the circular polarization changes its sign. Consequently, the position angle behaviour (Fig. 3, lower panel) is noisy over the whole orbital cycle.

5 SPECTROSCOPY

5.1 Doppler tomography

Doppler tomography has become a standard tool in the analysis of interacting binary star research. Given a high enough spectral and binary orbital resolution, a map can be made of the emission from a line in velocity space. The first such map of a polar was made of VV Pup (Diaz & Steiner 1994). Since then the technique has been applied to several other polars (e.g. Schwepe, Schwarz & Staude 1999). Here we obtain emission velocity maps of V1309 Ori using the code of Spruit (1998).

Since our spectra of V1309 Ori cover 0.7 of an orbital cycle rather than a full cycle, we first determined whether we could obtain useful tomograms using spectra sampling an incomplete binary orbital cycle. We extracted spectra of the polar HU Aqr from the data archive of the Isaac Newton Group, La Palma. When we use only 0.7 of the orbital cycle we find that the resulting Doppler tomograms are remarkably similar to the results when we use the full orbital cycle. There are, however, some circular artefacts present in the maps and the leading face of the secondary appears to be more strongly irradiated rather than the trailing compared with the maps made using the full data set. This test indicates that we can expect to obtain meaningful tomograms using spectra that do not fully sample the orbital cycle of V1309 Ori. Indeed, Marsh & Horne (1988) showed using simulations that useful Doppler maps can be made even when the orbital cycle has been undersampled. However, care should be taken in not overinterpreting the details of those tomograms.

V1309 Ori was found to be in a high accretion state in 1998 December with the spectra showing prominent emission lines of H and He. We generated Doppler tomograms of V1309 Ori in three emission lines (Hα, Hβ and He II λ4686), where we assume i = 78° and q = 0.7 (Staude et al. 2001). We show in Fig. 8 the resulting tomograms. Emission is seen from the heated face of the secondary star and from the ballistic component of the accretion stream. In the case of Hα, the bulk of the line emission originates from the secondary star with the stream emission being weaker. In He II the relative strength of these two components is more equal.

Doppler maps of V1309 Ori have been presented by Shafter et al. (1995) (although the spectral resolution was rather low), Hoard (1999) who presents maps in Hβ and He II λ4686 (they cover 0.8 of the orbital cycle) and also Staude et al. (2001) who show maps in Hγ, He II λ4686, 8236 and He I 4471 (they cover the complete orbit). In the case of the He II map of Staude et al. (2001) the secondary and the stream are approximately equal, while in our map the secondary is stronger and in the map of Hoard, emission from the heated face of the secondary is much weaker than the stream. Since our maps do not sample the phase range between φ = 0.71 and 0.92, this could be the reason why the secondary appears brighter.

6 ARCHIVE X-RAY DATA

ROSAT was an imaging X-ray satellite launched in 1990 with an energy range of ~0.1–2.0 keV. It had two X-ray instruments, the
on the viewing angle $\alpha$ (the angle between the line of the sight and the magnetic field) have been adopted from the model grids of Wickramasinghe & Mggit (1985) for constant-temperature shocks ($T_{\text{shock}} = 10-40$ keV). These were originally presented in 10$^i$ divisions, which we have then interpolated to 1$^i$ divisions over the whole range of viewing angle $\alpha$. Calculations are then made by dividing emission regions into equidistant points along a line on the white dwarf surface, for which Stokes parameters $Q$, $U$, $V$ and $I$ are calculated independently as an approximation for flat and extended regions. The height of the shock is assumed to be negligible compared with the white dwarf radius.

### 7.1 Unpolarized background

Based on the earlier studies of V1309 Ori (Shafer et al. 1995; Schmidt & Stockman 2001; Staude et al. 2001) and our observations (Section 3) it is clear that variations in the light curves are mostly caused by prominent stream emission with a smaller fraction owing to cyclotron emission. It is therefore necessary to include a large unpolarized background when modelling the polarized light curves. We have done this in two different ways: (i) with a constant background as a first approximation and (ii) adopting the observed total flux as a function of the orbital phase as the variable unpolarized background. The latter case is more realistic for V1309 Ori owing to the large amount of unpolarized flux from the stream emission that varies during the orbital cycle. The diluting flux from stream emission in V1309 Ori is 5$-10$ times larger than the peak cyclotron flux, estimated from the fast drop of intensity at the eclipse of the compact source observed at phase $\Phi = 0.952$ (Section 3.1). The X-ray temperature is chosen as $kT_{\text{sems}} = 10$ keV according to the observations of de Martino et al. (1998).

### 7.2 Parameters for accretion geometry

Two-pole accretors, for example VV Pup (Wickramasinghe, Ferrario & Bailey 1989), UZ For (Schwope, Beuermann & Thomas 1990), DP Leo (Cropper & Wickramasinghe 1993) and QS Tel (Schwope et al. 1995), have been found to show different magnetic field strengths in the accretion regions located in opposite hemispheres: up to factor of 2 difference in the field strengths has been measured. The more strongly accreting pole normally has the weaker magnetic field. In the case of V1309 Ori there are no major differences seen in the wavelength dependence of the positive and negative excursions of the observed circular polarization curves (Fig. 2), suggesting that both accreting regions are accreting nearly equally. Therefore, we have chosen the electron temperature and the plasma parameter ($\Lambda = 10^3$) to be the same in both regions. We assume an inclination of $i = 78^\circ$ (Staude et al. 2001). Parameters such as the longitude of the emission region(s) on the surface of the white dwarf and the extension of the accretion regions were varied to match the gross features seen in the circular polarization behaviour. Owing to the very low level of the linear polarization (less than 0.5 per cent), and noisy position angle variations, we have not tried to use linear polarization to fix any model parameters. Another reason for not doing so is that scattering from free electrons of the stream can introduce significant linear polarization effects, dominating over the low linearly polarized flux of cyclotron origin.

Estimates of the colatitude of the accretion region $\beta$ can be made if we assume that the observed circular polarization from different poles is not significantly affected by possible overlap of the polarized emission from another accretion region. We can estimate $\beta$ for this region using the duration of the self-eclipse of the accretion region.
and equation (1) of Visvanathan & Wickramasinghe (1981). Using the circular polarization data shown in Fig. 2, we find $\beta = 145^\circ$ for the positive pole, and $\beta = 35^\circ$ for the negative pole, assuming an inclination $i = 78^\circ$ from Staude et al. (2001).

7.3 Results from the modelling

The observed circular polarization variations can be reproduced reasonably well with a model consisting of two separate emission regions, one centred at colatitude $\beta = 145^\circ$ (the positive pole), seen closest to the observer at $\Phi = 0.20$, and another region centred at $\beta = 35^\circ$ (the negative pole), seen closest to the observer at $\Phi = 0.70$. For both regions we have adopted in Fig. 10 longitudinal extension of $35^\circ$ (in white dwarf rotational coordinates), but these values are not strongly constrained. Extensions in the range $10^\circ$–$60^\circ$ give almost similar results. A point-like emission region gives polarization variations that are too sharp and very extended emission regions ($>60^\circ$) that are too smooth and low-amplitude curves.

The model shown in Fig. 10 assumes that cyclotron harmonics 6, 5, 4, 3 and 2, dominate in the $UBVR$ passbands, respectively. This corresponds to a magnetic field of approximately 50 MG, which is similar to the estimated values for the magnetic field (33–55 MG, Garnavich et al. 1994; 61 MG, Shafter et al. 1995). For a 50-MG field the wavelengths of harmonics 6–3 are at 3580, 4300, 5370 and 7160 Å, respectively, i.e. only one cyclotron harmonic clearly dominates in each of the $UBVR$ bands. Our $I$ band (8300 Å) falls approximately half-way between the third and second harmonics at $B \sim 50$ MG. The best correspondence to the observed circular polarization variations is achieved using the model where an unpolarized background varies in a similar way to the total observed flux over the orbital cycle (Fig. 10, continuous line).

Our model parameters for the location of accretion regions (in white dwarf rotation coordinates), positive pole at $\beta = 145^\circ$, $\Psi = -70^\circ$ and negative pole at $\beta = 35^\circ$, $\Psi = 110^\circ$, are similar to the values reported by Harrop-Allin et al. (1997), who modelled white light data from Buckley & Shafter (1995); $\beta = 40^\circ$ and $140^\circ$. In contrast Staude et al. (2001) derived values of $\beta = 17^\circ$ and $\Psi = -16^\circ$ from their Doppler maps. In that study it was assumed that only one accretion region was visible. Although it is possible for an accretion region to show both positive and negative circular polarization, it is only for a short phase duration if we observe the ‘underside’ of the shock.

8 DISCUSSION

8.1 A well-synchronized system

By comparing our circular polarization curves with those found in the literature we confirm that the spin of the white dwarf in V1309 Ori is synchronized with the orbital period to a high degree. The zero-crossings of circular polarization take place at the same phase of the orbital period as found by Buckley & Shafter (1995), which sets an upper limit of $\sim 0.002$ per cent for the difference of the white dwarf spin and orbital period. There are four polars that have been found to show a small ($\sim 1$ per cent) degree of asynchronism. The polar showing the smallest, V1432 Aql, is 0.28 per cent asynchronous (Garcéller & Staubert 1997): over two orders of magnitude greater than V1309 Ori.

8.2 Accretion geometry

Our circular polarimetry curves (Fig. 2) show clear positive and negative excursions which indicate that V1309 Ori has two accreting poles. This is consistent with previous polarization observations. The X-ray data from the ROSAT archive suggests that the negative circularly polarized pole is brighter in the X-ray band. It is possible that it is bright because of the increased mass transfer at this pole. Alternatively, it might be caused by the fact that the accretion flow to this pole is very inhomogeneous, with the dense parts of the flow accreting directly into the white dwarf without causing a shock and therefore liberating its energy at soft X-rays.

We note that Staude et al. (2001) (based on optical/UV photometry and optical spectroscopy) did not find any evidence for a second accretion pole, although they could not exclude one. Their modelling predicts that the one accreting pole would show a maximum in the
soft X-ray light curve at $\Phi = 0.045$ and would show a self-eclipse at $\Phi = 0.55$. However, the ROSAT data does not confirm this view. Indeed, we see maximum flux at $\phi = 0.55$ and a minimum at $\Phi = 0.045$.

The X-ray data does show a dip around $\Phi \approx 0.7$. This is unlikely to be caused by absorption of X-rays by the accretion stream since the stream does not cut through our line of sight to the accretion region at this phase. It is also unlikely that this dip is caused by that observation being at a lower accretion state since the same observation shows a peak at $\phi \approx 0.6$. The cause of the dip in X-rays is unclear but may be caused by a fraction of the accretion region being self-eclipsed by the white dwarf at these phases.

8.3 The mass of the white dwarf

Along the ballistic flow, emission extends to $V_s \sim -800$ km s$^{-1}$, $V_f \sim -200$ km s$^{-1}$ in our maps and also the maps of Hoard (1999). The maps of Staudte et al. (2001) show the flow extending to $V_s \sim -100$ km s$^{-1}$. Taking $V_s$ and $V_f$ from our maps (giving a velocity of 820 km s$^{-1}$) and using $r = (2GM_{wd}/r)^{1/2}$ (where $r$ is velocity and $r$ is the distance from the white dwarf), we find that the end of the ballistic flow is $r = 2.4$ and $2.8 \times 10^{10}$ cm distant from the white dwarf for $M_{wd} = 0.6$ and 0.7 M, respectively.

We can compare these estimates with the expected distance from the white dwarf at which material becomes coupled by the magnetic field ($R_\mu$) using equation (1b) of Mukai (1988). We assume $B = 50$ MG (typical of the estimates made for V1309 Ori), $\sigma = 3$ (the radius of the stream in units of $10^6$ cm, the value estimated for HU Aqr, Harrop-Allin et al. 1999) and $M_{16} = 10$ (the mass transfer rate in units of $10^{16}$ g s$^{-1}$, Harrop-Allin et al. 1997). We find that for $M_{wd} = 0.6$ and 0.7 M we obtain $R_\mu = 3.4$ and $2.1 \times 10^{10}$ cm, respectively. Although there is some considerable degree of uncertainty in how applicable the above formulation for $R_\mu$ actually is, it is interesting that for masses of between 0.6 and 0.7 M the predicted value of $R_\mu$ is consistent with our Doppler maps. This range of mass is consistent with that estimated by Staudte et al. (2001).

8.4 QPOs and their time-scales

Our photometric observations show evidence for QPOs on time-scales of 10 min with amplitudes up to 0.2 mag. This compares with 6.7 and 15.5 min: Shafter et al. (1995). There are some examples of other AM Her systems where flickering on time-scales of a few minutes have been observed: 4.5 min in BL Hya (Singh, Agrawal & Riegler 1984), 4–11 min in QQ Vul (Osborne, Cropper & Christiansen 1987) and in AI Tri 6.5–7 and 13.5–14 min (Schwarz et al. 1998). We speculate that the QPOs in V1309 Ori are caused by ‘blobby accretion’, already observed in X-ray data (Walter et al. 1995; de Martino et al. 1998).

We compare these time-scales with those derived by King (1989, 1995) (see also Chanmugam 1995). The irradiation of the accretion flow may ionize the subsonic accretion flow below the inner $L_1$ point and modulate gas flow through this point on the time-scale of the dynamical time-scale in the Roche potential near $L_1$. The equation presented by King (1989)

$$T_{osc} \sim \frac{H_s}{c_s} \times 5.5 \times 10^{-2} \, \sigma,$$

where $H_s$ is the scaleheight and $c_s$ is the local speed of sound near $L_1$, predicts the time-scales for these oscillations. The orbital period of 479 min gives us a prediction of 26 min for V1309 Ori. The observed time-scales of QPOs in V1309 Ori, 10 and 15 min, are approximately half of the predicted value. The QPOs are seen to be strongest in $UBV$, and are negligible at longer wavelengths, which may be because only a fraction of the flow will undergo these oscillations near $L_1$, as pointed out by King (1995).

8.5 Eclipse profiles

Several eclipsing polars have been observed with high signal-to-noise ratio and high time resolution. These include HU Aqr (Harrop-Allin et al. 1999) and UZ For (Perrymnan et al. 2001). Both of these systems show a sharp eclipse ingress lasting several seconds. This sharp drop in intensity is associated with the eclipse of the bright accretion region on the white dwarf. In the case of UZ For there are two sharp intensity drops, indicating that there are two accretion regions visible during the eclipse.

One of the most striking features concerning the eclipse profiles of V1309 Ori is the obvious lack of a sharp ingress or egress, which indicate the (dis)appearance of the white dwarf and/or hotspots in the surface of the white dwarf behind the secondary. The relative faintness of the accretion region(s), compared with the bright accretion stream in V1309 Ori, may be the reason for this.

After the eclipse of the white dwarf, the accretion stream is still visible for a length of time. Observations of other polars such as HU Aqr (Glenn et al. 1994; Bridge et al. 2002) show that this length of time can vary from one cycle to the next. The fact that we observe a variable eclipse ingress of the accretion stream in V1309 Ori is therefore not untypical of polars. However, what does make V1309 Ori unique amongst polars is the fact that the eclipse egress is highly variable: all other polars show a rapid rise at the same phase coming out from eclipse. The fact that V1309 Ori does not imply either that we can observe the stream above the orbital plane before the white dwarf is visible, or that the accretion stream travels far enough around the white dwarf so that it is visible before the white dwarf itself.

To investigate this further, we shown in Fig. 11 the view of the system at two different phases ($\Phi = 0.96$ and 1.04). We use the following system parameters in determining these: $i = 78^\circ$, $q = 0.67$, $M_{wd} = 0.7$ M (Staudte et al. 2001) and a white dwarf–secondary star separation of $1.47 \times 10^{11}$ cm (determined using the above parameters and standard Roche geometry). We also show a single magnetic field line originating from the negative circularly polarized accretion region ($\beta = 35^\circ$ and face on to the observer at $\Phi = 0.7$, Section 7.3). In Fig. 11, the accretion stream leading to both poles are visible at $\Phi = 0.96$. At $\Phi = 0.04$ only the stream leading to the negative pole is visible. The white dwarf appears before the stream leading to the positive pole is visible. Even if the negative pole is not visible at $\Phi = 0.04$, the emission from the stream leading to that pole is. We take $R_\mu/a = 0.2$: this implies $R_\mu = 2.9 \times 10^{10}$ cm. This is consistent with our findings in Section 8.3. This shows that for this accretion stream geometry the accretion stream is visible after the white dwarf has been eclipsed and also before the white dwarf comes out of eclipse. If the stream emission was highly variable then this could explain the variable egress profile.

8.6 Evolution

Garnavich et al. (1994) and Shafter et al. (1995) noted that the secondary star in V1309 Ori is oversized for its spectral type (M0–M1) and mass (0.4–0.6 M). Indeed, recent binary evolution models (e.g. Smith & Dhillon 1998; Baraffe & Kolb 2000) that assume an unevolved donor star and typical mass transfer rates, all predict
either a much earlier or later spectral type for V1309 Ori than is observed (cf. fig. 1 of Baraffe & Kolb 2000). However, by assuming an evolved donor it is possible to match the observed spectral type to the predicted value. For instance, from fig. 3 of Baraffe & Kolb (2000), for an initial secondary star mass of $M_2 = 1.2$ M$_\odot$, a central hydrogen abundance at the start of mass transfer of $X = 0.05$, and a mass transfer rate of $M = 1.5 \times 10^{-9}$ M$_\odot$ yr$^{-1}$ ($\sim t \times 10^{17}$) g s$^{-1}$ we find that a spectral type of M1 is predicted for an orbital period of 8 h. This is within the estimated range of values required to satisfy the conditions for the observed oversized secondary to fill its Roche lobe (the main uncertainties are the distance and the mass of the white dwarf, e.g. Harrop-Allin et al. 1997; de Martino et al. 1998).

As already noted by King, Osborne & Schenker (2002), V1309 Ori is indeed a good possible candidate for a binary system that has gone through a supersoft source phase and contains a nucleus evolved donor star. Szkołdy & Silber (1996) and Schmidt & Stockman (2001) have noticed that V1309 Ori has extraordinarily strong excitation lines of N v $\lambda$ 1240 and O v $\lambda$ 1370, which may support such an interpretation.

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