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Simultaneous optical polarimetry and X-ray observations of the magnetic CV CP Tuc (AX J2315–592)

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ABSTRACT

CP Tuc (AX J2315–592) shows a dip in X-rays which lasts for approximately half the binary orbit and is deeper in soft X-rays compared with hard X-rays. It has been proposed that this dip is due to the accretion stream obscuring the accretion region from view. If CP Tuc was a polar, as has been suggested, then the length of such a dip would make it unique amongst polars since in those polars in which a dip is seen in hard X-rays the dip lasts for only 0.1 of the orbit. We present optical polarimetry and *RXTE* observations of CP Tuc which show circular polarisation levels of $\sim$10 per cent and find evidence for only one photometric period. These data confirm CP Tuc as a polar. Our modelling of the polarisation data imply that the X-ray dip is due to the bulk of the primary accretion region being self-eclipsed by the white dwarf. The energy dependence of the dip is due to a combination of this self-eclipse and also the presence of an X-ray temperature gradient over the primary accretion region.

Key words: binaries: eclipsing - stars: individual: CP Tuc, AX J2315–592 - stars: magnetic fields - stars: variables

1 INTRODUCTION

The X-ray source AX J2315–592 (CP Tuc) was discovered by Misaki et al (1995) using *ASCA* data. Follow up observations by Thomas & Reinsch (1995) identified the optical counterpart (V $\sim$17) and suggested it was a polar (or AM Her) system. These are cataclysmic variables - CVs - in which the accreting white dwarf has a sufficiently strong magnetic field to lock the spin of the white dwarf into synchronous rotation with the binary orbital period. If the photometric variation of 89 min is attributed to its orbital period (Misaki et al 1996), then this would place it at the shorter end of the polar orbital period distribution.

CP Tuc shows a prominent dip which in X-rays lasts approximately half the orbital cycle (Misaki et al 1996). Misaki et al suggested that this dip is caused by the accretion stream far from the white dwarf obscuring our line of sight to the bright accretion region since the dip was deeper in soft X-rays compared to hard X-rays. In all other polars where absorption dips are seen in hard X-rays, they are visible for only $\sim$0.1 of a cycle. In some of the polars which show these hard X-rays dips, a much broader dip is also seen in the EUV – these broader dips are thought to be due to the accretion column obscuring the accretion region and have not been seen in hard X-rays.

One of the defining properties of polars is their high level of polarisation. To confirm the polar nature of CP Tuc we have obtained the first optical polarimetric data of this source. To complement these data and to determine the nature of the dip feature we obtained quasi-simultaneous X-ray data using the *RXTE* satellite (Bradt, Rothschild, Swank 1993).

2 X-RAY LIGHT CURVES

The most prominent feature of the X-ray light curve is the deep dip first noted in *ASCA* data by Misaki et al (1996). We use this dip to derive an precise ephemeris for CP Tuc using data from *ASCA* which is in the public archive (GIS: 0.5–12keV) (Misaki et al 1996), *SAX* (MECS: 1–10keV) and *RXTE* (1–20keV) (both Wheatley, in prep). Since the data obtained using *ASCA* and *SAX* are described elsewhere we will not discuss them in any detail here.

The data taken using *RXTE* have not been published elsewhere and so are described in more detail. *RXTE* was launched in Dec 1995, its prime aim being to observe sources

Date	Telescope	HJD Start	Duration	
X-ray:				
1997 July 19	*RXTE*	648.54	19.0ksec	
1997 July 20	*RXTE*	649.56	17.5ksec	
1997 July 23	*RXTE*	652.61	21.6ksec	
1997 July 24	*RXTE*	653.68	18.7ksec	
1997 July 29	*RXTE*	659.35	19.4ksec	
1997 July 30	*RXTE*	660.35	9.4ksec	
1997 July 31	*RXTE*	661.35	9.4ksec	
CCD Photometry:				
1995 Nov 24/25	SAAO 1.0m	46.30	1h55m	B, I
1995 Nov 25/26	SAAO 1.0m	47.27	1h40m	B, V, R
Optical polarimetry:				
1996 Sept 15/16	SAAO 1.9m	341.54	2h33m	WL
1996 Sept 16/17	SAAO 1.9m	342.56	1h31m	WL
1997 July 29/30	SAAO 1.9m	659.41	6h22m	WL
1997 July 30/31	SAAO 1.9m	660.41	5h45m	WL
1997 July 31/1	SAAO 1.9m	661.33	2h22m	WL
1997 Aug 7/8	SAAO 1.9m	667.64	59m	WL
1997 Aug 10/11	SAAO 1.9m	670.63	1h5m	WL

Table 1. Observing log for CP Tuc. The HJD start time is HJD-2450000.0. WL refers to white light observations.

with maximum time resolution and moderate energy resolution. CP Tuc was detected in the 1–20keV energy range in observations using *RXTE* between 1997 July 19 and 1997 July 31 (cf table 1). The total usable exposure time was 115 ksec and was spread over 7 different epochs. The mean background subtracted count rate over the 1–20keV energy range was 12.9 ct s^{-1}.

Using the *ASCA*, *SAX* and *RXTE* data we obtained a total of 24 estimates for the time of the center of the X-ray dip. From these timings we obtained the following linear ephemeris:

$$T = \text{HJD } 2450024.8015(7) + 0.06183207(8) \times E$$

The number in brackets refers to the error on the last digit. This ephemeris is sufficiently precise to phase all our data to within 0.02 cycles. This best fit period (89.0382±0.0001 mins) is consistent with the period derived from optical photometry by Thomas & Reinsch (1996) (89.041±0.004 mins) and also the period derived by Misaki et al (1996) from *ASCA* data (89.34±0.78 mins). We use the above ephemeris throughout the paper. Assuming the 89.0382 min period is the spin period of the white dwarf then the best estimate of the orbital period (89.051±0.014 min Thomas & Reinsch 1996) is consistent with the CP Tuc being synchronised and therefore a polar.

We show the background subtracted folded and binned *RXTE* light curves covering 1–4keV and 4–13keV in the upper panels of Fig. 1. Both light curves show a prominent dip lasting $\Delta\phi \sim$0.45 and 0.35 cycles in the 1–4keV and 4–13keV range respectively. The dip minimum coincides with the point in the orbital cycle where the circular polarisation is ~0%. The light curves obtained using *ASCA* and

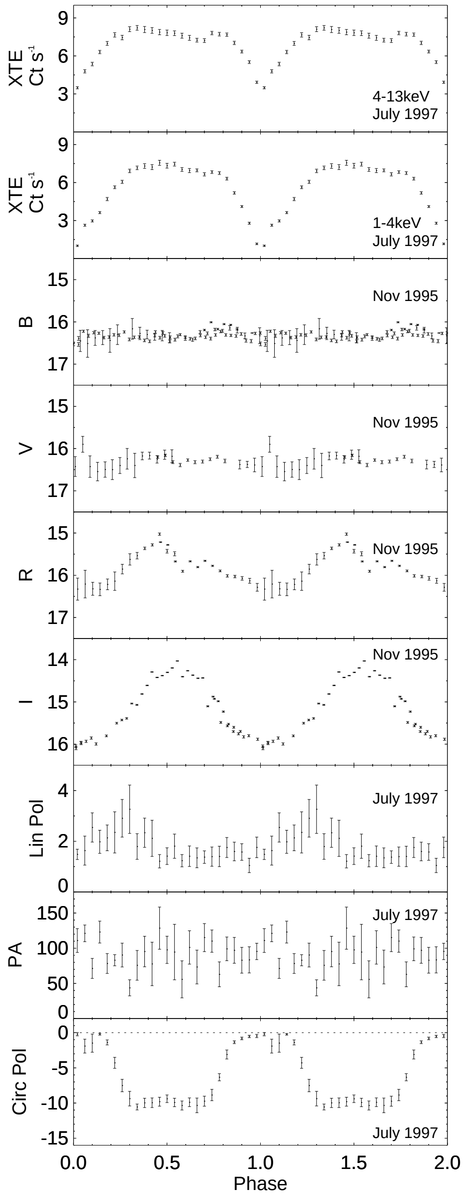

Figure 1. From the top – the folded: *RXTE* data (4–13keV), *RXTE* data (1–4keV), CCD photometry in B, V, R, and I bands, the linear polarisation, the position angle of the polarisation, and the circular polarisation (the polarisation data were white light observations). The X-ray and polarimetric data have been binned into 0.04 phase bins. The phasing zero corresponds to the start of the increase in negative polarisation and is phased according to the ephemeris in §2.

SAX data have the same general shape and features as the *RXTE* light curves (not shown).

3 POLARIMETRY

3.1 The Observations

CP Tuc was observed at 2 epochs (cf table 1) using the SAAO 1.9m telescope and UCT polarimeter (Cropper 1985). At both epochs white light data were obtained and conditions were photometric. Polarised and non-polarised standard stars (Hsu & Breger 1982) and calibration polaroids were observed at the beginning of the night to set the position angle offsets and efficiency factors. The data were reduced in the standard way (eg Cropper 1997).

3.2 The folded data

The polarisation data were folded on the spin period derived in §2 and shown in the lower panels of Fig. 1. The circular polarisation is at a maximum of $\sim -10\%$ for around half the orbital cycle which corresponds with the bright phase seen in the white light intensity data (not shown). The mean linear polarisation is 1.7±0.7 percent with a peak at ϕ ∼0.3 of 3 percent. The position angle is roughly constant throughout the orbital cycle.

4 MULTI-COLOUR PHOTOMETRY

CCD photometry in the BVR_cI_c system was obtained on CP Tuc during 1995 Nov (see Table 1) using the SAAO 1.0m telescope and the Tek8 CCD (512 x 512). Repetitive time series observations in two (B, I) or three (B, V, R) filters were conducted, with exposure times of 60sec. Following the usual flat-fielding and bias corrections, the individual CCD frames were processed using the DoPHOT reduction package (Mateo & Schechter 1989) to derive differential magnitude estimates. The three brightest stars on the frames were used to define canonical frame standards, and their magnitudes derived from photometric frames obtained on the first night (conditions were photometric on the first night and for the first half on the second). These magnitudes were transformed to the standard system using observations obtained of E-region standards on the same night. The data were folded on the ephemeris derived in §2 and are shown in Fig. 1. There is no significant modulation in B or V, while in R and I the modulation is 1.5 mag and 2.0 mag respectively. In R and I the minimum brightness occurs at the same phase as the X-ray minimum.

5 PHOTOMETRIC VARIATIONS

To search for all possible photometric periods we subjected the optical photometry obtained in July 1997 to a standard Discrete Fourier Transform. This gave an amplitude peak at 88.960 mins: the amplitude spectrum is shown in Fig. 2. We then pre-whitened the data using the period found from the timings of the X-ray minimum (89.0382 mins: §2) and its first harmonic. This successfully removes power at the 88.960 min period indicating that this period is consistent with the period found in §2. Further, there is no evidence for a second period with comparable or longer period than the 89 min spin period in the pre-whitened spectrum. Although there is evidence for variations on time scales shorter than the spin period in the unfolded light curve, there is no evidence for a coherent modulation in the DFT: this suggests these shorter period variations are due to flickering. We made a similar analysis using the full set of *RXTE* data. We show the amplitude spectrum and the pre-whitened data (again using the period found in §2 and its first and second harmonics) of the *RXTE* data in Fig. 2. There is no evidence for a significant modulation at periods near or at shorter periods than the 89 min spin period. The increased power at shorter frequencies is probably due to cycle to cycle variations. We make a similar conclusion from an analysis of the circular polarisation data taken in July and August 1997.

6 MODELLING THE POLARISATION DATA

To model our polarisation data we fitted the data using the optimisation method of Potter, Hakala & Cropper (1998). Until very recently polarisation data was modeled by constructing accretion regions on the surface of the white dwarf by hand and then a good fit to the data was achieved by trial and error. The method of Potter, Hakala & Cropper finds the best fit to the data and maps the shape, location and structure of the cyclotron emission region(s) in an objective manner. The best fit is the simplest solution found using a maximum entropy technique. Strictly speaking the model maps the accretion region(s) in terms of an optical depth parameter (a dimensionless parameter describing density/ optical depth). In this paper we assume a simple dipole magnetic field for the white dwarf. While it is possible that the geometry of the magnetic field maybe more complex, we do not consider the additional parameters that an off-set dipole (or multi-pole model) would require are justified in this case.

A wide range of parameter space was initially searched: the inclination of the system, i, was searched between 0–80° (there is no evidence for an eclipse), the angle between the spin axis and the magnetic axis, β, was searched between 0–90° and the phase at which the magnetic dipole crosses our line of sight is searched through all phases. The magnetic field strength at each pole was fixed at 15MG and the shock temperature was fixed at 17keV (Thomas & Reinsch 1996).

For each model fit to the data a goodness of fit was calculated. We found that we were not able to place tight constraints on the geometry of the system: i was found to be $\gtrsim 20°$, the phase that the magnetic dipole crosses our line of sight clustered around ϕ ∼0.3 and β was not constrained. We show in Fig. 3 one of the best model fits (i=42° and β=50°). The fits to the circular polarisation and intensity data is reasonably good. During the bright phase the model linear polarisation has the same general level of polarisation as the data. During the faint phase the model underestimates the linear polarisation. This is partly due to the fact that the linear polarised flux is much less than the circularly polarised flux and hence the optimisation method we use gives greater weight to the circular polarisation curves in the fitting process.

We show in Fig. 4 the position of the accretion regions predicted by our model superimposed on globes representing a complete rotation of the white dwarf for the same model fits as shown in Fig. 3. An extended cyclotron accretion region, which is offset by a large distance from the visible magnetic pole, is first seen at ϕ ∼0.3 (and may account for the increase in the linear polarisation seen at this phase) and disappears at ϕ ∼0.9 – the primary accretion region. The 'tail' of this region is optically thin cyclotron radiation. Fig. 4 shows that the leading edge of the primary region (optically thick cyclotron radiation) quickly appears over the limb of the white dwarf and accounts for the rapid increase

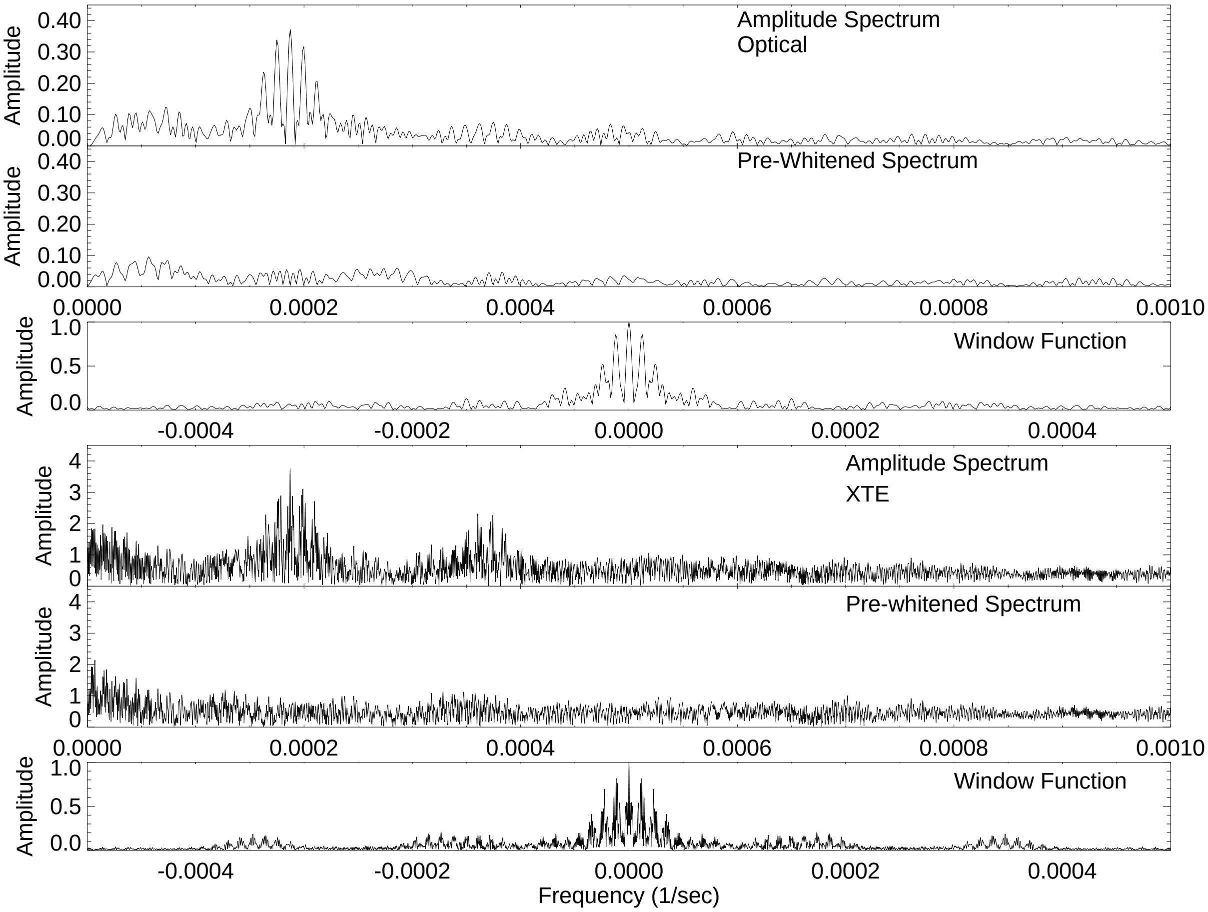

Figure 2. From the top: the amplitude spectra of the white light intensity data taken during July 1997 (3 nights); the data pre-whitened using the period found by fitting the times of X-ray minimum and its window function. The next three panels are as before but for the *RXTE* data.

in circularly polarised flux at $\phi \sim 0.3$ (Fig. 3). On the other hand the 'tail' of the accretion region takes a longer time to disappear over the limb of the white dwarf resulting in a less rapid decrease in the circularly polarised flux. A much smaller accretion region is predicted very close to the spin pole and is always visible – the secondary accretion region. For higher values of β ($> 50^\circ$), we find other models which fit the data equally well. In these cases the primary accretion region is less extended in magnetic longitude and the secondary accretion is brighter and vice-versa for $\beta < 50^\circ$. We consider the $\beta < 50^\circ$ set of models to be the most likely solutions since in these cases the secondary region is much less significant than the primary and hence the most simple scenario (as is the rationale of our optimisation technique).

While we are confident that all our best fitting models predict the same general location, extent and phasing of the primary accretion region, we cannot be certain of the finer details of its structure as the resolution of the image is limited due to the finite sampling of our data and the fact that the optimisation technique tends to smooth out fine structure. We now go on to compare our model results with the scenario of Misaki et al (1996) who suggest that the deep X-ray dip is due to the accretion stream far from the white dwarf obscuring the emission from the bright accretion region.

7 DISCUSSION

The optical and X-ray data reported by Thomas & Reinsch (1996) and Misaki et al (1996) respectively are consistent with CP Tuc being a polar although their data could not rule out an Intermediate Polar interpretation (IPs - the non-synchronous magnetic CVs). One of the main characteristics of polars is their high levels of polarisation. However, until now, no polarimetry data was available on this object. Our polarimetry shows circular polarisation of up to 10 per cent. Such high levels of polarisation together with the detection of only one photometric period confirm that CP Tuc is a polar and not an IP (IPs show complex amplitude spectra).

The one unusual feature that CP Tuc exhibits for a polar is the prominent X-ray dip which lasts approximately half the orbital cycle. Misaki et al (1996) suggested that this dip is caused by obscuration of the accretion region by the accretion stream. This conclusion was reached mainly due to the dip having a greater depth in soft X-rays (1–4keV) compared to hard X-rays (4–13keV) which is indicative of photoelectric absorption (Fig. 1). In contrast, the much broader dips seen in the EUV are grey. It is very unusual for a polar to have an absorption dip lasting such a large fraction of the binary orbit. In hard X-rays, absorption dips lasting $\sim$0.1 of the binary orbit have been seen in a number of systems (eg

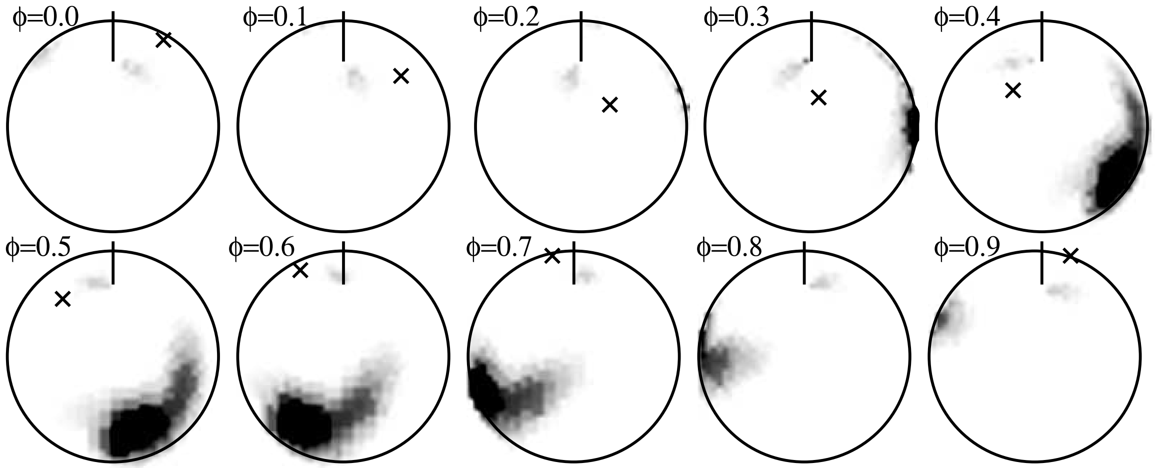

Figure 4. The predicted location of the accretion regions on the white dwarf as a function of spin phase for $i = 42°$, and $\beta = 50°$. The magnetic axis is shown as a cross.

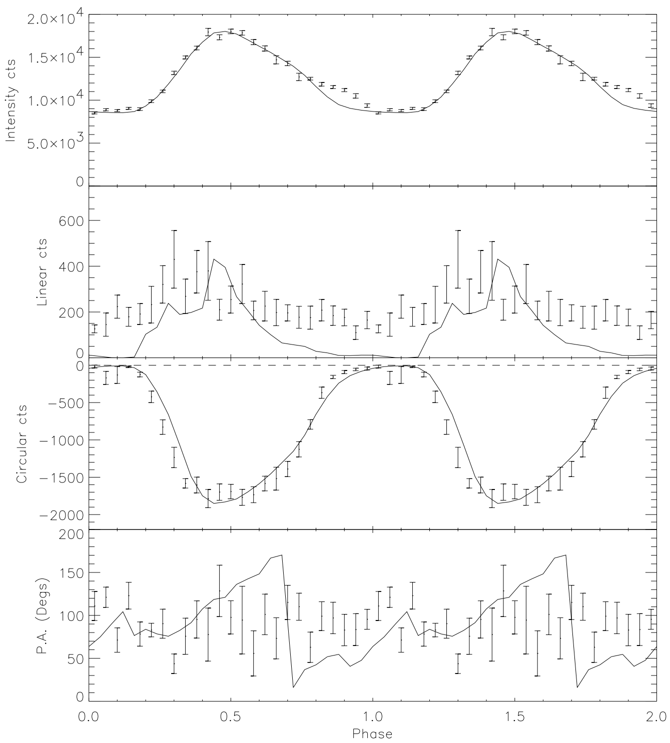

Figure 3. The polarisation data (white light) together with the model fit where $i = 42°$ and $\beta = 50°$.

EF Eri: Done, Osborne & Beardmore 1995), but dips lasting ∼0.5 of the binary orbit have not.

Our modelling of our optical polarimetry data suggests that the bulk of the optical flux originates from an extended accretion region far from the visible magnetic pole. It is reasonable to assume that the polarised optical flux and the X-ray flux originate close to the shock region above the white dwarf. Thus, the dip seen in X-rays between ϕ ∼0.9–0.2 is simply due to the bulk of the primary accretion region being self-eclipsed by the white dwarf according to our polarisation modelling. However, even at the deepest point of the X-ray dip a significant X-ray signal is present with hard X-rays being more dominant than soft X-rays.

By examining Fig. 4 it can be seen that the trailing edge of the primary accretion region is still just visible at the deepest point of the X-ray dip (although this maybe not be so clear in the reproduction of Fig. 4). In models where β is $> 50°$ this is more obvious. On the other hand the larger (and leading) edge of the region is self-eclipsed for the phases centered on the X-ray dip. If the leading edge of the region is predominately emitting in soft X-rays and the trailing edge predominates in hard X-rays then this can account for the energy dependance of the X-ray dip.

The structure of the accretion region in polars depends on how and where the accreting flow attaches to the magnetic field lines. A magnetic field can be thought of as acting as a density filter in which less dense material from the accretion flow is threaded first while denser material is threaded futher along its trajectory. This results in a variation in the local specific accretion rate over the region and hence a range of X-ray energy. Our model suggests that (at least in the case of CP Tuc) the trailing edge of the primary accretion region has a higher mean X-ray temperature than the leading edge.

Until this stage we do not know how our spin phase convention relates to the binary orbital phase. We can use the optical spectroscopy of Thomas & Reinsch (1996) to roughly locate the position of the secondary star. Thomas & Reinsch obtained low resolution (32 Å) spectroscopy of CP Tuc and were able to resolve the Hα line into broad and narrow components. In low resolution spectra such as these the broad component is likely to originate from the accretion stream close to the white dwarf. On the other hand the narrow component is likely to originate in the stream much further from the white dwarf, perhaps closer to (or at) the secondary star. The maximum red shift of the broad and narrow components are expected to occur just before inferior conjunction (the point where the secondary is closest to the observer) and in that order.

The spectroscopic phase 0.0 of Thomas & Reinsch (1996) corresponds to our polarimetric phase 0.08. From Fig. 3 of Thomas & Reinsch (1996) the broad component has a maximum blue shift at our $\phi \sim$0.5 while it reaches maximum red shift at our $\phi \sim$1.0. Examining Fig. 4, we can see that at $\phi \sim$0.4–0.5 the magnetic field configuration is such the magnetic field lines feeding the accretion region appearing over the limb of the white dwarf will result in the accreting material being maximally blue shifted. Similarly at $\phi \sim$0.8–0.9 our model predicts the accreting material will have maximum red shift. Bearing in mind the uncertainties in the relative phasing, our model results are reasonably consistent with the spectroscopy of Thomas & Reinsch (1996).

Let us compare this result to the low resolution spectroscopy of the eclipsing polar MN Hya (Ramsay & Wheatley 1998) where ϕ=0.0 defined the eclipse center. Ramsay & Wheatley (1998) found a maximum red shift for the broad component at $\phi \sim$0.9 and maximum blue shift for the broad component at $\phi \sim$0.4. Therefore to obtain the inferior conjunction of the secondary in CP Tuc we need to add $\phi \sim$0.1 to the phase of maximum red shift, ie inferior conjunction occurs at $\phi \sim$0.1. From the location of the secondary star, it appears that the accretion flow has not accreted onto the field lines of the more favourable magnetic pole (which is never visible). Instead it has preferentially accreted onto the field lines of the visible magnetic pole. This may suggest that the magnetic field of the white dwarf maybe more complex than a dipole field as we assume in the modelling of our polarisation data.

Finally, we briefly discuss the optical photometric observations which show no modulation in B or V, but show an increasingly large modulation as we move further to the red (cf Fig. 1). Thomas & Reinsch (1996) modeled their optical spectra and determined a magnetic field strength $<$17MG. This is consistent with the good fits we achieved in fitting our polarimetric data with a fixed field strength of 15MG. As the magnetic field decreases, cyclotron radiation is shifted towards redder wavelengths and hence for low field strengths light curves will be much less modulated in the blue compared to the red, as is the case in CP Tuc.

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