Slingshot prominences during dwarf nova outbursts?

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ABSTRACT

Two dwarf novae, IP Peg and SS Cyg, were observed with the William Herschel Telescope at La Palma as part of a spectropolarimetric study on cataclysmic variables. We present phase-resolved spectroscopy, covering almost a full orbit, of these systems during their outburst state, and use Doppler tomography to map the observed emission lines. Secondary star emission is strong for both systems, especially in the Balmer lines. The IP Peg accretion disc emission is clearly asymmetric. Both systems also display peculiar low-velocity emission components in several emission lines, producing emission spots near the origin of the Doppler maps. We investigate these components and discuss possible sources of this emission. We propose slingshot prominences as a possible interpretation of this stationary emission and discuss this model in more detail. The observed emission can be attributed to prominence material at a temperature of 2 \times 10^4 K and a number density of 10^{12} cm^{-3}. We find that kG fields for the secondary star are sufficient to store the ~ 10^{18} g in a typical prominence.

Key words: accretion, accretion discs - stars: emission-line, Be - stars: individual: IP Peg - stars: individual: SS Cyg - stars: magnetic fields - novae, cataclysmic variables.

1 INTRODUCTION

Dwarf novae are a subclass of cataclysmic variables (CVs), i.e. binary stars in which a white dwarf accretes matter from a Roche lobe filling secondary star. Dwarf novae show semi-periodic outbursts during which they brighten by several magnitudes. Recurrence times for these outbursts range from weeks to months with a duration of several days to a few weeks. (For an extensive review of these systems see la Dous 1993.) Two basic models for the origin of these outbursts have been proposed, either an instability in the accretion disc which results in a high mass transfer through the disc on to the white dwarf, or an instability of the secondary star, resulting in a high transfer of mass from the secondary star on to the disc. Up to now observations have not been able to disprove either of these models (in their recent incarnations, see e.g. Lasota 1996). However it is clear that during an outburst state there is enhanced mass transfer through the accretion disc on to the white dwarf. This makes the dwarf nova one of the most interesting CVs to study from the perspective of accretion disc physics. One feature observed in several systems during outburst is enhanced emission (usually in the Balmer lines) from the secondary star. Although this might indicate high activity on the secondary star and possibly high mass transfer, it could also be a result of the irradiation of the secondary by the bright disc. Hotspot emission is usually strong during quiescence (e.g. U Gem, Marsh et al. 1990), but during outburst the bright disc dominates the hotspot emission. In this paper we study the line emission of two dwarf novae, IP Peg and SS Cyg, during their outburst state. We use time-resolved spectroscopy and Doppler tomography (Marsh & Horne 1988) to map the emission lines during this high state. The data are part of a spectropolarimetric study of several bright CVs.

SS Cyg is one of the first dwarf novae observed, and as such a prototype for this class of systems. SS Cyg has been extensively studied with a wide variety of techniques, allowing us to compare our observations with previous findings (e.g. recently Martinez-Pais et al. 1994). The orbital period of the binary is 6.6 h and the outburst recurrence time is 4–10 weeks. The object brightens by about 4 mag during an outburst, going from visual magnitude 12 to about 8.5. IP Peg is another well-known bright dwarf nova with an orbital period of 3.8 h, which because of its high inclination also features eclipses, an extra diagnostic for studying the emission sites.

In Sections 2 and 3 the observational setup and data reduction will be discussed. Sections 4 and 5 deal with the observational results and Doppler maps. In Section 6 we discuss the peculiar components we see in our data, and the slingshot prominence model is investigated in Section 7.
2 THE OBSERVATIONS

The data used in this paper were acquired on two nights using the 4.2-m William Herschel Telescope operating on La Palma. The dual-beam ISIS spectrograph on this instrument is capable of spectropolarimetry, which was used during the IP Peg observations. A journal of the observations together with instrumental settings is given in Table 1.

When in circular polarization mode, the incoming light first passes through a dekker to select object and sky regions. A quarterwave plate converts circular polarization to linear polarization. Finally a calcite active crystal splits the light into two linearly polarized beams, with perpendicular polarization directions. The two beams together with their accompanying sky regions are then mapped on to a CCD. For more information on the instrument see Tinbergen & Rutten (1992). For the present study we averaged the spectra from the two beams to obtain a single spectrum per CCD frame. In polarimetry mode only one arm of the spectrograph can be used at a time, in our case the red arm.

The IP Peg data were acquired on 1993 August 27 with the polarimetry setup. Data reduction for this case will be discussed in the next section. Since SS Cyg was just at the maximum of an outburst, the dual-beam spectroscopy mode was used for this object. This allowed us to acquire spectra with both arms of the ISIS simultaneously and without light losses introduced by the polarization optics. Data were acquired on 1993 August 28 (see Table 1 for details).

3 DATA REDUCTION AND ANALYSIS

In polarization mode, two object spectra and two sky spectra for each beam are mapped on to the CCD. The CCD frames were first de-biased using standard FIGARO commands. Due to problems with the EEV3 CCD, resulting in correlations between pixel rows (perpendicular to dispersion), we decided not to apply pixel-to-pixel flat-field corrections on the red arm spectra, since this introduced unwanted artefacts in the spectra, which dominated the pixel-to-pixel artefacts. Blue arm spectra (TEK1 chip), on the other hand, were corrected using a median image of tungsten lamp frames for pixel-to-pixel sensitivity corrections. Scattered light between the spectra made it necessary to correct for this first. A low-order polynomial fitted at each wavelength was subtracted to remove this scattered background component from the spectra. Object and sky spectra for each beam were then optimally extracted (Horne 1986) using the pAMEla extensions to FIGARO. Twilight frames were used to calibrate and flatten the spatial response of the system. The sky spectra were then averaged and subtracted from the object spectra. For this study we averaged the two beams to form one spectrum for each frame, losing the polarimetric information but producing higher signal-to-noise ratio spectra.

SS Cyg was observed simultaneously on both arms, with the polarimetry setup disabled, producing a single object spectrum on each CCD frame. Standard spectral reduction was applied to extract the spectra optimally (Horne 1986).

Wavelength calibration, flux calibration and atmospheric extinction correction were done using the MOLLY package. Neon (red arm) and argon (blue arm) arc lamps were used for wavelength calibration. The resulting fourth-order fit yielded rms residuals of 0.0034 Å, interpolated in time to account for instrumental drift and/or flexure. Standard flux stars (HD 19445 and BD+26°2606), reduced in exactly the same way as the object spectra, were used for flux calibration. Since a suitably bright comparison star was not available, corrections for slit-losses, etc., were not possible, making the flux calibration limited in accuracy (~10 per cent).

4 IP PEG

4.1 Spectroscopy

The average spectrum of IP Peg is shown in Fig. 1. The 40-mJy mean continuum flux level, compared with ~2 mJy in quiescence (Marsh & Horne 1990), indicates that the system was in an outburst state. AAVSO data show that the observations were a few days after the system reached $V\sim 12$ near
1993 August 22, and IP Peg was still in the high state (Mattei, private communication). The equivalent width of the Hα line is 43 Å, much smaller than quiescent values ~100 Å (Harlaftis et al. 1994).

Continuum and emission line light curves are shown in Fig. 2. Although systematic effects like slit losses limit the accuracy of the light curves, producing the large scatter of data points in the light curves, qualitative remarks can be made. We see a broad continuum eclipse as the accretion disc is occulted by the secondary star. This is reflected in both line light curves as well, the Hα showing considerable flux at mid-eclipse, especially at low velocities. In the case of He I, there is little line flux left at mid-eclipse (Fig. 2), but the eclipse is total at low velocities, as can be seen from the trailed spectrogram in Fig. 3 or the line profiles in Fig. 4. The fact that the eclipses are fairly well centred around phase 1.0 gives us confidence in the orbital ephemeris.

The orbital ephemeris of IP Peg is somewhat uncertain. A claimed $P$ term (Wood et al. 1989) was not compatible with more recent eclipse timings (Wolf et al. 1993), which suggest a sinusoidal period variation with a period of 4.7 yr and a semi-amplitude of 1.57 ± 0.14 min.

We used the orbital ephemeris of Wolf et al. (1993), without the sinusoidal period changes, to calculate the binary phases ($\phi$):

$$\phi(t) = (t - T_0)/P$$  

with $T_0$ in HJD and $P$ in days from Table 2.

The individual spectra are shown in Fig. 3 in the form of a trailed spectrogram. We can distinguish three different emission components in the data: double peaks from the disc, a sharp 'S-wave' from the companion star and a stationary component. We discuss these below.

The double-peaked component, moving with the binary phase, is a standard signature for an accretion disc. The orbital motion reflects the motion of the centre of the disc, the white dwarf, and is compatible with its K-velocity (~150 km s$^{-1}$). This disc emission component is sharper in the He I line compared with Hα. The separation of the emission peaks varies as a function of binary phase, from 1250 km s$^{-1}$ at quadratures to 1000 km s$^{-1}$ at conjunctions, indicating a variation in circular velocity with azimuth around the rim of the disc. Note that the blueshifted part of the disc is eclipsed before the redshifted side, caused by the secondary star first covering the approaching side and later the receding side of the disc.

In both Hα and He I ($\lambda 6678$), the clear 'S-wave' antiphased with the disc emission can be attributed to the secondary star. The amplitude of the observed S-wave is smaller (~240 km s$^{-1}$) than the actual K-velocity (~300 km s$^{-1}$), indicating that this emission comes from the side that faces the white dwarf. This is supported by disappearance of the S-wave during phases ~ 0.8–0.1, when it is obscured by the back part of the star. In previous observations of IP Peg, during and just before outburst, enhanced secondary star emission was also observed (Harlaftis et al. 1994; Marsh & Horne 1990).

A nearly stationary feature is visible in Hα, but not in the He I line. This stationary emission component does not fit in with the standard picture. It clearly does not follow either the motion of the white dwarf or that of the companion star. The low velocity makes it unlikely that this emission is connected with the compact white dwarf or boundary layer, and suggests a position near the centre of mass, or at least along the axis through the centre of mass, perpendicular to the orbital plane. It is clearly separated from the secondary star S-wave, especially near phases 0.25 and 0.75. During eclipse we see (Figs 2 and 3) that there is residual flux at mid-eclipse in the Hα line, while eclipse is total for He I (Fig. 3).

To examine this stationary emission further, we plot the velocity profiles of the Hα and He I emission lines at mid-eclipse and out of eclipse (Fig. 4), to compare the presence

Table 2. Adopted system parameters and ephemeris.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>IP Peg</th>
<th>SS Cyg</th>
</tr>
</thead>
<tbody>
<tr>
<td>conjunction, $T_0$ (HJD)</td>
<td>2445615.4156$^1$</td>
<td>2444841.8682$^4$</td>
</tr>
<tr>
<td>period, $P$ (d)</td>
<td>0.15820616$^3$</td>
<td>0.27512973$^4$</td>
</tr>
<tr>
<td>$K_1$ (km s$^{-1}$)</td>
<td>147$^3$</td>
<td>92$^2$</td>
</tr>
<tr>
<td>$K_2$ (km s$^{-1}$)</td>
<td>300$^3$</td>
<td>155$^2$</td>
</tr>
<tr>
<td>white dwarf, $M_1$ ($M_\odot$)</td>
<td>1.02$^3$</td>
<td>0.97$^2$</td>
</tr>
<tr>
<td>companion, $M_2$ ($M_\odot$)</td>
<td>0.5$^3$</td>
<td>0.56$^2$</td>
</tr>
<tr>
<td>mass ratio, $q=M_2/M_1$</td>
<td>0.49$^3$</td>
<td>0.58$^2$</td>
</tr>
<tr>
<td>separation, $a$ ($R_\odot$)</td>
<td>1.41</td>
<td>2.05</td>
</tr>
<tr>
<td>Roche lobe, $R_R$ ($R_\odot$)$^5$</td>
<td>0.45</td>
<td>0.70</td>
</tr>
</tbody>
</table>

1 : from Wolf et al. (1993)
2 : from Martinez-Pais et al. (1994)
3 : from Marsh & Horne (1990)
4 : from Hessman et al. (1984)
5 : Roche lobe radius, from $q$ and $a$
Apart from disc and secondary star emission, there is a clear eclipse. In Fig. 5 we can see the two disc peaks, a stationary component in the He line, spanning ±100 km/s. In Fig. 4 we can estimate this to be less than 15 mJy. Since the total flux at zero velocity out of eclipse is about 60 mJy, the total excess flux due to this stationary source is \( \sim 45 \) mJy out of eclipse, down to \( \sim 15 \) mJy at mid-eclipse. Therefore the only source that contributes at this velocity during mid-eclipse is the back of the secondary star or our central emission source. Such a considerable flux from the central emission source is not fully eclipsed. The dotted lines show the expected ingress and egress of the white dwarf (\( \Delta \phi_w = 0.086 \)). The dashed lines show when the front side of the secondary becomes eclipsed.

**Figure 3.** Trailing spectrogram of the full IP Peg dataset, including eclipse. Apart from disc and secondary star emission, there is a clear low-velocity emission source visible in the Hα line (top). The He I data are in the bottom panel.

**Figure 4.** Top panel: Hα velocity profiles at mid-eclipse (bottom profile) and \( \phi=0.35 \). The flux at zero velocity is substantially eclipsed, going from 60 to 15 mJy. Bottom panel: He I (λ6678) profiles, constructed by averaging three spectra centred on mid-eclipse (lower profile), and \( \phi=0.5 \) (upper profile, offset by 10 mJy). No central component is visible during mid-eclipse in this line, while the blueshifted side of the disc has reappeared.

**Figure 5.** Light curve of the flux around the rest wavelength of the Hα line (IP Peg). The average flux of the area covering ±100 km s\(^{-1}\) around the line centre is calculated for each spectrum. At mid-eclipse there is still considerable flux at this velocity, indicating that the source of this emission is not fully eclipsed. The dotted lines show the expected ingress and egress of the white dwarf (\( \Delta \phi_w = 0.086 \)). The dashed lines show when the front side of the secondary becomes eclipsed.

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eclipse is similar to that of the compact source out of eclipse, mid-eclipse. There is a possibility that there are two stationary sources: one large circumstellar component, still visible at mid-eclipse, and the compact source which is eclipsed. Although this cannot be ruled out, the width of the component at mid-eclipse is similar to that of the compact source out of eclipse, suggesting a common origin.

In He I (λ6678) this component is not visible, suggesting a lower ionization than the disc or secondary star components.

4.2 Doppler tomography

We also used Doppler tomography to study the emission-line behaviour. This technique uses the velocity profiles of the emission lines at each phase to construct a two-dimensional map in the Doppler coordinates $(V_x, V_y)$ showing at which velocities, projected on to the orbital plane, the line emission is produced. In order to use this technique the continuum (determined by a spline fit) was subtracted from the individual spectra since the line flux is the quantity needed to make these maps. Doppler maps were calculated using the so-called filtered backprojection method (Horne 1991). This is a linear method resulting in a direct calculation of the velocity image of the system without the need of techniques like maximum entropy. The velocity maps provide us with a picture of the system in which contributions like secondary star and disc emission are easy to separate (Fig. 6). For an atlas of Doppler maps of CV systems see Kaitchuck et al. (1994) and for an extensive discussion of Doppler tomography see Marsh & Horne (1988).

Fig. 7 shows the calculated Doppler tomograms for the two lines, together with observed and predicted data. We can clearly see the above-mentioned components in the maps as well. The disc emission is visible as an elliptical ring centred around the white dwarf, the ellipticity reflecting the above-mentioned non-axisymmetry and peak-to-peak velocity change. The accretion disc structure is similar to that found during outburst in 1990 (Marsh & Horne 1990, who presented Doppler maps of IP Peg in quiescence as well as outburst). Marsh & Horne (1990) discuss outburst Doppler maps of the He II (λ4686) line, showing disc structure very similar to our He I map. Enhanced disc emission on the upper right and lower left part of the disc in Marsh & Horne's He II map can be found in our He I (λ6678) map as well.

Secondary star emission is visible and fits the predicted Roche lobe calculated using the system parameters in Table 2. It is clearly concentrated on the inner part of the secondary, the He I being even closer to the L1 point than the Hβ emission.

Finally the stationary emission source is mapped near the centre of mass, reflecting its low velocity. Since its position on the map is well outside the Roche lobe, roughly one stellar radius from the surface, the emission cannot originate from the secondary star directly. Its position near the centre of mass is what we expect from the low orbital motion observed in the

5 SS Cyg

SS Cyg is a dwarf novae which features three types of outburst, long, short and anomalous ones. The usual outburst features a quick rise (2–3 d) followed by a high state with a duration of about 10 d (long) or just a few days (short) and then a rapid dropoff again into quiescence. Sometimes, however, the rise time of the outburst is far longer (~5 d).
These long rise time outbursts are called anomalous outbursts. Our observations were a week after maximum light of an anomalous outburst which reached $V \sim 8.3$ on 1993 August 20. The same outburst was observed with EUVE, a few days before our observations (Mauche, Raymond & Mattei 1995).

5.1 Spectroscopy

SS Cyg was observed at two wavelength ranges simultaneously. System parameters are summarized in Table 2 and orbital phases were calculated as for IP Peg (equation 1). The red arm covered Hα and He I (λ6678), while the blue arm included Hβ, Hγ, He I (λ4472), He I (λ4713) and He II (λ4686). The average spectra are shown in Fig. 8. Broad absorption wings are present.
Due to the low inclination of SS Cyg (~40°), providing a more direct view of the hot, optically thick, inner face of the accretion disc. The presence of a strong He II (λ4686) line, without absorption wings, is a typical sign of the outburst state of the system. Hessman et al. (1984) presented spectroscopy of SS Cyg as it declined from an outburst, showing a strong He II (λ4686) line which gradually became weaker as the outburst declined.

The observed spectra in trailed spectrogram format are shown in Figs 9 and 10 together with the Doppler maps.

Double-peaked disc emission is visible in all observed lines, the Balmer lines showing a more extended disc than the He lines. Both absorption and emission from the disc are visible in some lines, the absorption wings arising in the optically thick inner disc, while the emission cores are formed by the optically thin outer disc. Fine structure in the double-peaked profiles suggests non-axisymmetric disc emission, similar to the IP Peg profiles. Again this is most obvious in the He I (λ6678) line.

A secondary star S-wave is visible in most lines except the He I line where only a low-velocity component is visible. The S-wave reaches maximum flux near phase 0.6 when the front side of the star faces the observer. Martinez-Pais et al. (1994) report secondary star emission and evidence for non-Keplerian regions in SS Cyg during quiescence as well.

Surprisingly, a low-velocity emission component is present in the Hα and He II (λ4686) lines, resembling the Hα feature in the IP Peg data. Again its velocity is too low to be white dwarf or secondary star emission. Unfortunately, since SS Cyg is not an eclipsing system, we have no further geometrical constraints on the source for this object. The observational similarities, in the trailed spectrograms, between the two systems are, however, striking.

5.2 Doppler tomography

The middle panels of Figs 9 and 10 show Doppler maps for the different lines. Again the three components that we saw before in the IP Peg maps are visible.

The accretion disc emission shows several features, indicating non-axisymmetric emission in He I (λ6678) and He II (λ4686). As for IP Peg there seems to be enhanced emission from the upper right and lower left parts in the Doppler maps. The Balmer lines produce fairly smooth disc rings without clear azimuthal structure.

Secondary star emission on the front side of the Roche lobe is strong except in the case of He II (λ4686) for which no emission inside the Roche lobe is found.

The stationary emission that we see in IP Peg is also clear in the SS Cyg Doppler maps (as expected from the trailed spectrograms). Again emission is clearly outside the Roche lobe in the case of Hα and He II (λ4686). Its position in the map near the centre of mass is similar to the low orbital motion observed in IP Peg.

Since more lines were covered we can say a bit more about the origin of the low-velocity emission. The fact that the stationary component is very obvious in Hα, only weak in Hβ and not visible in Hγ indicates a steep Balmer decrement for this gas, i.e. optically thin emission. The fact that it is so strong again in He II (λ4686), on the other hand, indicates a high ionization.

6 DISCUSSION

Both systems have similar features in their emission lines during outburst. Secondary star emission is very strong in Balmer and He I lines, and is concentrated on the inner face of the secondary. Our Doppler maps of IP Peg look very similar to the outburst maps of Marsh & Horne (1990), increasing confidence that the azimuthal disc structure, implying non-Keplerian motion in disc, is real. The SS Cyg disc emission shows similar features, further strengthening the case.

Probably the most remarkable similarity is the stationary emission observed in several lines in both systems. The components are very clear in our data and the Doppler maps, and there have been previous remarks about low-velocity emission. Piche & Szkody (1989) note a strong single-peaked He II (λ4686) line in their outburst spectra of IP Peg. The He II map of the IP Peg outburst discussed by Marsh & Horne (1990) shows a similar emission source. Although our IP Peg observations did not cover that emission line, the SS Cyg observations did, and again a stationary component is visible in that line, in a different system, at a different epoch. Their low-velocity orbital motion (smaller than ~50 km s⁻¹), and small velocity width (~150 km s⁻¹), makes it hard to interpret these features.
Marsh & Horne (1990) suggested a wind as a possible source of central emission observed in some systems. Although this is possible, the velocity dispersion of this material is very low, requiring a very slow, steady wind. Also one would expect the wind to be launched from either the white dwarf or the secondary star, so their orbital motion should be reflected in the wind as well, something we do not observe. Furthermore this material cannot be too extended, but must be fairly closely confined in the orbital plane since most of this emission, but not all, is eclipsed (Figs 4 and 5).

There is no obvious part of the binary system moving with the observed velocity, but a possible other interpretation may be 'slingshot prominences', material trapped in magnetic loops and co-rotating with the secondary star (similar to the prominences observed from single, rotating dwarf stars (Collier Cameron 1991)).

Figure 9. Hα (left) and He I (λ6678) observations of SS Cyg. Top: the observed data in the form of trailed spectrograms. The middle panels show calculated Doppler maps; the predicted data are in the bottom panels. The line flux was normalized to the continuum, to remove fluctuations due to slit losses.
7 SLINGSHOT PROMINENCES

Prominences are observed in numerous rotating stars (including the Sun). Secondary stars in close binaries are tidally locked and therefore effectively have a rotation period equal to the binary period, of the order of several hours. Prominences are formed by active magnetic regions on the surface of stars. The centrifugal force acting on material (due to stellar rotation) in this area then pulls magnetic fieldlines (loops) from this region outwards, reaching a stable point where the inward centrifugal force (hence the name slingshot prominences) and therefore effectively have a rotation period equal to the centrifugal force acting on material (due to stellar rotation). In a binary system the Roche potential is a bit more complicated than for single stars, but similar regions exist where extended magnetic loops would be stable. The region between the L1 point and the white dwarf is obviously one of them. A magnetic structure extending past the Roche lobe (due to an active spot on the secondary) is pulled towards the white dwarf (by definition), causing the loop to expand. Plasma is flowing along the fieldlines to the top of the loop, where it can collect and is confined by the magnetic tension of the loop. This dense clump of gas, illuminated by the disc and the face of the secondary star, results in an emission source co-rotating with, but well separated from, the secondary star. This might well explain the stationary emission that we see. Although prominences can in principle appear anywhere on the surface of the secondary, the binary potential provides a special geometry near the inner face of the star, where matter is loosely bound and the effective potential decreases as one goes closer to the white dwarf.
The magnetic field needed to support this kind of material is fairly low. As suggested by stellar work on prominences (Collier Cameron et al. 1990; Collier Cameron & Woods 1992), we assume that H and He ionization is mainly triggered by radiation (rather than collisions) and that the region we consider is optically thick to the ionizing radiation. We also assume that radiative recombination dominates and that excitation obeys local thermodynamic equilibrium. Populations are then given by the Saha–Boltzmann equations. If we further assume that the Balmer and He lines we observe are optically thin (the Balmer decrement we observe), line fluxes become proportional to populations. The emission coefficients ($K$) are taken from Osterbrock's tables (recombination case B, Osterbrock 1989), and depend on the gas temperature and on the line atomic parameters. Physically speaking, $K$ is the emitted energy per second in the specific emission line, per unit volume, per unit electron density, per unit ion density, integrated over $4\pi$ steradians (erg cm$^{-3}$ s$^{-1}$).

If we assume a roughly spherical clump of gas with size $l$ at a distance $d$ we can write:

$$4\pi d^2 J_{\text{obs}} = K N_e N_i \frac{4}{3} \pi l^3$$

(2)

or

$$N_e N_i = \frac{3 J_{\text{obs}} d^2}{K l^3}$$

(3)

with $J_{\text{obs}}$ the observed line flux. From the spectra we obtain an estimate for the flux of the central component using the line profiles (e.g. Fig. 4). The unknown parameter is the source size, characterized by $l$. In order to get an order of magnitude estimate we can use the velocity width ($\Delta V \sim 150 \text{ km s}^{-1}$) of the emission source in the tomograms to get an upper limit to its size. If we assume that the prominence is co-rotating with the secondary star we can write:

$$\frac{\Delta V}{K_1 + K_2} = \frac{l}{d}.$$  

(4)

This gives an upper limit for $l \sim 10^{10}$–$10^{11}$ cm. On the other hand, spectral resolution, thermal broadening and saturation broaden all increase the apparent velocity dispersion, and thus lead to an overestimate of $l$. Furthermore the volume filling factor might be much smaller than unity (like solar prominences). Therefore we will use $l \sim 10^{10}$ cm as a reasonable estimate.

We have flux information for three lines on these prominences: Hx only, in the case of IP Peg, and Hx and He II in the case of SS Cyg. We can now calculate the density at a certain temperature by using the corresponding $K$-values, and use Saha–Boltzmann to calculate the ionization fractions. In particular, the He II flux provides crucial information on temperature since He is mostly in the He II state between 15000 and 25000 K only. The best fit between the different densities was achieved at 17500–20000 K: the numbers below will therefore be evaluated using a prominence temperature of 20000 K.

For the Hx emission in SS Cyg, we have a source flux density of $\sim 250$ mJy, and a width of $\sim 150 \text{ km s}^{-1}$. We have $N_e=N_i$ so:

$$N_e^2 = \frac{3 J_{\text{obs}} d^2}{K l^3}.$$  

(5)

Again taking $l \sim 10^{10}$ cm and a distance of 75 pc we obtain, using equation (5), $N \sim 7.0 \times 10^{11}$ (1/10$^{10}$)$^{-1/3}$ cm$^{-3}$. In order to calculate a similar density estimate from the Hx II observations of SS Cyg, we need to assume a certain He abundance and ionization fraction. We have $K_{\text{He II}} = 4\pi j_{\text{He II}}/N_e N_{\text{He}} = 7.21 \times 10^{-22}$ erg cm$^{-3}$ s$^{-1}$. We assume a helium abundance of 0.08 and full ionization (Saha equation at $2 \times 10^4$ K). The stationary flux is again estimated using the line profiles, the flux density being roughly 160 mJy. We now find $N \sim 1.0 \times 10^{12}$ (1/10$^{10}$)$^{-1/3}$ cm$^{-3}$.

We saw before that, for the Hx feature in IP Peg, the estimated flux density was 45 mJy. The width of the component is $\sim 150 \text{ km s}^{-1}$ resulting in a line flux of $1.0 \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$. Taking a distance of 150 pc (Marsh 1988), a source size of $10^{10}$ cm and the value for $K_{\text{H}} = 4\pi j_{\text{H}}/N_e^2 = 1.82 \times 10^{-25}$ erg cm$^{-3}$ s$^{-1}$ at $2 \times 10^4$ K, we find $N \sim 6.0 \times 10^{11}$ (1/10$^{10}$)$^{-1/3}$ cm$^{-3}$. The fact that the densities match up reasonably well, considering the uncertainties in the flux from the components, suggests that case B recombination is indeed a reasonable assumption for the origin of the observed emission.

In order for the magnetic field to hold the material in the top of the loop, the tension of the loop has to exceed the local effective gravity acting on the gas:

$$\frac{B^2}{4\pi R_c} \geq \rho g_{\text{eff}}$$

(6)

where $\rho$ is the mass density (g cm$^{-3}$), $g_{\text{eff}}$ the effective gravity in the Roche potential, $B$ the magnitude of the field at the top of the loop (G) and $R_c$ the radius of curvature of the loop. For $g_{\text{eff}}$ we can write:

$$g_{\text{eff}} = \frac{-GM_1}{(r-r_1)^2} - \frac{GM_2}{(r-r_2)^2} - \omega^2 r$$

(7)

representing the gravitational and centrifugal forces present in binary systems. Here $\omega$ is the angular velocity of the binary, and $r$ is the distance from the centre of mass. Using the calculated (number) density above, and assuming a position near the centre of mass, we can calculate a lower limit for the magnetic field in order to confine that density.

Using the system parameters as in Table 2, we find $B \approx 320 (R_c/R_\odot)^{1/2}$ G at the top of the loop for IP Peg and $B \sim 250 (R_c/R_\odot)^{2}$ G for SS Cyg.

If we assume a dipolar field structure ($B \propto R^{-3}$), a prominence altitude of $1.5 R_\odot$ (from the Doppler maps) and a loop curvature radius of $R_\odot$, such magnetic strengths translate to kG fields at the surface of the secondary star.

We find for this gas physical parameters in good agreement with what is found in stellar prominences. However in our case the temperature of the material is higher ($2 \times 10^4$ rather than $8 \times 10^4$ K), since the prominence is illuminated by the hot accretion disc rather than a cool star. The fact that we only see a prominence near the disc might be a selection effect due to this effect; only these prominences are sufficiently illuminated and therefore detectable.

An interesting possibility is that, as material is flowing to the top of the loop and is collected there, there comes a point where the total mass can no longer be confined by the tension of the loop (i.e. inequality (6) is violated), forcing it to open up and release the stored material in the white dwarf potential. The total mass in the prominences we observe ($10^{12} \sim 10^{18}$ g) is smaller than the total mass transfer for a typical outburst, however ($\sim 10^{20}$ g).

Our current observations are limited in dealing with any
time-dependent process; this would require extensive monitoring of the Balmer emission in these systems.

A very detailed modelling of the physics and properties of prominences in binary systems is beyond the scope of this paper. Using the Doppler maps and eclipse information, we can say that the emission source must be close to the axis through the centre of mass, perpendicular to the orbital plane, since its observed orbital motion is so small. Furthermore the eclipse tells us that a significant part of this emission is eclipsed, requiring a fairly compact source, but, since there is still considerable flux at mid-eclipse, its position must be above or below the orbital plane (for at least part of the source). It is difficult to store material at these positions without an extra force to hold it there, in our case the magnetic tension of the loop.

8 SUMMARY

New observations of two dwarf novae in outburst reveal unexpected stationary components in several emission lines. Apart from the expected emission from the accretion disc and secondary star, we observed low-velocity material in the two systems. In a rotating binary system it is difficult to think of a natural area where one can produce this stationary emission.

We propose magnetic loops as a possible mechanism of producing emission with such a very low velocity. Although the slingshot prominence model is not strictly favoured by the observations, it is an interesting possibility especially since single dwarf stars with short rotation periods (~hours, similar to CV binary periods) are known to have active structures like large prominences. The emission that we see is compatible with this sort of emission source, and might be a quite general feature in dwarf novae. Unfortunately, the fact that we see prominences with no orbital motion does not have an obvious reason. In principle one expects prominences to form at numerous positions, including areas removed from the centre of mass. Are large prominences always present, but just lit up during the outburst, or could they somehow be a cause or effect of the outburst? More observations of the Hα and Balmer lines of CVs in their different states are necessary to investigate this emission further.

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