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ASTRONOMY AND ASTROPHYSICS

Spirals in the disk of EX Dra

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Abstract. Observations at high spectral and temporal resolution are presented of the dwarf nova EX Dra in outburst. The Doppler maps are very similar to those of IP Peg in outburst as observed by Steeghs et al. (1997) and are interpreted as evidence for the presence of spiral shocks. The eclipse as seen in the red continuum indicates a disk radius of 0.31 times the orbital separation. The eclipse in the Balmer line profiles, well resolved in our observations, indicates a somewhat smaller disk size (0.25).

Key words: accretion disks – hydrodynamics – Cataclysmic Variables – stars: EX Dra

1. Introduction

Spiral shocks in accretion disks have been predicted from numerical simulations (Sawada et al. 1986, 1987, Różyczka & Spruit 1993, Yukawa et al. 1997), and analytic considerations (Spruit 1987, Spruit et al. 1987, Larson 1990). They are excited by the tidal field of the secondary if the disk extends far enough into the Roche lobe and can result in two prominent spiral arms. If shock dissipation is the main mechanism damping the wave, it extends over the entire disk and causes accretion at an effective α-value of $0.01(H/r)^{3/2}$ (Spruit 1987, Larson 1990, Godon 1997).

The first observational evidence for shock waves in accretion disks of cataclysmic variables (CVs) was the detection of a clear two–armed structure in the disk of IP Peg during rise to outburst (Steeghs et al. 1997). The spiral pattern, visible in a Doppler map (Marsh & Horne, 1988), is interpreted as emission from spiral waves. The pattern has also been seen in IP Peg, in He II, during outburst maximum (Harlaftis et al. 1999).

At the temperatures expected from dwarf nova disks models, whether in outburst or in quiescence, the predicted spirals are tightly wound and would be hard to detect observationally (Bunk et al. 1990), so that their presence in the observations is somewhat unexpected. Spirals this strong are most naturally explained if the disk temporarily extends rather far into the primary Roche lobe, so that the tidal force of the secondary causes a strong disturbance. A strong non-axisymmetric disturbance, however, would also cause the gas to loose angular momentum quickly (transfered to the secondary), so that the disk would shrink to a smaller radius where the tidal force is weaker. Spirals in disks of CVs would then be understandable if they are a temporary phenomenon, perhaps restricted to outbursts. To test this, more observations of different systems at sufficient spectral resolution and signal-to-noise are needed (Steeghs & Stehle 1999).

With high quality spectroscopic studies of different CVs it should also be possible to answer the question if spiral shocks in CV accretion disks are a common phenomenon. Systems suitable for this purpose would be bright and have frequent outbursts, such as SS Cyg and EX Dra.

EX Dra is a double–eclipsing dwarf nova with a 5-hour orbit (Barwig et al. 1993, Billington et al. 1996, system parameters by Fiedler et al. 1997). There is suggestive evidence for asymmetric structures in the He I Doppler map reconstructed from outburst data taken in 1993 (Joergens et al. 2000). From eclipse maps obtained at various stages in the outburst cycle Baptista & Catalan (1999) conclude that spiral waves form at the early stages of an outburst. We report in this paper on observations at high spectral and temporal resolution during an outburst in 1996.

2. Observations and reduction

EX Dra was observed on the nights of July 27 and 28 1996, with the ISIS spectrograph on the 4.2 m William Herschel Telescope. The red ISIS arm was equipped with the TEK 5 CCD, the blue arm with TEK 1 CCD, covering the wavelength ranges 6375-6778 Å and 4585-4993 Å respectively, at a dispersion of 0.4 Å/pixel. The spectra were observed during seeing of 1.4 – 1.7 arc sec, using an exposure time of 60s, corresponding to 0.3% of the binary orbit. The spectra were optimally-extracted, including the elimination of cosmic ray hits but not the correction of Pixel-to-pixel variations of the detector sensitivity. Slit losses due to variable atmospheric conditions were corrected using a faint comparison star on the slit. The red spectra, but not the blue spectra, were flux calibrated.

Our spectra were taken roughly in the middle of an outburst. Photometric observation at the Wendelstein observatory showed that the system was already in outburst on 26 July, and in quiescence on 4 August (Barwig, private comm.). VSNET (1998) records show that the system was in quiescence on 24 July and in outburst one day later and in quiescence again on 1 August. The outburst therefore started on 25 August, three days before our observations.

3. Interpretation of the Doppler maps

Doppler maps were computed from the phase-folded spectra of 28 July, using the IDL-based fast-maximum entropy package described by Spruit (1998)[1]. For further details on Doppler tomography see Marsh & Horne (1988).

Fig. 1 shows the results for the four strongest lines in the spectra, H_α, H_β, He I λ6678 and He II λ4686. The phase–folded spectra are shown in the left column, the corresponding Doppler maps in the right column and in the middle the spectra reconstructed from the maps. The theoretical trajectory of the mass transfering stream has been plotted in the He II image, together with the Keplerian velocity along the stream path (see Marsh & Horne (1988) for details). Bars connecting the two arcs indicate correspondence in physical space, and are annotated with radius r/a and the azimuth Φ relative to the primary. The system parameters ($K_1 = 167\,\mathrm{km\,s^{-1}}$, $K_2 = 223\,\mathrm{km\,s^{-1}}$, $M_1 = 0.75, q = 0.75, i = 84.2$) and the ephemeris are from Fiedler et al. (1997).

The He I image shows the spirals clearest: asymmetric disk emission is concentrated in two arms in the first and third quadrant. We interpret this deviation from a Keplerian disk as indication of the presence of spiral shock waves in the accretion disk. The image looks quite similar to the He I map of IP Peg published by Steeghs et al. (1997). As in the case of IP Peg, the arms do not follow a circle centered on the white dwarf, but are somewhat elongated along the V_y-axis. This is the pattern expected from spiral shocks (Steeghs & Stehle 1999). The asymmetry of the spirals in the EX Dra disk is smaller than in the IP Peg observation of Steeghs et al. (1997), perhaps indicating that the shocks are somewhat weaker. The spiral arm in the upper right is stronger in intensity as well as in asymmetry than that one in the lower left. This pattern is also seen in the He I and H_α maps (Steeghs et al. 1997) and the He II map (Harlaftis et al. 1999) of IP Peg. As in the case of IP Peg, the Balmer lines show similar, but less clearly defined structures.

The Doppler images, with the exception of He II, show strong emission from the secondary star, also visible during the outburst of the system in 1993 (Joergens et al. 2000). This indicates heating of the secondary by radiation from the inner disk. The temperatures are obviously not high enough to excite the He II line. The He II line also differs from the other lines by the presence of a prominent emission patch near the expected hot spot location. As the trajectories plotted in the image show, however, there is a significant offset from the hot spot location seen in Doppler maps of systems in quiescence.

4. The disk radius

The large width of the He II line is as expected for a high excitation line produced near the center of a disk in outburst. The eclipse of the He II line is visible in the spectrum up to a velocity of about 1500 km/s. The orbital velocity at the disk edge is about 4.3 times lower than this. Assuming Keplerian rotation, the disk region eclipsed at 1500 km/s is about 20 times smaller in radius than the outer radius of the disk. At our phase resolution, the 1500 km/s emission is thus point-like, and can be used to measure the width of the secondary's shadow on the orbital plane, $\Delta\phi = 0.08 \pm 0.005$. From the position of the hot spot in the He II map, we can estimate a disk size of $r/a = 0.32 \pm 0.04$.

The eclipse of the Balmer and He I lines shows that the blue disk emission reappears (at V$\approx$ 350km/s) at the same phase as the last red emission disappears, within the measurement uncertainty. The size of the disk as seen in these lines is thus, by a coincidence, nearly as wide as the occulting shadow of the secondary. Hence the disk radius as seen in the Balmer lines is $r_{\mathrm{dB}}/a \approx 2\pi\Delta\phi/2 = 0.25 \pm 0.02$.

We can compare this with the disk size as measured from the eclipse in the continuum. The light curve in the continuum between 6400 and 6500Å, extracted from our spectra, is shown in Fig. 2. The width of the eclipse is $w = 0.17 \pm 0.005$ orbits. With $\Delta\phi = 0.08$, this implies a disk radius $r_{\mathrm{d}}/a = 0.31 \pm 0.01$.

Fiedler et al. (1997) find a value of 0.11 for the eclipse width of the white dwarf, from analysis of a mean blue light curve in quiescence. The disk as seen in the continuum thus appears to be larger in outburst than in continuum, as expected. The eclipse width values of 0.17 in outburst and 0.11 in quiescence are also compatible with the eclipse light curves of Baptista & Catalan (1999). These authors measured the eclipses of EX Dra at various stages in the outburst cycle.

5. Discussion and conclusions

We find evidence for spiral structures in the outburst accretion disk of EX Dra similar to those found in IP Peg by Steeghs et al. (1997). The pattern of intensity and velocity perturbations agrees with that predicted from numerical

[1] available at http:www.mpa-garching.mpg.de/~henk

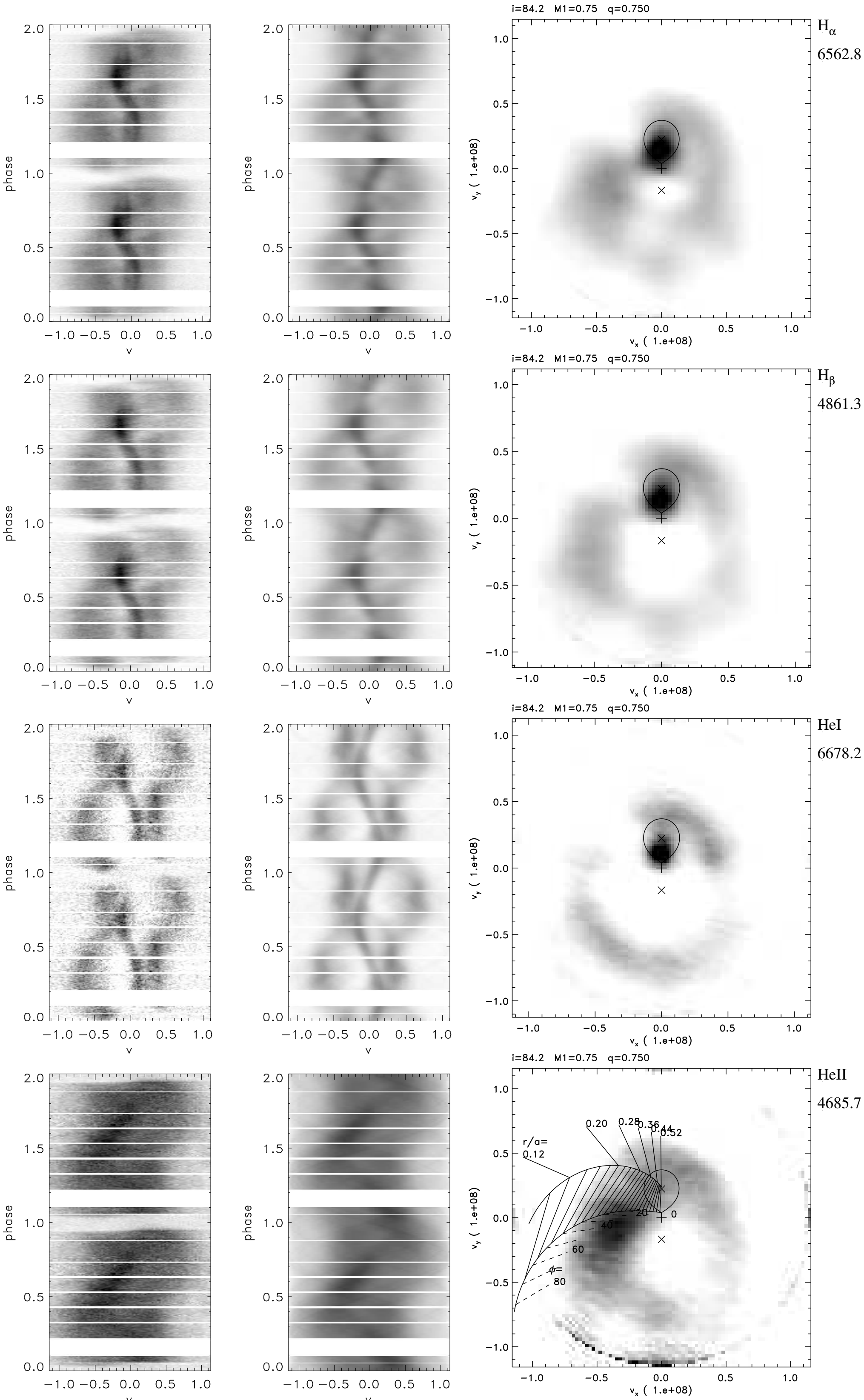

Fig. 1. Phase-folded spectra of EX Dra in outburst on 28 July 1996 (left column), corresponding Doppler maps (right column), and the spectra reconstructed from the maps (middle). Top to bottom: H_α, H_β, He I, He II. The mass transferring stream (see text) and Doppler image of the Roche lobe of the secondary star are over plotted on the He II image. Upper and lower intensity cuts of the Doppler maps have been adjusted such that the disk emission has roughly the same contrast in each image.

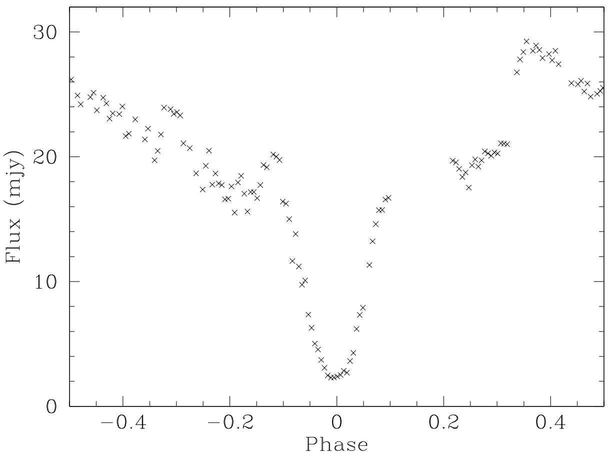

Fig. 2. Spectrophotometric light curve of the wavelength range 6400–6500Å.

simulations of spiral shock waves (Steeghs & Stehle 1999). It is best seen in the He I line, somewhat less clearly in the Balmer and He II lines. In EX Dra the pattern appears somewhat less clearly than in IP Peg, and is somehwat less asymmetric. In particular, it is less clear in the He II line, suggesting lower temperatures and shock strengths of the spirals of EX Dra.

We derive a disk radius of $r/a = 0.31 \pm 0.01$ from the red continuum eclipse light curve. From numerical simulations, Steeghs & Stehle find that disk sizes $r_{\rm d}/a = 0.3-0.4$ are needed to excite spirals that are strong enough to generate an observable pattern in the spectra. Since the tidal force is a very steep function of r/a, the spirals rapidly become weak at smaller disk sizes. The detected disk size of EX Dra is at the lower limit of the required size.

Further evidence for the size of the disk in EX Dra in outburst was obtained by Baptista & Catalan (1999). The radial intensity distributions presented there show that the disk radius varies between $0.56\,R_{L_1}$ in quiescence and $0.93\,R_{L_1}$ in outburst. The authors see hints of spirals in their eclipse maps, during the early outburst stages. This may be compared with the present observations, which show spirals and a disk size of $0.6\,{\rm R}_{L1}$ 3 days after the beginning of an outburst.

The eclipses of the Balmer lines in our spectra yield significantly *smaller* disks sizes than the continuum eclipse, $r_{\rm dB}/a = 0.25 \pm 0.02$. Since it is known that the line emission is produced primarily in the outer parts of the disk (e.g. Rutten et al. 1994), one might have expected the disk as seen in the lines to be larger, if anything, than in the continuum. A possible resolution of this conflict may lie in the optical depth effects affecting the emission lines in systems seen at high inclination. As shown by Horne & Marsh (1986), the low central intensity of the Balmer lines in dwarf nova disks at high orbital inclination are the result of self-absorption in the lines. The self-absorption is strong along lines of sight perpendicular and tangential to the orbits of the gas, where the velocity gradient is small. The effect is weakest along lines of sight at intermediate angles to the orbit, where the gradient of the orbital velocity (projected along the line of sight) is largest. At the very high inclination of EX Dra, the effect could be strong. The outer parts of the disk that determine the eclipse width are seen with the line of sight nearly parallel to the orbital motion. We may expect the emission in these regions to be weakened by self-absorption, thus mimicking a somewhat smaller disk. A more detailed comparison of the Horne & Marsh (1986) optical depth effect with observations is needed to establish if this explanation is quantitatively adequate.

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