The 1996 dwarf nova outburst of the intermediate polar
GK Persei

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Abstract. GK Persei is an intermediate polar that exhibits a dwarf nova outburst approximately every 1000 days. During previous outbursts the system has displayed kilo-second quasi-periodic oscillations (QPOs) in X-ray emission. These oscillations are unique in that they are an order of magnitude longer than QPOs usually observed in disc-fed cataclysmic variables. We have detected the optical counterpart of these QPOs in spectrophotometry collected during the 1996 outburst. The presence of these QPOs in Doppler-broadened emission lines originating from the highly-supersonic accretion flow enables us to place useful constraints on the location of the QPO source and its formation mechanism.

1. Introduction

GK Per is an intermediate polar – a cataclysmic variable, where the magnetic field of the white dwarf is strong enough to truncate the inner accretion disc if such a disc is at all present. Material accreting through the disc is threaded onto the field lines, forced out of the orbital plane along the accretion curtains and deposited directly onto the magnetic poles of the white dwarf. This system is highly variable over several timescales – the orbital period of the binary – 2-d (Crampton, Cowley & Fisher 1986), and the spin period of the white dwarf and accreting curtains – 351-s (Ishida et al. 1992). In addition, the outburst cycle is caused by thermal instabilities within the accretion disc, occurring over a $\sim 1000$-d timescale, and variability intermediate between orbit and spin is provided by the Keplerian frequencies of gas in the disc.

We observed GK Per in February 1996 (Morales-Rueda, Still & Roche 1996) during one of its outburst states. A frequency search across the strong emission lines of H\textbeta and He\textit{II} revealed signal at the spin frequency and 5-6 cycles/d window aliases (Fig. 1). However, the strongest signal occurs at $\sim 5000$-s – the optical counterpart of the X-ray QPOs observed in a previous outburst by Watson, King & Osborne (1985).

Watson et al. (1985) suggested that the X-ray QPOs were the consequence of modulated mass transfer through the magnetically-threaded accretion curtain – where 5000-s is the beat between the spin frequency and the Keplerian frequency of dense blobs of gas orbiting close to the inner rim of the disc.

Hellier & Livio (1994) proposed an alternative mechanism, where the accretion stream from the companion star does not dissipate in a shock at the outer
disc edge, as is usually assumed. Instead it overflows the upper and lower disc surfaces and deposits blobs at its point of closest approach to the white dwarf where it finally crashes into the disc (Lubow & Shu 1975; Armitage & Livio 1996). Blobs have higher vertical structure and larger column densities than the surrounding disc, and will have a Keplerian frequency of \( \sim 5000 \text{-s} \). The X-rays emitted by shock-heated material from where the curtains impact the white dwarf poles illuminate the disc and the blobs. Consequently, obscuration of the central X-ray source by the vertically-extended blobs provides the X-ray QPOs, whilst, if we adopt this scenario, X-ray reprocessing off the blobs provides the optical counterparts to these oscillations. This model also explains the X-ray hardness ratio measured from the data collected by Watson et al. (1985) which is consistent with the photo-electric absorption of soft X-rays by cool intervening gas.

However, Fig. 1 shows that the optical QPOs are not symmetrically distributed across the emission profiles. The blue wings of the lines provide more power than the red wings at the QPO frequency. This asymmetry is also obvious in the line profiles when binned into the QPO period (see Fig. 2 of Morales et al. 1996), and is independent of the orbital phase as seen in the trails presented in Morales-Rueda, Still & Roche (1998). We find this observation impossible to explain in terms of the accretion stream overflow model.

2. A beat model incorporating shear line broadening

Consider a dense blob of gas close to the inner edge of the accretion disc and orbiting at a Keplerian frequency which will be close to the co-rotation radius of the magnetic curtain. On the order of every few thousand seconds the base of the magnetic curtains will sweep over the blob, increasing the density of material passing through the threading regions and providing a cool absorbing body for the X-ray QPOs. We expect to see modulation in the line intensity on the beat period between the 351-s white dwarf spin and the orbital frequency of the inner accretion disc.

Now consider the schematic of GK Per provided in Fig. 2. For this figure, we take the orbital inclination to be consistent with \( 46^\circ < i < 72^\circ \) (Reinsch 1994). We have assumed that the magnetic axis of the white dwarf is misaligned with the rotational axis of the system by \( 45^\circ \), although its true inclination is unknown.

In Morales-Rueda et al (1998) we see that, similar to the X-ray QPOs, this optical counterpart in the emission lines is the result of absorption. There are at least two possible mechanisms which can modulate the line emission by absorption over the beat cycle. First consider the observed absorption to be of line flux from the accretion curtain. At the point in the spin cycle we label \( \phi_{\text{spin}} = 0 \), the velocity gradient across the emitting surface behind the white dwarf attains a maximum and the region is blue-shifted in the rest frame. The surface in front of the accretor is redshifted and has the same velocity gradient, but is obscured from Earth by the inner edge of the accretion disc. Half a spin cycle later, at \( \phi_{\text{spin}} = 0.5 \), both surfaces are equally visible but their velocity gradients are at a minimum. Horne & Marsh (1986) have shown that in the saturated case the strength of the absorption of a line element increases \( \sim \) linearly with the
Figure 1.  Power spectra as a function of line velocity in the Doppler-broadened emission profiles of Hβ and He II λ4686 Å, where negative and positive velocities represent the blue and red wings of the line respectively. We see power at the spin frequency of the white dwarf (246 c/d), and low-frequency observational aliases (5-6 c/d). However the power spectra are dominated by QPO signal at ~18 c/d, where we see a blue–red asymmetry in the peak.
velocity gradient across the line source. The effects of shear broadening require maximum absorption to occur when the upper accretion curtain and the blob are aligned behind the white dwarf – consistent with observing the majority of QPO power in the blue wings of the emission lines. A QPO period of 5000-s suggests that blobs are orbiting the white dwarf with a period of 380-s or 320-s. Power at 380-s has been detected previously in optical photometry (Patterson 1981).

A second mechanism could be that the absorption is of continuum light from the accretion disc behind the white dwarf. Continuum absorption by the upper accretion curtain will occur when it is behind the white dwarf i.e. once per spin cycle. At other spin phases this curtain has no back-illuminating source. The lower curtain has no back-illuminating source at any time during the spin cycle. This provides a natural blue asymmetry in the emission line signal.

The beat mechanism explains the long-timescale QPOs from GK Per using pre-existing models of QPO generation. The driving mechanism has a timescale of a few hundred seconds in agreement with the QPOs observed in other dwarf novae. In the above discussion we have considered the QPO in terms of a blob orbiting in the inner accretion disc but the alternative models of radially-oscillating acoustic waves in the disc work equally well (Okuda et. al 1992).

3. Conclusions

The detection of kilo-sec QPOs across the optical emission line profiles of GK Per have provided the opportunity to test the mechanism behind the unique long-timescale QPOs in this object, which are an order of magnitude longer than QPOs normally observed in disc-accreting cataclysmic variables. We have rejected the model of Hellier & Livio (1994) considering the direct effects of blobs orbiting at the Keplerian frequency of the annulus associated with a disc-overflow impact site. Our favoured model considers the long QPO period to be the consequence of beating between “usual” timescale QPOs at ∼ 300 s with the magnetic accretion curtain spinning with the white dwarf. As a result of this, we do not require a new model to explain these long timescales: the curiously-long oscillations are merely a consequence of the magnetic nature of the binary.

Acknowledgments. We thank Tom Marsh for making his reduction software available, and the Nuffield Foundation for a grant to PR in order to facilitate this collaborative work. The reduction and analysis of the data were carried out on the Sussex node of the STARLINK network. Ths Isaac Newton Telescope is operated on the island of La Palma by the Isaac Newton Group in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofisica de Canarias.

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Figure 2. Schematics of the accretion flow in the intermediate polar GK Per. The position of the observer corresponds to orbital phase zero. The two diagrams are slices through a vertical plane across the binary line of centres, separated in time by half a spin cycle.
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