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DISK-OVERFLOW ACCRETION IN GK PERSEI?

COEL HELLIER[1]
Department of Astronomy, University of Texas, Austin, TX 78712

AND

MARIO LIVIO[2]
Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218; and
Department of Physics, Technion, Haifa, Israel
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ABSTRACT

We reanalyze the 1983 *EXOSAT* observations of GK Per during an outburst to investigate the ~5000 s quasiperiodic modulation. We find that the spectral behavior is reminiscent of dipping low-mass X-ray binaries and note that the time scale is characteristic of the radius where an accretion stream overflowing the disk would collide back onto the disk. We suggest that structure caused by such disk-overflow accretion was periodically obscuring the white dwarf, producing the modulation.

Subject headings: accretion, accretion disks — binaries: close — novae, cataclysmic variables — stars: individual (GK Persei) — X-rays: stars

1. INTRODUCTION

In the classical picture of accretion in close binaries such as cataclysmic variables (CVs) and low-mass X-ray binaries (LMXBs), the accretion stream from the low-mass companion is stopped by a collision with the outer edge of an accretion disk around the compact star. However, as pointed out by Lubow & Shu (1976) and Lubow (1989), part of the accretion stream might flow over the disk, where it would continue on an essentially ballistic trajectory, until plunging back into the disk near the radius of closest approach to the compact star. Several observational phenomena might be explained by this effect (e.g., Livio 1993). For example, Frank, King, & Lasota (1987) proposed that the disk structure responsible for the dips in high-inclination LMXBs is caused by the overflowing stream. Also, the anomalous phase shifts seen in the emission lines of SW Sex stars (Thorstensen et al. 1991) and the high-velocity S-wave features seen in EX Hya (Hellier et al. 1989) and V795 Her (Haswell et al. 1993) might be explained by the stream penetrating far beyond the edge of the disk. Furthermore, Hellier (1991, 1993) proposed that in the magnetic intermediate polars, the presence of X-ray pulsations at both the white dwarf spin period and the beat period in some systems could be explained by disk-overflow, with the overflowing stream coupling directly to the magnetosphere of the white dwarf.

GK Per has the longest orbital period among the CVs (2 days) and has long dwarf nova–like outbursts. During such an outburst, Watson, King, & Osborne (1985) detected a large-amplitude, quasi-periodic modulation of the X-ray light curves with a timescale of ~5000 s.

Although clearly important to the accretion process, this modulation has not been satisfactorily explained so far. In this work, we reanalyze the data set and present evidence that the modulation represents a further manifestation of disk-overflow accretion.

2. THE *EXOSAT* OBSERVATIONS

EXOSAT made observations of GK Per on 1983 August 9, 15, and 24, during the peak of an outburst. Watson et al. (1985) described the ME experiment data in detail, concentrating on the coherent 351 s pulsation caused by the spinning white dwarf. Both the spin pulse and a slower, incoherent modulation are obvious in their Figure 2. In Figure 1 we present the same data (1.5–8.5 keV) binned at a resolution of 350 s to remove the spin pulse. We also show the ratio of the count rates in the bands 4.5–8.5 and 1.5–4.5 keV, to provide a crude measure of the spectral changes. A Fourier transform of the three observations combined (Fig. 2) shows excess power in the period range 2000–7000 s. Fourier transforms of the individual observations confirm that the modulation is not coherent and has a timescale wandering within this range.

In most of the data, *the hardness ratio is anticorrelated with the intensity*. This is seen directly in Figure 1, and also in Figure 3 where we have plotted the hardness ratio against the count rate for each 350 s bin. The first observation does not show the anticorrelation, although if the hardness ratio is shifted forward by ~17 minutes, the effect is restored, as confirmed by a cross-correlation analysis (Fig. 4). However, there is too little data in the first observation to be confident that this represents a real effect and is not simply due to chance.

3. THE ORIGIN OF THE QUASI-PERIODIC OSCILLATION

We first remark that the 2000–7000 s QPO timescale is an order of magnitude shorter than the 2 day orbital period, and an order of magnitude longer than the 351 s spin period of the white dwarf. Also, the Keplerian orbital period near the magnetosphere cannot be much longer than the spin period, otherwise accretion could not occur.

3.1. *Modulation of the Accretion Rate?*

Watson et al. (1985) proposed that the modulation was caused by a variation in the rate of accretion of material onto the white dwarf, originating where the magnetic field couples

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[1] Hubble Fellow; E-mail: ch@astro.as.utexas.edu.

[2] E-mail: mlivio@stsci.edu.

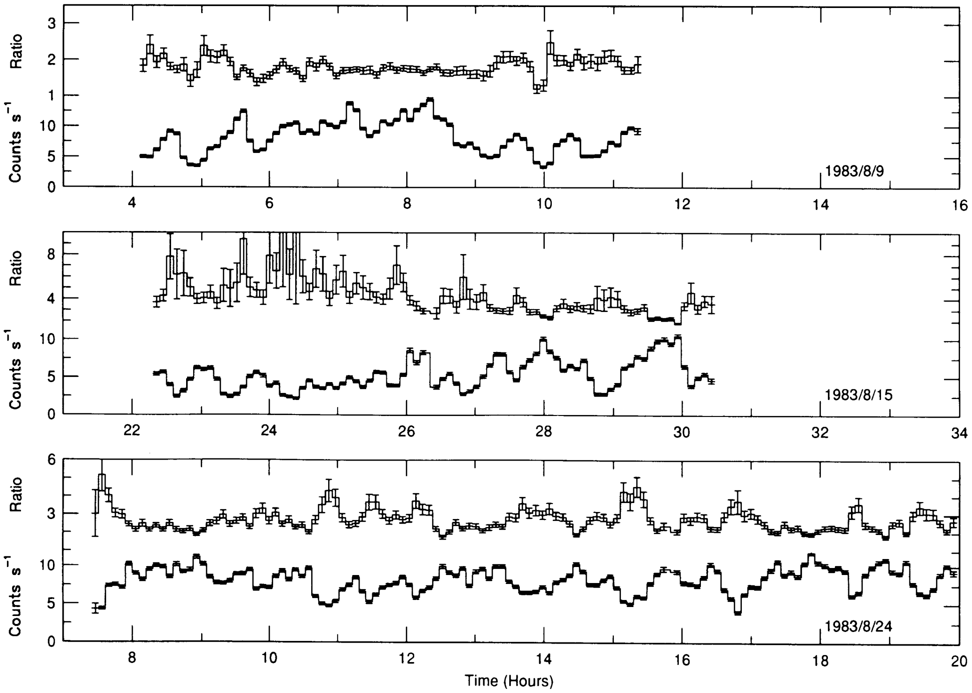

FIG. 1.—The *EXOSAT* data of GK Per during outburst. In each panel the lower curve is the 1.5–8.5 keV count rate, binned at 350 s to remove the spin pulse and reveal the slower QPO. The upper curve is the 4.5–8.5/1.5–4.5 keV hardness ratio.

to the accreting material. For example, a bulge or some other asymmetry in the azimuthal spread of material just outside the magnetosphere would in this scenario modulate the accretion flow onto the white dwarf. Since the accretion geometry would repeat with the beat cycle between the magnetospheric spin frequency and the circular motion of the bulge, a modulation at the observed QPO timescale would be obtained given a Keplerian velocity at the magnetosphere of either ~325 or ~375 s. This idea is similar to one of the proposed explanations for the >1 Hz QPOs seen in some LMXBs (e.g., Stella 1988). However, it should be noted that in addition to the difference in periods, the QPO of GK Per has a much larger amplitude, with intensity variations of a factor 3, compared to typical QPO strengths of less than 10% in the LMXBs. Such large variations would have to reflect a similar (factor of 3) asymmetry in the azimuthal distribution of the orbiting material, which we regard as unlikely. We therefore explore below an alternative explanation for the QPO, which retains steady accretion from a disk as one of its basic features.

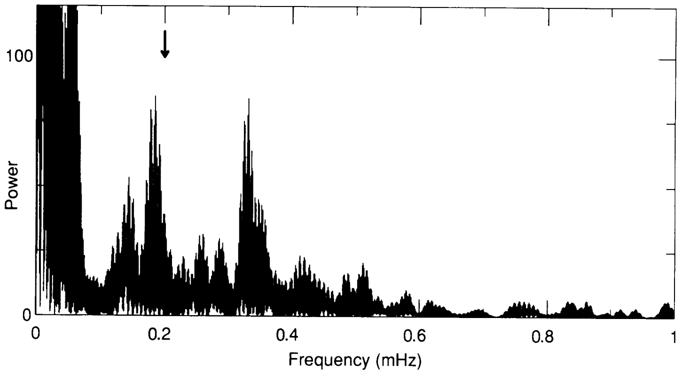

FIG. 2.—The Fourier transform of the entire data set in Fig. 1 (although with 10 s binning). The QPO produces power between 0.1 and 0.5 mHz—analysis of subsets of the data show that the period is not stable or coherent. The arrow marks the Keplerian frequency at the point where an overflowing stream collides onto the disk.

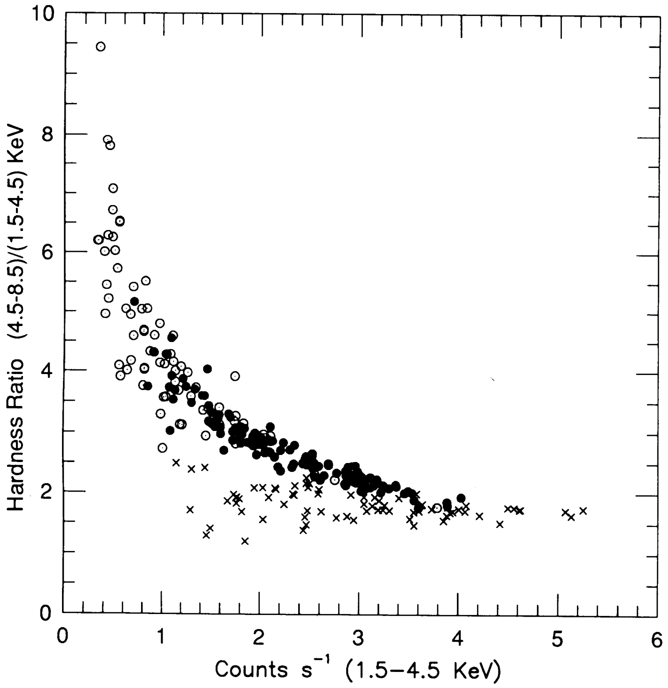

FIG. 3.—The hardness ratio plotted against the count rate, showing an anticorrelation in the second and third observations (*filled and open circles*), although not in the first (*crosses*).

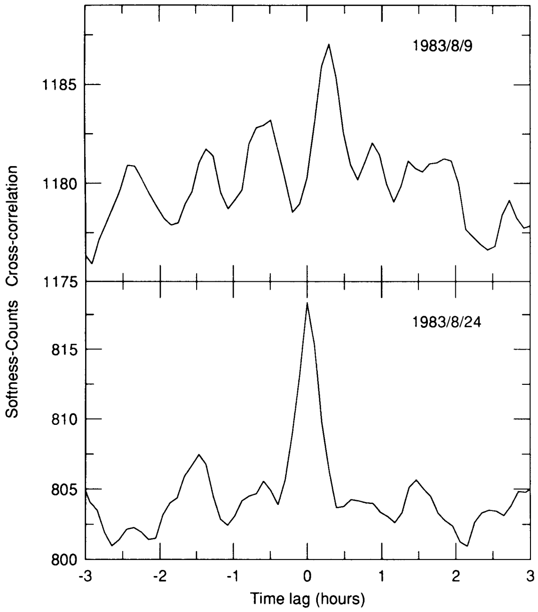

FIG. 4.—A cross-correlation of the softness (reciprocal hardness) against count rate, showing an apparent time lag in the first observation (*upper panel*), in contrast to the third observation (*lower panel*).

3.2. "*Dipping*" *Structure in the Inner Disk*?

The spectral behavior of the modulation, increasing hardness as the intensity drops (Fig. 3), is typical of the "dipping" LMXBs (e.g., Mason 1989). In the case of the LMXBs, instead of arising from a variation in the accretion rate onto the compact star, this is due to obscuration of the central X-ray source by structure in the accretion disk, with photoelectric absorption reducing the lower energy emission preferentially. The large amplitude of the dips and their variability is also characteristic of dipping sources. We therefore propose that the quasi-periodic modulation in GK Per is also associated with obscuration of the central source. However, in LMXBs, the dips generally recur with the orbital period, in contrast to GK Per where the timescale is much shorter than the orbital cycle.

In order to explain the observed timescale, we adopt the orbital parameters of GK Per found by Crampton, Cowley, & Fisher (1986). From an analysis of both the emission lines from the accretion disk and the absorption lines from the companion, they derive a 2 day orbital period, a primary mass of 0.9 $M_\odot$, and a secondary mass of 0.25 $M_\odot$ with a system inclination of 63° ± 10°. For this mass ratio, a stream overflowing the disk will collapse back onto the disk at a radius of 0.085 of the binary separation (Lubow 1989), which in GK Per is at 4.1×10^{10} cm. The Keplerian orbital period at this radius is ~ 5000 s, consistent with the QPO timescale (Fig. 2).

We thus envisage a model in which a sporadically overflowing stream causes vertical structure at the point where it converges onto the disk. A steady overflow would continually form structure at a point locked in orbital phase, and would tend to create structure smeared out onto orbital timescales (we are unable to investigate possible orbital variations since the total length of the *EXOSAT* data is only one-half cycle). If the overflow were sporadic, however, each "blob" of material would create structure which would then orbit with the local Keplerian motion. This could periodically obscure the white dwarf, producing the observed QPO.

Given the above radius and inclination, the vertical structure would have to extend $\sim 2 \pm 1 \times 10^{10}$ cm above the disk in order to obscure the white dwarf. Similar heights have been deduced for the disk structure in LMXBs (Hellier & Mason 1989) and in the dwarf nova U Gem during an outburst (Mason et al. 1988). Since the GK Per data were also taken during an outburst, the obscuration may be a consequence of the disk (and thus the bulge) becoming thicker during outburst. This is consistent with the behavior obtained in disk instability models, where the disk height varies roughly as $(Tc)^{1/2}$ (where Tc is the midplane temperature; e.g., Cannizzo 1994). Thus, in quiescence, stream overflow might produce structure that is not high enough to obscure the white dwarf (though note that since the quiescent data of GK Per have a lower count rate and shorter coverage, we cannot exclude the possibility that a similar effect is occurring). The possible time lag between the hardness and the intensity seen in the first observation, might (if real) be explained by an asymmetry in the bulge structure. For instance, a bulge with a sharp leading edge but a more diffuse trailing edge would produce an energy-dependent dip ingress but would suppress the soft X-rays for longer on egress, causing an apparent time lag in the hardness ratio.

4. DISCUSSION

In summary, we propose that an accretion stream overflowing the disk and causing vertical structure where it collapses back onto the disk can account for the hitherto unexplained ~ 5000 s modulation seen in the X-ray light curves of GK Per during outburst. Our model is similar in some respects to that of Frank et al. (1987) who suggested that an overflowing stream could circularize into a second disk above the main disk, and that this structure could cause the dips in LMXB light curves. The latter model has been criticized by Hellier & Mason (1989) who found that the light curves of X1822−371 were better modeled by a structure at the edge of the disk, and by Lubow (1989) who suggested that the overflowing stream collapses back into the disk. The major difference between our model and that of Frank et al. is that we do not require a long-lived structure, which would produce dips recurring with the orbital cycle, but only transient bulges produced by a sporadically overflowing stream, which then orbit on the local Keplerian timescale.

Further support for the importance of the radius at which the stream reimpacts the disk ($\sim 4 \times 10^{10}$ cm) comes from the work of Kim, Wheeler, & Mineshige (1992) in modeling the outbursts of GK Per as disk instabilities. They find that a model inner disk radius of $\sim 3 \times 10^{10}$ cm is required to produce the outburst light curves and to reproduce the observed *IUE* spectrum in outburst. Since these values are a factor of 4–5 larger than the magnetospheric radius at equilibrium rotation, it is unlikely that this is the true inner edge of the disk, since the centrifugal barrier would then prevent accretion. Further, Kim et al. argued that this radius did not change appreciably between outburst and quiescence. This is natural if the cause is the stream reimpact (with a location determined solely by the orbital period and mass ratio) but not expected if it is the magnetospheric radius. Since Kim et al. determine that the accretion flow through the disk rises from $\sim 2 \times 10^{16}$ g s^{-1} in quiescence to $\sim 3 \times 10^{19}$ g s^{-1} in outburst, we would expect the magnetosphere to shrink by a factor 8 ($r_{\rm mag} \propto \dot{M}^{-2/7}$).

In addition, our proposed disk-overflow model might help explain the small change in observed X-ray flux, which, during this increase in the flow through the disk, rises by only a factor of 10 (Yi et al. 1992). If some proportion (say ~10%) of the steady mass transfer from the secondary (~10^{18} g s^{-1}) bypasses the outer disk and arrives close to the magnetosphere, it could dominate the accretion rate in quiescence, and so explain the relatively high X-ray flux.

Finally, it is interesting to point out the difference between GK Per and another magnetic CV, FO Aqr. In GK Per the exceptionally large orbit and small magnetosphere mean that the overflowing stream collides with the disk at ~5 magnetospheric radii. In FO Aqr ($P_{\rm orb} = 4.85$ hr, $P_{\rm spin} = 1254$ s) the equivalent impact occurs at 0.4 magnetospheric radii, allowing the stream to couple directly with the magnetic field, and so producing beat period pulsations in the X-ray light curves (Hellier 1993).

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