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A MODEL FOR THE 35 DAY VARIATIONS IN THE PULSE PROFILE OF HERCULES X-1

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ABSTRACT

The substantial differences between the X-ray pulse profiles seen during the "long-on" and the "short-on" stages in the 35 day cycle of Hercules X-1 are explained by a model that contains a tilted, twisted, precessing accretion disk, and an obliquely magnetized, nonprecessing neutron star which rapidly rotates about a fixed axis, perpendicular to the binary plane. The novel aspect of this model is a raised portion of the inner edge of the accretion disk that rotates synchronously with the neutron star. This additional component modulates the relative intensities of the main pulse and interpulse by attenuation of the emergent flux. The neutron star is thus not required to undergo free precession or to be inclined to the binary plane. The structure within the main pulse and interpulse is assumed to depend on the details of the accretion column and is not addressed by this model.

Subject headings: stars: accretion — stars: individual (Her X-1) — X-rays: binaries

1. INTRODUCTION

The 35 day cycle of the binary X-ray source Hercules X-1 is still not completely understood. It was discovered nearly 20 years ago (Tananbaum et al. 1972) as a periodic on-off variation in the X-ray intensity of the system, and has in the meantime proven to be also observable through several more subtle effects in the binary system, including variations in its optical light curve (Deeter et al. 1976; Gerend & Boynton 1976), and variations in its X-ray spectrum and pulse shape (Doxsey et al. 1973; Holt et al. 1974; Boynton & Deeter 1976; Pravdo et al. 1977; Joss et al. 1978; Staubert et al. 1979, Gruber et al. 1980; Bai 1981; Ohashi et al. 1984; Trümper et al. 1986; Soong 1988; Soong, Gruber, & Rothschild 1987). Interpretation of these effects, and the wealth of detailed information obtained to date, have clarified the central role in the 35 day phenomenon played by an accretion disk tilted out of the binary plane and precessing retrogradely with respect to the binary motion with a precession period of 35 days (Katz 1973; Roberts 1974; Petterson 1975, 1977, 1978; Gerend & Boynton 1976). This precessing disk periodically obscures the X-ray source as viewed from Earth, thus causing the long term on-off variation in the X-ray intensity of Hercules X-1.

It may be of some importance for the complete understanding of the 35 day cycle to remember that long-term cycles have been found in several other X-ray binary systems, e.g., SS 433 (Anderson, Margon, & Grandi 1983), Cyg X-1 (Priedhorsky, Terrell, & Holt 1983), and LMC X-4 (Lang et al. 1981). Evidence for a tilted and precessing accretion disk is indirect but quite strong in SS 433, and seems convincing also in LMC X-4 (Heemskerk 1987). However, Hercules X-1 is presently still by far the best documented case of long-term periodicity in an X-ray binary involving disk precession. It is therefore probably the system of choice to try to understand throughly first.

In this paper we show that the dominant pulse profile variation observed during the 35 day cycle is explainable by adopting standard values (Joss & Rappaport 1984; Gerend & Boynton 1976) for the parameters of the system, including tilt and retrograde precession of the accretion disk, with the additional feature of a regular vertical displacement of the inner edge of the disk by the oblique magnetic field of the neutron star (see Trümper et al. 1986), resulting in a regular pattern of modulation of the X-radiation from the magnetic pole regions of the neutron star. This feature of the model, with its modulation at 1.2 s from the spin motion and at 35 days from the disk precession, permits us to explain the observations while keeping the spin axis of the neutron star normal to the orbital plane and nonprecessing, in contrast to the free precession model proposed by Trümper et al. (1986). While their model is attractive in providing a stable "clock" mechanism which could support the 35 day disk precession cycle, it has a strong disadvantage in that it requires a large inclination ~40° of the neutron star's rotation axis to the binary plane for best-fit to the observations. Since the accretion process transfers considerable angular momentum to the neutron star and this is expected to bring its rotation axis into alignment on a time scale very short compared to the X-ray lifetime of the system, rather special circumstances would have to be invoked to produce a strong inclination.

With our model, the observed pulse profile variations result entirely from disk motions. Thus any clock mechanisms which can control the precession rate of the disk to be 35 days per cycle also produces the pulse profile modulation, thus these profile variations cannot provide a strong argument for any particular proposed clock mechanism for the 35 day cycle.

The remainder of this paper is organized as follows: in § 2 we summarize the observational results on pulse profile variations in Her X-1, and in § 3 we describe their explanation on the basis of the model with a precessing accretion disk. Summary and conclusions follow in § 4.

2. X-RAY PULSE PROFILE OBSERVATIONS

The Her X-1 pulse profile has been monitored by several instruments on spacecraft, balloons, and rockets since the discovery of Her X-1 (e.g., Holt et al. 1974; Pravdo 1976; Joss et al. 1978; Gruber et al. 1980; Trümper et al. 1986; Soong et al. 1990). Until 1984, however, pulse profiles had only been monitored during the ~12 day "long-on" stage. During this stage, the hard (more than 1 keV) X-rays show a strong, double-peaked main pulse and a much weaker interpulse about 180° of pulse phase later. The leading edge of the main pulse decreases (and thereby narrows the main pulse) as the "long-on" stage progresses, and the main pulse declines in intensity more rapidly than the interpulse during the turn-off portion of this stage. For example, Soong et al. (1987) observed a large decrease in the main pulse over 18 hr near the end of a particular "long-on," while, at the same time, the weaker interpulse intensity increased slightly.

Occasional observations during the "short-on" (Staubert et al. 1979; Soong et al. 1990) have shown, albeit with weak statistical significance, that the pulsation at this time consists of two pulses, each at about the intensity level of the "long-on" interpulse. *EXOSAT* observations have strongly confirmed this indication (Trümper et al. 1986; Kahabka 1989, 1986). During the "short-on" stage the hard X-ray main pulse is reduced dramatically relative to what it is during the "long-on," but detailed aspects of the pulse shape are preserved. Kahabka (1989) shows two "short-on" profiles from observations over a year apart, and differing in 35 day phase by 0.07, or the equivalent of about 2.5 days. In the earlier of the two, the main pulse intensity is apparently about twice that of the interpulse, whereas in the second observation the main pulse has essentially disappeared, leaving just the interpulse. Both observations therefore show that during the "short-on" stage the intensity ratio of interpulse to main pulse is considerably higher than it is during the "long-on," and this is also demonstrated very clearly in the profiles published by Trümper et al. (1986), reproduced in our Figure 1.

3. MODEL FOR X-RAY PULSE PROFILE CHANGES

3.1. *Description of the Model*

The model we propose in order to explain the observations of pulse profile changes in Her X-1 adopts the basic features of the tilted, twisted, precessing accretion disk that has been successfully applied to many Her X-1 features (Roberts 1974; Petterson 1975, 1977; Gerend & Boynton 1976; Crosa & Boynton 1980).

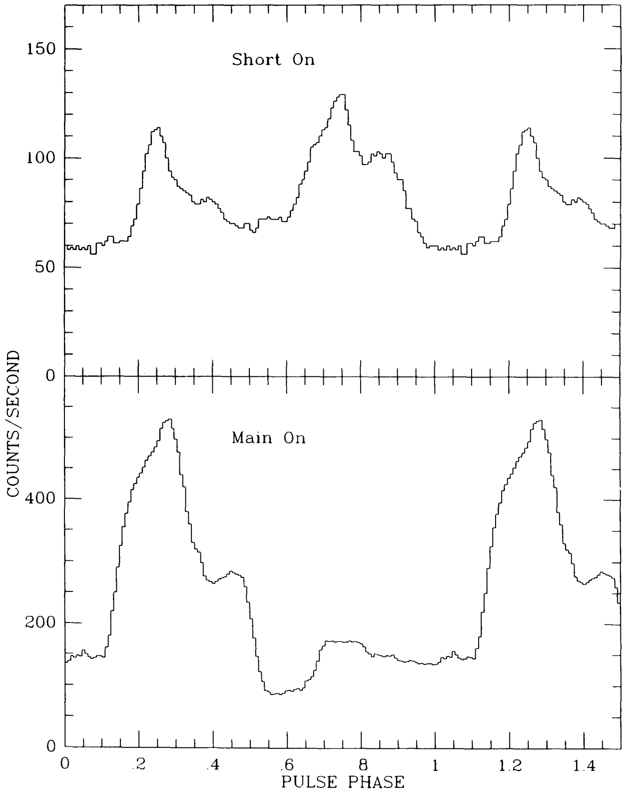

FIG. 1.—Hard (1–30 keV) X-ray profiles at opposing stages of the 35 day cycle. The figures have been copied from Trümper et al. (1986).

We assume that the spin axis of the neutron star remains normal to the binary orbital plane, and that the magnetic axis is inclined with respect to the spin axis. This, we emphasize again, is in contrast to the free precession model of Trümper et al. (1986), which requires a large angle between the spin axis and the normal to the orbital plane. But such a large angle would be very surprising in light of the fact that the disk accretion process is expected to force the rotation axis of the neutron star into alignment on a time scale which is short compared to the X-ray lifetime of the system (Petterson 1976). Our assumption is therefore the more natural one to make.

To this familiar basic model we now add the new element that a portion of the inner edge of the accretion disk is vertically displaced, and that this displacement circulates synchronously with the rotation of the neutron star. This feature can be visualized as a wave with an upward crest opposite one magnetic pole of the neutron star and a downward crest opposite the other pole, moving around the inner edge of the accretion disk, with the spin frequency of the neutron star.

The proposed wave component of the inner disk results from the inner portion of the accretion disk experiencing a varying magnetic pressure, due to the rotation of the magnetic axis, which is not aligned with the rotation axis. The maximum vertical component of this pressure is of order $(B^2/4\pi)\eta$, where η is the angle (expressed in radians) by which the magnetic field axis is inclined with respect to the spin axis of the neutron star. For the case of Her X-1, the pulsing behavior strongly suggests a substantial misalignment angle, so $\eta \sim 1$.

The importance of this vertical magnetic pressure on the disk structure can be seen by comparing it to the magnetic stress component which tries to enforce corotation of the orbiting disk material with the rotating neutron star in the "transition." This latter component is of order $B_z B_\phi/4\pi$ (Ghosh & Lamb 1979). Near the inner disk edge, where magnetic stresses are sufficiently strong to affect the Keplerian motion significantly, one may assume that the magnetic field lines are well swept back by the field-disk interaction, so that in order of magnitude: $B_\phi \sim B_z \sim B$. Thus, the vertical magnetic pressure is of the same order as the magnetic stress component which attempts to enforce corotation. It follows that the vertical magnetic pressure component should be expected to affect noticeably the orbital motion of disk matter in the vertical direction, at least at radii near the inner edge. Furthermore, the vertical distortion of the inner edge must corotate with the magnetic field structure that causes it. This results in the accretion disk acquiring an extra component of 1.24 s phase dependent opacity, in addition to its 35 day phase dependent component.

Trümper et al. (1986) also discussed a deviation of the inner accretion disk due to the interaction of the plasma with the magnetic field of the neutron star. Their motion of the inner edge, however, was linked to a *precession* of the neutron star and not to its rotation. Consequently, the time scale for the variation in the inner edge of the disk in their model is 35 days and not 1.24 s, as in the present discussion.

The hard X-rays in the main pulse originate from one of the hot magnetic poles of the neutron star, which are assumed to radiate in a wide "pencil-beam," such that the maximum is observed when the pole is most directly facing the observer

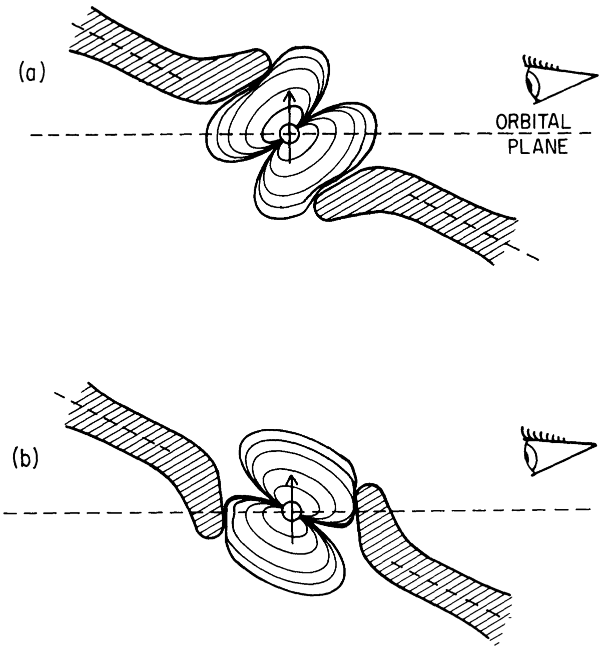

FIG. 2.—Orientation of disk and neutron star during "long-on" stage of X-ray emission in the 35 day cycle, in a precessing disk model. The observer on Earth (represented by the eye) has best unobscured view of neutron star during this stage. The magnetic axis of the neutron star rotates rapidly, and is shown at the time the main pulse is seen (*a*), and at the time the interpulse is seen (*b*).

(Fig. 2*a*). The double-peak structure of the pulse profile may relate to the shape of the accretion column and how it modifies the outflowing radiation (hollow cone structure, etc., see, e.g., Meszaros 1984). The interpulse is presumed to come from the opposite pole on the neutron star surface.

Two more effects determine the X-ray flux observed from the two poles: first, the poles present themselves to the observer at different inclination angles because the observer is not displaced slightly from the binary plane (Gerend & Boynton 1976); second, magnetic pressure will push the inner edge of the disk toward the line of sight, causing increased obscuration at certain times and not at others (see Figs. 2 and 3).

The change in angle beween magnetic axis and disk axis may, in the course of the 35 day disk precession cycle, naturally lead to more complicated changes in the accretion flow pattern inside the magnetosphere with possible consequences for the pulse profile. It is difficult at this time, however, to estimate the precise consequences of the changing accretion flow patterns between Alfvén radius and stellar surface, in the absence of a detailed model of that complicated region. By contrast, it is easy to see that the inner edge of the accretion disk must tilt by a noticeable angle due to the magnetic pressure from the oblique magnetic field, as we showed above.

The described model is qualitatively illustrated in Figures 2 and 3 in highly simplified form, using disk inclination and viewing angles inspired by the values suggested in Gerend & Boynton (1976). These figures do not show details of the disk matter leaving the inner edge when entering into the magnetospheric region, and do not incorporate a full account of the time-dependent effects of the disk-field interaction. However, they illustrate how an inner disk edge which fluctuates vertically at the pulse period of the neutron star can cause the observed differences in pulse profile between "long-on" and "short-on" described above in § 2. A much needed completely time-dependent treatment of the misaligned magnetic rotator problem will hopefully someday fill in all the quantitative details of the pulse profile variations throughout the 35 day cycle. For now, these qualitative pictures illustrate the net effect of the variable magnetic pressure, displacing particles of the inner disk in the direction of the instantaneous magnetic equator. We will now show how this explains the observed pulse profile differences between "long-on" and "short-on."

3.2. *Observational Implications of the Model*

Figure 2 displays schematic cross sections of the disk and the magnetic field at the moments of maximum intensity of the main pulse and of the interpulse during the "long-on" stage with the effect of the vertical displacement of the inner edge included. As the neutron star rotates, the distortion of the disk's inner edge corotates with the magnetic field structure. Figure 3 similarly shows the disk and field configuration at main pulse and interpulse during the "short-on" stage. Note how the geometry of the inner edge structure has changed to favor the viewing of the interpulse versus that of the main pulse. Hence, in the above described model the interpulse to main pulse ratio should be larger during the "short-on," if the difference in viewing angle of the two magnetic poles is not too important. And indeed, this is precisely what has been observed in the real system (see Fig. 1), and is one of the most striking variations in the pulse profile on the 35 day time scale (Trümper et al. 1986).

The observed reduction in intensity of the main pulse during "short-on" by a factor of about 5 compared to its intensity during the maximum of the "long-on" is consistent with the different angle between line of sight and disk plane for the two situations. During the "short-on" stage the line of sight to the neutron star must be closer to the disk plane, so that the disk

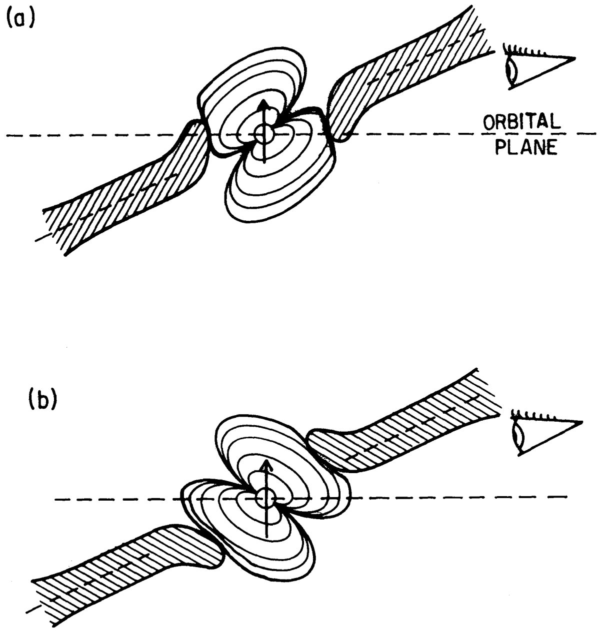

FIG. 3.—Orientation of disk and neutron star during "short-on" stage in the 35 day cycle. The observer on Earth (eye in the picture) sees the neutron star directly by "peeking underneath the disk." The magnetic axis of the star is shown at the time the main pulse is seen (*a*), and at the time the interpulse is seen (*b*). Disk obscuration evidently favors view of the star during interpulse, at this stage of the 35 day cycle.

atmosphere causes more obscuration (see Figs. 2 and 3). Evidently, the observer lies out of the system's orbital plane by an angle which is not altogether negligible compared to the disk's inclination angle. For simplicity we have shown the disk tilted but *flat* in the figures; in reality the disk must be twisted due to differential precession.

Observations (e.g. Trümper et al. 1986) show the main pulse to be about 4 times as intense as the interpulse during the "main-on," while the observed intensities are nearly equal during the brighter parts of "short-on." Our model attributes the difference of these ratios almost entirely to the effect of the flap of matter at the inner disk edge, which attenuates the interpulse during the "main-on" and the main pulse by an almost equal amount during the "short-on." The net factor of 4 corresponds to an attenuation factor of order 0.5 due to the flap at the inner edge or an optical depth of about 0.7, which is less than 1% of the optical depth of a standard accretion disk model near the inner edge (Shakura & Sunyaev 1973; Ghosh & Lamb 1979) for parameter values appropriate for Her X-1, which we have assumed to be $m = 1.3\ M_\odot$, $\dot{m} = 10^{-9}\ M_\odot\ \mathrm{yr}^{-1}$, and a viscosity ≈ 1. Thus, the disk edge should easily be able to supply the attenuation factor needed in our model, perhaps even by only applying its "atmosphere."

The interpulse seen during "short-on" can sometimes get stronger than the main pulse seen during that stage. The orientation of the neutron star and its magnetic axis with respect to the observer should favor the viewing of the main pulse (Fig. 3), but obscuration by material of the inner disk ring lowers the main pulse intensity during the "short-on." Apparently, the obscuration effect by the inner disk edge can get stronger than the effect due to the difference between viewing angles of the two magnetic poles.

Naturally, one can predict that the obscuration effect from the vertical displacement of the inner disk edge will be strongly dependent on how close the inner disk lies to the observer's line of sight. Since the angle between line of sight and inner disk is smoothly dependent on the 35 day phase, one can expect a gradually varying ratio of main pulse and interpulse, throughout the 35 day cycle, not just two different pulse patterns, one for "long-on" and one for "short-on." This is therefore yet another complication in the situation, which can hopefully be addressed by more quantitatively detailed future work.

A final prediction of the model we have presented above, and a useful observational test of it, is that pulse profiles seen during the brighter parts of the "short-on" stage of *future* 35 day cycles should repeat the pattern observed by *EXOSAT*, shown in Figure 1. The explanation we have provided above for the "short-on" profiles nowhere depends critically on anything that changes drastically from 35 day cycle to cycle. Hence our prediction that the "short-on" profile should be a rather constant feature from cycle to cycle (not constant within one cycle, of course, as we just demonstrated). Since observations of the "short-on" profile in only very few cycles have been gathered up to now and since minor differences were found, the prediction of long-term stability from cycle to cycle is still in need of further observational confirmation.

4. SUMMARY AND CONCLUSIONS

We have shown that the variation in the relative intensities of the main pulse and the interpulse from Her X-1 can be understood utilizing a standard tilted, twisted, precessing accretion disk, an obliquely magnetized neutron star whose spin axis remains normal to the binary plane, and a vertical displacement of the inner edge of the accretion disk that rotates synchronously with the neutron star. A large inclination of the spin axis of the neutron star, as well a free precession, are therefore not required to explain this variation. Consequently, nearly all clock mechanisms which can control the precession rate of the disk to be 35 days per cycle can also produce the observed pulse profile variations. Hence these profile variations do not provide a strong argument for any proposed 35 day clock mechanism, and in particular, for the free precession model of Trümper et al. (1986). We hope that this paper stimulates a renewed interest in finding the underlying clock of the 35 day cycle, now that the discussion is wide open again.

We also hope that in future work the important (but formidable) problem of the misaligned magnetic rotator interacting with the inner parts of a slowly precessing accretion disk can be treated in fully time-dependent fashion. Its solution is sure to shed much light on all qualitative details which had to be omitted from our present, rather qualitative first exploration of the influence of the inner disk edge on the Her X-1 pulse profile, and its 35 day variations.

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