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TEMPORAL BEHAVIOR OF HERCULES X-1: THE LONG-TERM VARIABILITY OF ITS PULSE PROFILE AND THE 35 DAY X-RAY INTENSITY MODULATION

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ABSTRACT

Hercules X-1, a binary X-ray pulsar, was observed by *HEAO 1* in the energy range 12–180 keV over a 17 month period in 1977–1979. The intensity variations of four complete 35^d on-off cycles were investigated during scanning observations. Thirteen pointed observations, distributed in 35^d phase, provided details on pulse shape and spectra, which were studied for their time and energy dependence. The energy dependence of the pulse profile is weak, although the highly energy dependent photon-electron scattering process across the cyclotron resonance energy points to the opposite way. A correlation between the geometry of pulse formation mechanism and the long-term intensity modulation is indicated. While wobble of the neutron star may be the ultimate clock of the 35^d cycle, evidence from the *HEAO 1* observations and previous long-term optical surveys seem to indicate that an intervening accretion disk modulating the X-ray flux is directly responsible for the 35^d cycle. *HEAO 1* observations also indicate that wobble of the neutron star cannot totally account for variation of the pulse profile. Structure and orientation of the inner edge of the accretion disk varying in long-term as well as in shorter time scale, as a cause or a consequence, is an important part of this phenomenon.

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

I. INTRODUCTION

Her X-1, one of the brightest binary X-ray pulsars (Tananbaum *et al.* 1972), has shown several interesting periodicities which have been related to the physical conditions of the binary system: a 1.24 s pulse period ascribed to rotation of the neutron star; a $1^d.7$ binary orbital period with a $0^d.24$ X-ray eclipse by the optical companion, HZ Her.

Even though the system has been studied for the last 16 years and many X-ray characteristics are understood quantitatively (Giacconi *et al.* 1973; Joss *et al.* 1978; Gruber *et al.* 1980; Ohashi *et al.* 1984; Trümper *et al.* 1986), the underlying mechanism for the 35^d X-ray on-off cycle remains uncertain. Trümper *et al.* (1986) revived the neutron star precession model (Brecher 1972; Lamb *et al.* 1975) to account for the change from single-pulsed to double-pulsed profile in going from the main-on state to the short-on state observed by *EXOSAT*, and they further proposed the precession of the neutron star to be the underlying 35^d intensity modulation mechanism. *HEAO 1* (Soong, Gruber, and Rothschild 1987) observed a similar pulse profile change on a much shorter time scale (15 hr instead of $\sim 17^d$). Neutron star precession apparently could not account for both of these changes on such vastly different time scales.

The *HEAO 1* data provide many avenues for studying the X-ray generation mechanisms near the magnetic pole of neutron stars and the transport of these X-ray photons through the geometrically, as well as physically, complex surrounding medium. The shape of the 35^d light curve with its main-on and short-on states, the 1.24 s pulse light curves along with their variability in time and energy, and the spectra of various phases of 1.24 s and 35^d periods all yield useful information on these mechanisms. This paper will concentrate on studies of the temporal variability. More information is also available in the study of spectral behavior, which is the subject of a companion paper (Soong *et al.* 1990). We will be regarding the variation of pulse formation as occurring under changing accretion conditions, e.g., accretion disk plane orientation with respect to the magnetic axis of the neutron star, which consequently affects the mass channelling at the inner edge of the accretion disk, and eventually, the pulse formation. In § II, a brief review of the instrument and observations will be given. Methods of analysis and results follow in § III, and discussion and conclusions are in § IV.

II. INSTRUMENT AND OBSERVATIONS

Data analyzed in this paper were collected by the two Low Energy Detectors (LEDs) of the UCSD/MIT Hard X-ray and Low Energy Gamma-Ray Experiment (A-4) on *HEAO 1*. Each LED had 103 cm^2 net area with an active energy range of 12–180 keV. The detectors were NaI(TI) scintillators, which were actively shielded by CsI(Na) crystals. The detailed instrument description can be found in Matteson (1978). Two observational modes were used. First, a regular scanning mode in which data from a given source were collected every 37 minutes as the satellite rotated about its spin axis, with about 17 s on-source time and two 13 s intervals taken immediately before and after the on-source time for background reference. The whole sky was scanned once every 6 months, which we designate an epoch. During the satellite lifetime, three epochs of scanning data of Her X-1 were gathered for about 48, 68, and 67 days, respectively. Earth occulation and South Atlantic Anomaly (SAA) passages were responsible for more than a 50% loss of the scanning data on Her X-1. Second, after 1977 November 15, pointing mode observations, with 1–19 hr of duration, were utilized to study individual sources in detail. Hercules X-1 was observed in this way during 13 such operations, which were distributed over different phases of the 35^d on-off cycle. A detailed pointing observation schedule is tabulated in Table 1.

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TABLE 1

POINTING OBSERVATIONS SUMMARY

Start[a]	Stop[a]	Duration	Source	Background	Ψ_{35}[b]	$\Phi_{1.7}$[c]	Comment[d]
Feb 24, 14:59	Feb 24, 18:12	3:13	1:59	...	0.10	0.31–0.39	P
Feb 27, 15:56	Feb 27, 18:50	2:54	1:38	...	0.19	0.10–0.17	P
Feb 28, 16:30	Feb 28, 19:40	3:10	1:54	...	0.22	0.70–0.78	P
Mar 6, 13:27	Mar 6, 16:37	3:10	1:44	...	0.38	0.16–0.23	P
Mar 7, 00:50	Mar 7, 04:37	3:47	1:51	...	0.40	0.43–0.51	P
Aug 13, 22:06	Aug 14, 04:01	5:55	2:46	...	0.02	0.48–0.62	P
Aug 15, 09:29	Aug 15, 19:23	9:54	3:03	1:57	0.07	0.34–0.58	P-P
Aug 18, 06:55	Aug 18, 17:50	10:55	3:43	2:27	0.15	0.07–0.31	P-P
Aug 21, 04:07	Aug 21, 12:20	8:13	2:49	1:51	0.23	0.74–0.93	P-P
Aug 24, 06:30	Aug 24, 11:55	5:25	1:37	1:11	0.32	0.58–0.70	P-P
Aug 28, 18:54	Aug 28, 19:45	0:51	0:25	...	0.44	0.23–0.24	P
Sep 22, 11:06	Sep 22, 20:59	9:53	3:08	2:05	0.14	0.73–0.93	P-P (off-axis)
Sep 23, 11:35	Sep 23, 21:30	9:55	2:39	1:56	0.17	0.33–0.57	P-P (off-axis)
Total		77:15	28:06	11:27	...	...	

[a] 1978 observations, universal time in hr : min.

[b] 35^d phase.

[c] $1^d.7$ binary phase.

[d] Straight pointing (P), ping-pong pointing (P-P), off-axis ping-pong pointing [P-P (off-axis) in which two LEDs did not take on-source spectrum simultaneously; instead, they took it alternatively. This was done due to spacecraft power considerations].

III. METHODS OF ANALYSIS AND RESULTS

a) *The Long-Term X-Ray Light Curve*

The 12–180 keV counting rate from Her X-1 averaged over half of each orbital cycle ($0^d.85$) from the scanning data is shown in Figure 1. The data have been corrected for background and aperture response, and the X-ray eclipses have been excluded. Each scanning epoch, which covers about 50^d of observations, was truncated at 10% detector collimator response for reasons of counting statistics. Four main-on states (35^d cycle numbers 59, 64, 69, and 70 as assigned in Staubert, Bezler, and Kendziorra 1983; Ögelman 1987) and four short-on states were observed. Several facts can be recognized: (1) The main-on states have similar maximum intensity, whereas that of the short-on states varies up to a factor of 4; (2) the turn-on time of each main-on state of the 35^d cycles is regular within half of an orbital period; (3) the main-on state duration was the same ($\sim 11^d$) for the first three, but was seen to be about two binary periods (i.e., $3^d.4$) shorter in the last of the four main-on states; and (4) the envelopes of the light curves of the main-on and the short-on states bear some resemblance to one another—both have similar durations plus they both show a quick turn-on and a slower turn-off. The main-on state in cycle number 72 following the shortened, last main-on state observed by *HEAO 1* (cycle 70), commenced at the expected time. Consequently, the 3^d shortening of the last main-on state

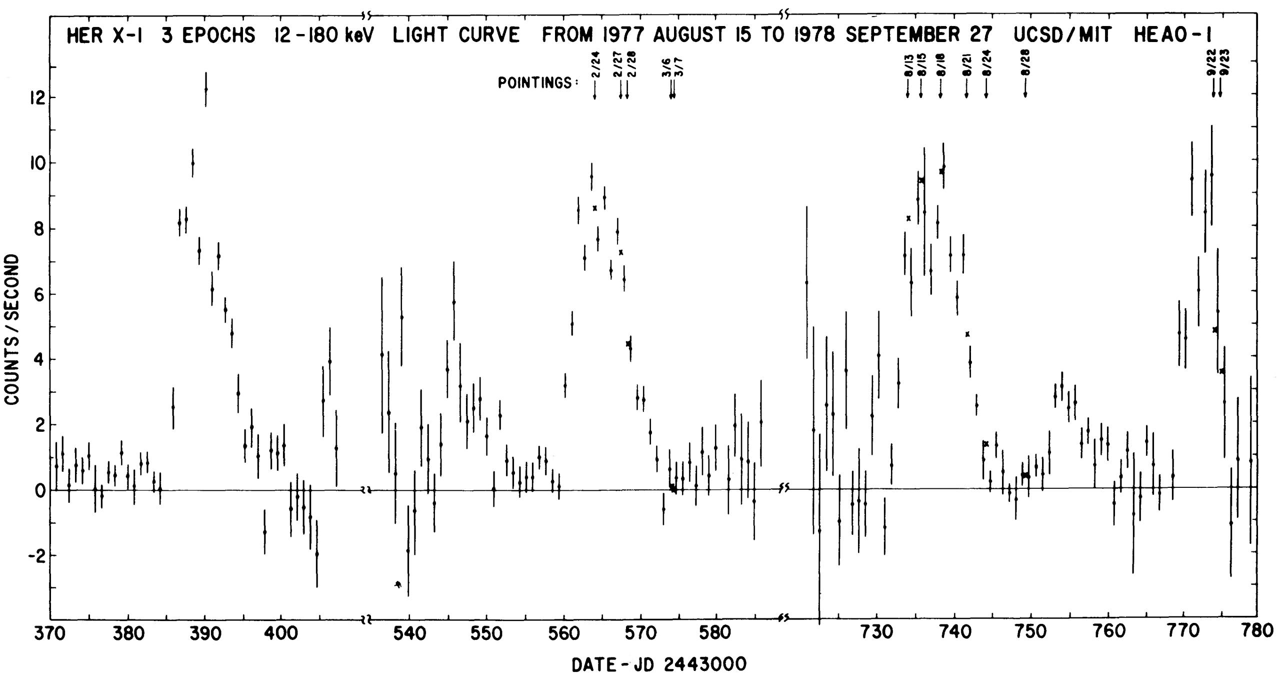

FIG. 1.—Her X-1 12–180 keV light curve from the three epochs scanning observation. The errors are 1 σ, and the epoch was truncated at about 10% aperture response. Pointing observations are marked by an " X " at the observed average X-ray intensities.

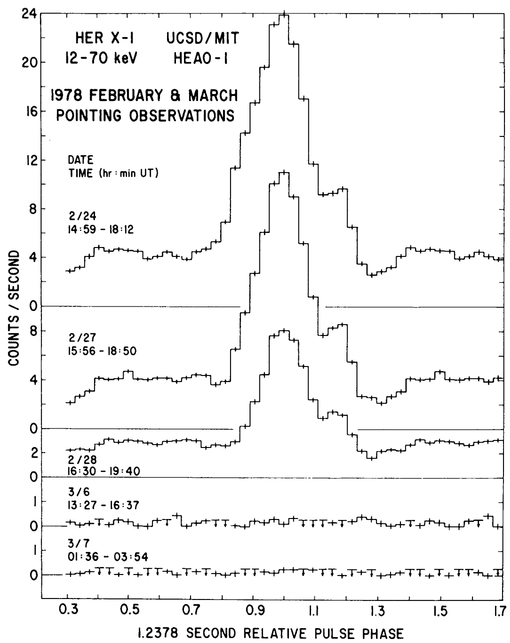

FIG. 2*a*

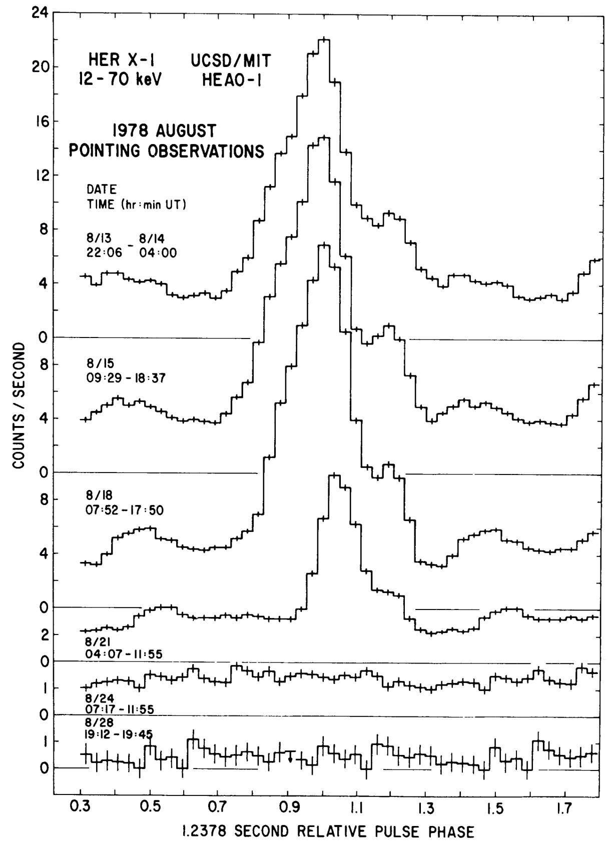

FIG. 2*b*

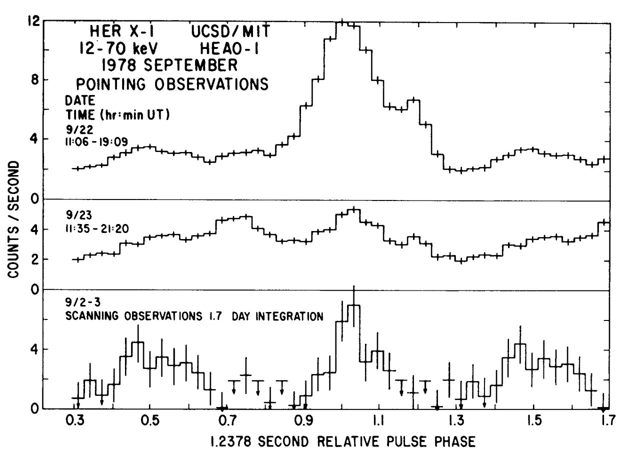

FIG. 2*c*

FIG. 2.—(*a*) 12–70 keV pulse profile of the 1978 February and March pointings marked with the observation times, (*b*) 12–70 keV pulse profile of the 1978 August pointings, and (*c*) 12–70 keV pulse profile of the 1978 September pointings. The errors are 1 σ.

was *not* a consequence of a shift in the 35^d cycle, unless this was soon followed by a compensating 3^d relaxation.

b) *Pulse Profile Variations with the 35 Day Phase* (Ψ_{35})

Detailed pulse profile studies were carried out using the pointed observations. Observed pulse profiles resulted from the folding of the time series by taking into account the binary orbital motion, and the satellite motion with respect to the solar system barycenter (Deeter, Boynton, and Pravdo 1981; Soong, Gruber, and Rothschild 1987). The pulse period for each main-on state was determined by aligning the main peak of those profiles from pointings that occurred during the peak intensity of each of the main-on state. Due to the length of the timing baseline ($\sim$1–5 days), these periods were determined to an accuracy of $1\text{–}5 \times 10^{-7}$ (Soong 1988). The pulse profiles from each main-on state, background-subtracted and corrected for aperture response, are shown in Figure 2.

Several features can be observed.

1. In the decline of the 1978 February main-on state, the overall intensity dropped 40% in one day from February 27 to 28 while the pulse width and the main features of the profile remained relatively unchanged.
2. The 1978 August 21 pulse profile shows an overall intensity reduction as well as a relative diminution of the leading edge of the main pulse.
3. Between the 1978 September 22 and 23 main-on state data show a 50% pulse amplitude drop in coincidence with a change of pulse shape from single to double in $\sim$15 hr.
4. During the main-on states not only are the peaks of each of the pointing profile aligned, but so are the subpeaks of the main pulse, which implies a high confidence in the period determination.
5. The profile of 1978 August 24—the last day of that main-on state—shows that the main features have disappeared, but the X-ray light curve was still not consistent with a constant level.
6. The off-state pointings, namely, 1978 March 6, 7, and August 28, had detectable flux at 3%–5% of the maximum level and the profiles were consistent with no pulsations.

The pulse profile during the short-on state in early 1978 September was accumulated from one binary cycle of scanning data and confirmed the *EXOSAT* result of a double-pulsation during a different short-on state (Trümper *et al.* 1986), in which the two peaks, 180° apart, were of equal intensity. The other three short-on states were observed at less ideal aperture response, which prevented statistically significant detection of the double-pulsation. The pulse form during the short-on state has also been observed by other experiments (Jones and Forman 1976; Ricketts, Stanger, and Page 1982), to have a single broad peak, but still with differing overall intensity levels. The short-on pulse profile of 1978 September was consistent with having no DC component, whereas all main-on pulse profiles contained such a component to a high degree of statistical certainty.

In order to show the change of the pulse profile during the main-on state quantitatively, we have employed a template comparison scheme. A template of the pulse profile was accumulated by summing the five high-state pointings, namely, 1978 February 24, 27, and August 13, 15, 18, over the energy range 12–70 keV. Then the pulse profiles for each of the pointings were normalized, from pulse maximum to minimum, to have the same pulse amplitude as the template and each profile's difference from the template in each phase bin was calculated in units of standard deviations. The results are plotted in Figure 3*a* as a function of 35^d phase. The general trend is for excesses in both wings of the overall main pulse at $\Psi_{35} < 0.10$, and for the leading edge of the main peak to diminish toward the end of the main-on state. The 1978 September pointings do not fit well into this trend. Due to the drastic change of the profile of September 23, we have excluded it from the comparison. In Figure 3*b*, we have rearranged the same data according to the overall X-ray intensity instead of 35^d phase, and the general trend of an ever-diminishing leading edge is supported by all the data. The September 22 intensity is equivalent to a shift in 35^d phase, Ψ_{35}, of $\Delta\Psi_{35} = 0.08$ or $\sim 3^d$ advance toward the end of the main-on state, *which corresponds to the 3^d shortening of that main-on state.* Consequently, the *HEAO 1* observations indicate that pulse shape is better correlated with the overall intensity than with the 35^d phase.

c) Energy Dependence of the Pulse Profile

The accumulated pulse profile from the high state pointings was divided into seven energy bands: 12–20, 20–30, 30–40, 40–55, 55–70, 70–90, and 90–120 keV, and these are plotted in Figure 4. Pulsations are detected up through the 70–90 keV band. Each band's profile was compared with an overall template as in the previous section and these results are plotted in Figure 5. Both wings of the main peak of the main pulse have a deficit at 12–20 keV, and this continuously changes into definite excesses above 40 keV. The peak of the main pulse of the 30–40 keV band shows a one-phase bin shift comparing with that of the two lower energy bands. This causes a differential change in the template comparison in the 30–40 keV band. Since the full width of the main peak does not change appreciably with energy, the pulse fraction (the relative height of the

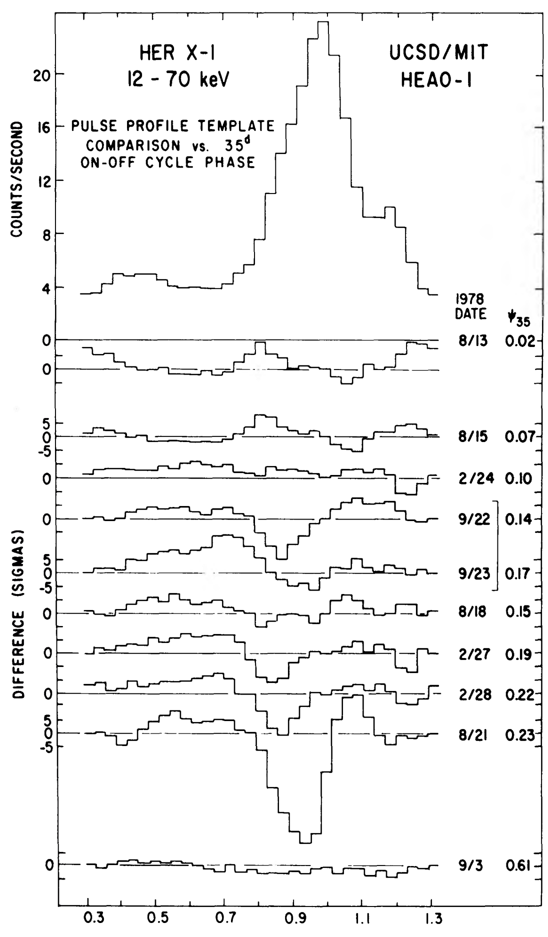

FIG. 3*a*

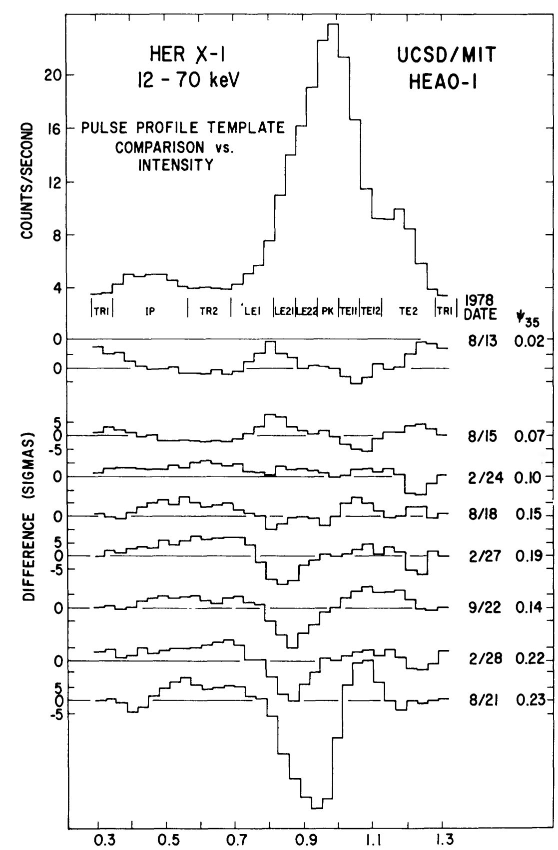

FIG. 3*b*

FIG. 3.—(*a*) Pulse profile template comparison vs. 35^d phase. The observation date and the corresponding 35^d phase are shown on the right. (*b*) Pulse profile template comparison vs. the X-ray intensity. The observation date and the corresponding 35^d phase are shown on the right. The tick mark represents 5 units of standard deviation in difference.

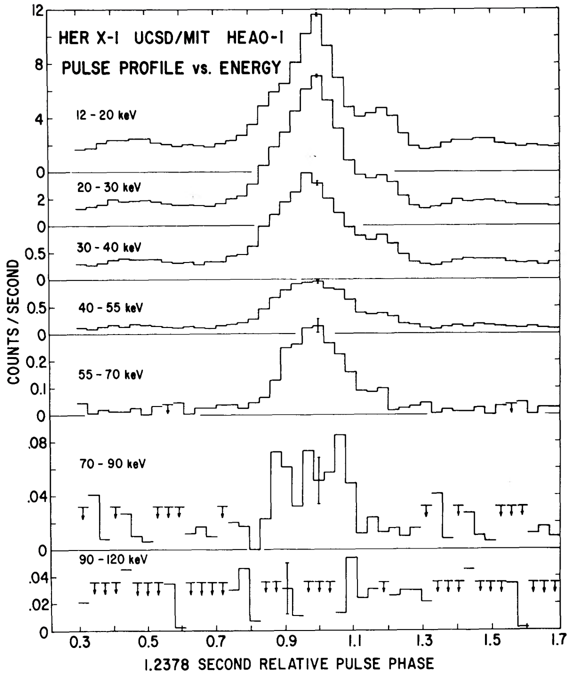

FIG. 4.—Her X-1 pulse profile of seven consecutive energy bands. Pulsation was marginally seen above 70 keV. The errors are 1 σ, and the upper limits are 2 σ.

main peak to the DC level in this case) must be growing with energy. This can be directly shown by integrating the flux in the entire main peak in each energy band and comparing it to the DC level. The variations across the suspected "cyclotron line" energy—36 keV or 50 keV depending on the assumption

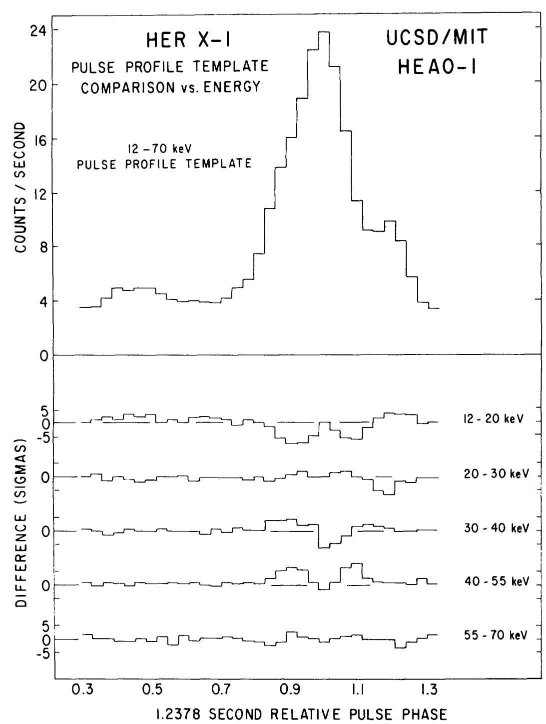

FIG. 5.— Pulse profile template comparison in the five consecutive energy bands observed by *HEAO 1*. The tick mark represents 5 units of standard deviation.

of an absorption or emission line respectively (Trümper *et al.* 1978)—are not very large. However, the 30–40 keV bin does not follow the overall trend of pulse fraction increasing with energy (Soong 1988; Soong *et al.* 1990).

IV. DISCUSSION AND CONCLUSIONS

The angle between the magnetic field axis and the inner accretion disk plane, which can vary during the 35^d cycle, is an important factor of the X-ray intensity modulation. This angle determines the "gating mechanisms" (Lamb *et al.* 1975) of the channelling process between the accretion disk and the emission region. The geometrical gate is determined by the magnetic latitude of the location where the structure of the inner disk is disturbed, while the centrifugal gate is determined by the distance of that disturbance with respect to the spin axis. Variations of the pulse profile and the X-ray intensity during the 35^d cycle have provided important information to advance the understanding of the underlying mechanism.

A strong magnetic field of the neutron star should have several important effects:

1. At the inner accretion disk edge, where the inflowing material encounters balancing magnetic pressure (Ghosh and Lamb 1978, 1979*a*, *b*), it will channel infalling highly ionized plasma to the magnetic poles.
2. It quantizes the electronic states in the plane perpendicular to the local field (Landau and Lifshitz 1977) to tens of keV levels.
3. It makes the emission region highly anisotropic to the X-ray photon transfer.

The pulse formation mechanism is highly dependent on these factors. Energy dependence of the pulse profile should be a direct reflection of these complex mechanisms as well.

Trümper *et al.* (1986) pointed out that the resemblance between the pulse profiles during both the main pulse and the interpulse could be understood in terms of pencil beam emission from a dipolar magnetic field configuration. In this model the main pulse originates at one polar region of the neutron star and the lower intensity interpulse, approximately 180° apart in phase, originates at the opposite polar region, whose beam has much larger aspect angle toward our line of sight. According to the results from the *EXOSAT* observations on Her X-1, this aspect angle would have changed due to the wobble of the neutron star. The structure within the main pulse, then, is due to the anisotropic nature of scattering in the 10^{12} G field and/or matter distribution over the polar region.

a) Time Dependence of the Pulse Profile

The apparently regular variation of the X-ray pulse profile—the gradual erosion of the leading edge of the main pulse through the main-on state, and the 35^d intensity variation are composite effects of the shape and the orientation variations of the X-ray beam, and accreting mass channeling variations plus the blockage caused by dynamics of the intervening material, namely, the disk structure and the magnetosphere, in the 35^d interval. In general, it would be difficult to separate these interlocking effects, of which the star-disk system has to be treated in a self-consistent way (Ögelman and Trümper 1988). The secular erosion of the leading edge of the main pulse is not caused by a simple material blockage of the beam, which could only reduce the overall intensity across the pulse phase. This differential intensity reduction can be shaped in several ways: a blocking region rotates synchronously with the beam, the inner accretion disk edge of Her X-1 at 2×10^8 cm possesses

Keplerian velocity, which can achieve the geometrical requirement; the neutron star precesses and our line of sight cuts through various part of the X-ray beam; or the inner disk plane changes its orientation with respect to the X-ray beam axis and the mass-channeling pattern changes accordingly. The 1978 September 22 observation shows that the pulse shape variations are related to the overall intensity and do not necessarily reflect the 35^d passage, which makes the association with the neutron star precession less likely.

The observed coincident event of early termination of the main-on state and change of the pulse profile in 1978 September indicates that whatever controls the overall X-ray intensity reduction must also affect the pulse formation, and the cause must lie near the edge of the inner accretion disk. McCray *et al.* (1982) have proposed an inner disk structure, extending to both sides of the orbital plane (up to 20°), as the low-energy (≤ 1 keV) pulse formation site by reprocessing the beam from the neutron star. We can estimate the photon scattering optical depth of this region as

$$\tau = \kappa \rho x = 0.4 \rho x = 0.4 \dot{M}/(2\pi r v_{\parallel}) , \quad (1)$$

where κ is the Thomson opacity, ρ is the mass density, x is the thickness of the magnetosphere at radius r, $v_{\parallel}$ is the velocity of the accreting plasma in the magnetic field direction, and $\dot{M}$ is the mass accretion rate. For Her X-1, τ is about $6.4 \times 10^{15}/(r v_{\parallel})$, which could be large at the pressure balance radius of $\sim 2 \times 10^8$ cm, since $v_{\parallel}$ is low. The variations of optical thickness of this extended structure, following the change with time of the relative orientation of the disk, could be responsible for the observed, steady long-term, as well as the rapid short-term, pulse profile variations. In addition to the disk obscuration of the X-ray beam, a perturbation of this edge can induce a variation in the distribution of accreting matter at the polar caps of the neutron star, which changes the individual beam intensity, and the consequences are the change of pulse profile and the accompanied X-ray intensity reduction. The pulse profile changed to a double form, rather resembling to that observed by Trümper *et al.* (1986) during the short-on state. These similar events happened in the vastly different time scales cannot come from the stellar precession alone. A local disturbance at the inner disk, e.g., accretion rate perturbation and/or channeling pattern change, could explain the 1978 September results. The overall 35^d cycle was not affected by the localized perturbation. Similar changes in the channeling pattern keyed to the 35^d cycle could also cause, as has been argued, the 35^d pulse shape changes.

b) *Energy Dependence of the Pulse Profile*

The subtle variation of the wings of the main pulse in Figure 5 reflects the angular and the energy dependence of the emerging photon. The pulsation at higher photon energies should consist of relatively unscattered photons and therefore give a closer indication of the original beam shape and width, which should be narrower toward higher energy (Gnedin and Sunyaev 1973). Because of very different scattering cross sections for ordinary and extraordinary photons in the magnetized plasma, Holt and McCray (1982) suggested a sizable change of pulse profile with the energy. Although such effects should be strong near the cyclotron energy, we observe a less dramatic change of profile with energy. It will need more detailed modeling of the emission region to understand this subtle variation. Energy dependence of the pulse fraction at the 30–40 keV band could be interpreted as strong evidence for the spectral feature being due to absorption as opposed to emission (Soong *et al.* 1990).

c) *Origin of the 35 Day On-Off Cycle*

A number of models have been proposed to explain the underlying mechanism of the 35^d cycle (Brecher 1972; Katz 1973; Roberts 1974; Lamb *et al.* 1975; Petterson 1975, 1977; Meyer and Meyer-Hofmeister 1984), and many observations provided partially supportive evidence (Crosa and Boynton 1980; Trümper *et al.* 1986; Kahabka 1986; Soong, Gruber, and Rothschild 1987). Attempts to model the 35^d X-ray intensity modulation involve either a change of the X-ray beam orientation (e.g., wobble of neutron star) or a time-varying accretion disk orientation and/or structure, which causes different degree of blockage of the X-ray beam in our line of sight (e.g., precession of the accretion disk). In either disk or stellar precession model, one would expect a modulation mechanism of the observed X-rays arising from the time-varying mass-channeling geometry, which is controlled by the angle extended between the magnetic axis of the neutron star and the inner disk plane causing the distribution of matter at the polar caps to change. Differentiation between these two models can be derived from detailed studies of the X-ray spectrum and the pulse profile at different 35^d phases as in §§ IV*a* and IV*b*. The steady X-ray flux reaching the companion HZ Her also provides an important constraint. Optical observations of HZ Her have shown convincing evidence of its $1^d_\cdot 7$ orbital dependence on the X-ray heating at the Roche lobe–filled stellar surface (Middleditch and Nelson 1976). The optical photometry folded in $1^d_\cdot 7$ orbital period by Boynton *et al.* (1973) and Hudec (1984) showed a shallow dip at the binary phase 0.5 (when Her X-1 is in between HZ Her and observer) for the data averaged over the main-on state, and the full width of the dip is about 0.25 binary phase. In contrast to that averaged over the short-on state, this feature was not present while the overall modulation amplitude kept at the same level, which can be interpreted as the X-ray luminosity being kept at a constant level, indicating a nearly constant accretion rate at the surface of the neutron star on these time scales. Thus the intensity variations forming the 35^d cycle are not due to changes in the average accretion rate onto the neutron star. The large-amplitude ($\sim 50°$) stellar precession estimated by Trümper *et al.* (1986) is not reflected in the optical photometry variation of HZ Her, since the precessing X-ray beam would have caused considerable change in X-ray reprocessing at the surface of HZ Her. On the other hand, the inner accretion disk moving above and below the disk plane can be accounted for the X-ray intensity modulation and the reprocessing of X-ray beam by a disk blockage effect.

The spectral analysis of Her X-1 in this experiment shows no evidence of variation of spectral parameters with 35^d phase. On the other hand, the pulse phase spectroscopy does show moderately strong pulse phase dependence (Soong *et al.* 1990). A similar effect is expected during the 35^d cycle, if neutron star precession with large angles as estimated by Trümper *et al.* (1986), and this has not been observed. Statistically, on the other hand, six binary X-ray pulsars, which possess long-term intensity modulation (Priedhorsky and Holt 1987), show that they are more or less edge-on systems with large eclipse angles (Joss and Rappaport 1984). This supports a disk intervening phenomenon as the underlying mechanism of the long term X-ray intensity modulation.

To summarize, *HEAO 1* data show the following:

1. Structural change at the inner edge of the accretion disk

but *not at the large radii* is likely to cause the 35^d as well as the observed short-term rapid variations of the pulse profile.

2. The energy dependence of pulse profile is less pronounced than the time dependence counterpart; the subtlety of the change needs more detailed modeling of the emission pattern.

3. The variable mass-channeling scheme and intervening effect at the inner accretion disk rather than the free precession of the neutron star is probably directly responsible for the 35^d X-ray modulation.

4. Future observations on the pulse profile variability at the turn-on and decaying phases of the main-on and the short-on states is desirable to the understanding of the X-ray modulation mechanism.

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