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DECREASE IN THE ORBITAL PERIOD OF HERCULES X-1

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ABSTRACT

From a pulse-timing analysis of *Ginga* observations of the binary X-ray pulsar Her X-1 obtained during the interval 1989 April–June we have determined local orbital parameters for a SHORT HIGH state. We have also determined an orbital epoch in the adjacent MAIN HIGH state. By comparing these orbital solutions with previously published results, we have detected a decrease in the orbital period for Her X-1 at an average rate of $\dot{P}/P = (-1.32 \pm 0.16) \times 10^{-8}$ yr^{-1} over the interval 1971–1989. This is substantially larger than the value predicted from current estimates of the mass transfer rate, and motivates consideration of other mechanisms of mass transfer and/or mass loss. A second result from these observations is a close agreement between orbital parameters determined separately in MAIN HIGH and SHORT HIGH states. This agreement places strong constraints on the obliquity of the stellar companion, HZ Her, if undergoing forced precession with a 35 day period. As a consequence further doubt is placed on the slaved-disk model as the underlying cause of the 35 day cycle in Her X-1.

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

1. INTRODUCTION

The basic phenomenological picture of Her X-1 was established soon after its detection as an X-ray source by Tananbaum et al. (1972): a neutron star rotating with a frequency of 808 mHz in a 1.7 day binary orbit about a stellar companion, HZ Her. Superposed on the flux variations associated with these periodicities is a regular 35 day cycle, consisting of alternating MAIN HIGH and SHORT HIGH states of 11 and 5 days duration, respectively, separated by intervals of relatively low X-ray flux (Jones & Forman 1976). Many observational features of the 35 day cycle can be explained by a tilted, precessing accretion disk (Petterson 1975, 1977; Gerend & Boynton 1976; Crosa & Boynton 1980; Ögelman et al. 1985), but the underlying physical cause of such a disk has yet to be established. Neutron star free precession has also been considered as the 35 day clock mechanism (Trümper et al. 1986; Bisnovatyi-Kogan et al. 1990).

We have observed Her X-1 with the *Ginga* satellite during a 44 day span in 1989 April–June, primarily to test various models of the 35 day cycle by studying the evolution of the pulse shape. As a first step in the treatment of these data, we applied a pulse-timing analysis to the portions where strong pulsations were evident. The primary goals of this initial phase of this work were to verify the orbital parameters reported by Deeter, Boynton, & Pravdo (1981, hereafter DBP), and to establish the behavior of the pulse frequency for subsequent aspects of the investigation.

In § 2 we report two new results from this pulse-timing analysis. First, the orbital parameters determined for a SHORT HIGH state in 1989 May are in close agreement with orbital parameters from the preceding MAIN HIGH state, and also with the MAIN HIGH states analyzed by DBP. In § 3.1 we discuss restrictions imposed on a forced-precession model for the 35 day cycle implied by this agreement. Second, the orbital period has become significantly shorter since the interval 1971–1979 studied by DBP, with an average rate of change $\dot{P}/P = (-1.32 \pm 0.16) \times 10^{-8}$ yr^{-1}. In § 3.2 we examine this change in orbital period in terms of simple mass transfer and mass loss processes in the Her X-1/HZ Her system.

2. DATA ANALYSIS AND RESULTS

Her X-1 was observed by the large area counter (LAC) aboard *Ginga* during the interval 1989 April 27 to June 9. (See Makino et al. 1987 and Turner et al. 1989 for details about *Ginga* and the LAC instrument.) Observations were made in two consecutive MAIN HIGH states (April 27–May 4 and June 2–9), and the intervening SHORT HIGH (May 16–20). The data used in this analysis consist of MPC-3 data (12 energy channels) at 8 and 62.5 ms time resolution, and MPC-2 data (48 energy channels) at 62.5 ms time resolution. For the pulse-timing analysis the 8 ms data were converted to 62.5 ms resolution by combining integrations, and the energy resolution was uniformly reduced to four bands: 1–7, 7–14, 14–23, and 23–37 keV.

2.1. *Pulse Folding*

The first step in the data analysis was to convert time of observation to the solar system barycenter. Time of observation (at the satellite detector) was initially assigned as UTC

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TABLE 1

LOCAL DETERMINATIONS OF ORBITAL PARAMETERS FOR HERCULES X-1[a]

HIGH State	Orbital Cycle[b]	$T_{\pi/2}$[c] (MJED)	(a_x/c) sin i (s)	Satellite
1982 Jun	2238	45134.05113 (17)	13.177 (14)	*Hakucho*
1983 May	2440	45477.485113 (44)	13.1896 (20)	*Tenma*
1989 Apr	3715	47645.198575 (25)	...[d]	*Ginga*
1989 May[e]	3726	47663.900428 (16)	13.1861 (15)	*Ginga*

[a] Numbers in parentheses following the parameter estimates indicate 1 σ errors in the final decimal place.

[b] Orbital cycle count from the epoch reported by Tananbaum et al. 1972.

[c] Time when the mean longitude equals $\pi/2$.

[d] (a_x/c) sin i was not included as a free parameter, but held fixed at the average value of 13.1831 s reported by DBP.

[e] SHORT HIGH state.

with 1 ms accuracy accuracy by comparison with a standard clock for the five orbits each day the satellite passed over the Kagoshima ground station. The stability of the *Ginga* onboard clock ($\sim 1 \times 10^{-6}$) was sufficient to maintain 1 ms accuracy over the 100 minute interval between consecutive contact passes (Deeter & Inoue 1989). For remote orbits, relying on a mean clock rate between consecutive clock comparison separated by some 17 hr can result in sizable (~ 10 ms) errors in time assignment. Most of our data consists of contact orbits, but there are two sets of remote orbits. To hold the errors in time assignment to 2–3 ms, we constructed interpolation tables for these remote passes, assuming smooth changes in the clock rate. The accuracy of this interpolation was checked by a comparison of the interpolated clock rate with that inferred from the housekeeping temperature data (see Deeter & Inoue 1989).

Time of observation was first corrected for satellite motion and then transformed to the solar system barycenter using an improved version of MIT planetary ephemeris PEP 311 (Chandler 1989). This ephemeris also converts UTC into ephemeris time, and we adopted MJED (modified Julian ephemeris day) as the uniform time scale for the pulse-timing analysis. MJED is the ephemeris time counterpart to MJD, being defined as MJED = JED − 2,400,000.5.

The orbital motion of Her X-1 was removed by subtracting the time delay given by the orbital ephemeris of DBP. The data were then folded on a uniform pulse ephemeris, using a constant frequency of 807.912 mHz determined in a quick-look analysis. Individual sample pulses were initially formed from 100 s segments of data, with a separate pulse for each of the four energy bands. Each folded pulse was represented by harmonic coefficients for the first 15 harmonics of the pulse frequency. Groups of two to six sample pulses were combined into average pulses in order to reduce the quantity of data.

A master pulse for each of the four energy bands was formed for each of the three large sets of data—the two MAIN HIGH states and the SHORT HIGH state. A phase offset with respect to the appropriate master pulse was determined separately for each energy band of each average pulse, along with an estimate of the phase uncertainty due to the finite number of photons. An analysis of these phase offsets is then used to determine local orbital parameters and pulse frequencies.

2.2. *Updated Orbital Parameters*

Pulse timing for the two MAIN HIGH states was based on the 14–23 keV energy band, since it provides a sharper and more stable pulse than the other bands do. However, for the SHORT HIGH data the counting rate in the 14–23 keV band was rather low, and the phases for the 7–14 keV band were used. This procedure is acceptable for the present analysis since there is no attempt to link phases across the three sets of data.

The best coverage in orbital phase was obtained during the SHORT HIGH state in 1989 May, with a strong pulse observed for 2.2 days. A least squares analysis of these data determined local values for the pulsation period, the semimajor axis (a_x/c) sin i, and the orbital epoch $T_{\pi/2}$ (DBP). During the 1989 April–May MAIN HIGH state, however, there was a noticeable spin-up trend. The coverage in orbital phase for this data set was not sufficient to allow a precise determination of five parameters in the least-squares fit (pulse ϕ_o, ν_o, and $\dot{\nu}_o$, together with the two orbital parameters), so we fixed (a_x/c) sin i at the value of 13.1831 s reported by DBP, and fitted for the remaining four. In each analysis the orbital period $P_{\rm orb}$ was fixed at the value determined by DBP, which is more accurate than redetermining $P_{\rm orb}$ locally from short spans of data. The coverage in the 1989 June MAIN HIGH state was relatively sparse, and here we were able to determine only a value for the local pulse frequency. In addition, we have determined two more orbital solutions for Her X-1 by utilizing previous analyses of *Hakucho* and *Tenma* data (Nagase et al. 1984; Ohashi et al. 1984). Values of orbital parameters determined in these analyses are reported in Table 1, and new pulsation frequencies based on *Ginga* data are given in Table 2.

The value for (a_x/c) sin i obtained for the 1989 May SHORT HIGH state is consistent with a determination of 13.1831 s from earlier MAIN HIGH states (DBP). In addition, the value for the orbital epoch, $T_{\pi/2}$, for the SHORT HIGH state is consistent with the value obtained in the MAIN HIGH state some 17 days earlier. In the following section we discuss the restictions this agree-

TABLE 2

NEW DETERMINATIONS OF PULSE FREQUENCY FOR HERCULES X-1[a]

HIGH state	t_o (MJED)	ν_o (Hz)	P_x (s)
1989 Apr[b]	47645.5362	0.807912389 (5)	1.237757973 (7)
1989 May[c]	47663.1911	0.807912529 (9)	1.237757758 (13)
1989 Jun	47681.9199	0.807911292 (2)	1.237759653 (3)

[a] Numbers in parentheses following the parameter estimates indicate 1 σ errors in the final decimal place.

[b] Derivative of pulse frequency included in the least-squares fit, with the result $\dot{\nu} = (+5.4 \pm 0.8) \times 10^{-13}$ Hz s^{-1}.

[c] SHORT HIGH state.

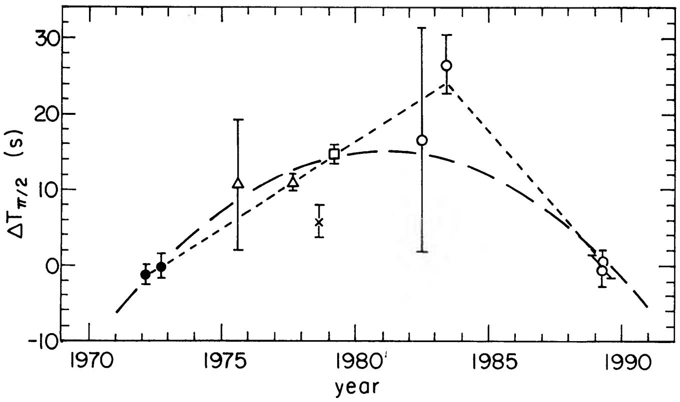

FIG. 1.—Residual orbital epochs for Her X-1, relative to a constant period determined from *Uhuru* data in early 1972 to *Ginga* data in 1989 May. Solid dots denote *Uhuru* data consolidated to two average epochs, triangles *OSO 8* data, the diagonal cross *HEAO 1* data, the open square *Einstein* MPC data (DBP), and open circles new results reported here based on *Hakucho*, *Tenma*, and *Ginga* data. The best-fit quadratic ephemeris given in Table 3 is indicated by the long-dash line. The first *OSO 8* point and the *HEAO 1* point are subject to possible systematic errors and were not included in the fit (see DBP). An alternative interpretation of these data which assumes a sudden change in orgital period in 1983 is indicated by the short-dash line.

ment in orbital parameters places on forced precession of the companion star as the origin of the 35 day cycle in Her X-1.

From the four new estimates of the orbital epoch and earlier determinations by DBP, we can now determine the orbital period over a baseline extending from 1971 to 1989. However, a plot of the differences of these epochs from a linear ephemeris reveals that the orbital period was not constant during this interval (see Fig. 1). At the present time, it is not possible to decide whether the change in period has been continuous, or whether there has been one or more "discontinuous" changes between 1972 and 1989. A simple characterization of continuous change in period is constant $\dot{P}$, whose value is empirically determined as the average $\dot{P}$ obtained by fitting orbital epochs represented in Figure 1 with a second-degree polynomial in N (orbital cycle number). The results of this fitting are given in Table 3, including $\dot{P} = (-2.25 \pm 0.27) \times 10^{-8}$ day yr^{-1}. This corresponds to an inverse time scale $|\dot{P}|/P = (1.32 \pm 0.16) \times 10^{-8}$ yr^{-1}, slightly smaller than the 2 σ upper bound of 2×10^{-8} yr^{-1} reported by DBP. It is, however, nearly an order of magnitude larger than the value associated with the mass transfer-accretion rate inferred from the X-ray luminosity of Her X-1 (Lamb, Pethick, & Pines 1973). In § 3.2 we discuss the restrictions on mass transfer in this system implied by this observed rate of change in the orbital period.

On the other hand, a discontinuous change in orbital period, $\Delta P \approx -4 \times 10^{-7}$ day (a change of slope shown by the dashed line in Fig. 1) occurring in the latter half of 1983 is also consistent with the pattern of measured orbital epochs. Such behavior might be linked to the extended X-ray LOW state constrained by *Tenma* (Nagase et al. 1984) and *EXOSAT* (Parmar et al. 1985) observations to begin in the latter part of 1983 May and to last for 5–9 months (no X-ray observations of Her X-1 have been reported for the 4 month interval from 1983 October 22 to 1984 March 1). If the change in orbital period were confined to the extended LOW state, then the local rate of change $\dot{P}/P$ would be between -6×10^{-7} yr^{-1} (5 month duration) and -3×10^{-7} yr^{-1} (9 month duration). The possibility of explaining both the extended LOW state and a simultaneous decrease in orbital period through a single cause, a temporary enhancement in mass transfer and consequent loss of mass and angular momentum from the system, is discussed below.

TABLE 3

MEAN ORBITAL PARAMETERS FOR HERCULES X-1[a]

$(T_{\pi/2})_{1456}$	43804.519980 (14)	MJED
P_{orb}	1.700167720 (10)	days
$\dot{P}_{orb}$	$(-2.25 \pm 0.27) \times 10^{-8}$	day yr^{-1}
$(a_x/c) \sin i$	13.1831 (3)	s[b]

[a] Numbers in parentheses following the parameter estimates indicate 1 σ errors in the final decimal place.

[b] From DBP.

3. DISCUSSION

3.1. *Limits on Forced Precession*

Forced precession of the companion star HZ Herculis together with a "slaved" accretion disk has been suggested as the underlying cause for the 35 day cycle in Her X-1 (Katz 1973; Roberts 1974; Petterson 1975). One consequence of such behavior is a compensating precession of the plane of the binary orbit that conserves the angular momentum of the system. The signature of this precession is a slow variation in the observed orbital parameters through the course of the 35 day precession cycle. This effect has been discussed by Deeter & Boynton (1976) who searched for it in data from four MAIN HIGH states of Her X-1 obtained with *Uhuru*.

This variation has two sinusoidal components, one at the precession period and a second at half the precession period. The second component is negligible unless the obliquity of the instantaneous orbit is larger than the orbital coinclination observed from the Earth. The present analysis shows that this condition is not satisfied in Her X-1, as the obliquity is about 1/20 of the coinclination (see below). We therefore need to consider only the first component, and a sensitive test for the presence of a 35 day precession of the orbital plane consists of comparing measured values of $(a_x/c) \sin i$ at roughly 17.5 day intervals; for example, during the MAIN HIGH and SHORT HIGH states.

It was noted in § 2.2 that there is good agreement between the orbital parameters in SHORT HIGH and MAIN HIGH states generally. This agreement can be expressed as a 2 σ upper bound on the product of the coinclination i' and the obliquity of the orbit β_o, $i'\beta_o < 2.3 \times 10^{-4}$. This is a factor of 5 smaller than the corresponding limit reported by Deeter & Boynton (1976). As shown in § 3.2, the inclination of the Her X-1 system is about 86°, so $i' \approx 0.07$ (4°), and hence $\beta_o < 0.0033$ (0°.19). However, the interesting limit is on the obliquity of the companion star. This depends on the ratio of the angular momenta of the star and the orbit, which is about 1/40 for the Her X-1 system (Deeter & Boynton 1976), yielding a 2 σ limit on the stellar obliquity $\beta_s < 0.13$ (8°).

This upper limit is not only significantly smaller than posed in Deeter & Boynton (1976) but is also much less than the corresponding tilt of the disk rim inferred from X-ray and optical modeling (Gerend & Boynton 1976; Crosa & Boynton 1980; Howarth & Wilson 1983). Putting aside the troubling question of how a fluid star can execute forced precession, this pulse-timing constraint on stellar obliquity limits further consideration of the slaved disk model.

3.2. *Orbital Period Change and Mass Flow*

Secular changes in orbital period have been reported for at least four X-ray binaries, including the high-mass system Cen X-3 (Fabbiano & Schreier 1977; Kelley et al. 1983), and three low-mass systems: Cyg X-3 (van der Klis & Bonnet-Bidaud 1981, 1989), X1822−371 (Hellier et al. 1990), and EXO 0748−676 (Parmar et al. 1991). A variety of explanations have been suggested for the period changes in these binaries; the most plausible involve mass transfer to the neutron star from its companion and/or mass loss from the system. We will not discuss alternative explanations for an *apparent* change in orbital period such as apsidal advance and orbital motion due to an otherwise unobserved third object, since they are either speculative or irrelevant to Her X-1.

The companion star to Her X-1 has a mass of 2.2 $M_\odot$, placing this system intemediate to high- and low-mass X-ray binaries (LMXBs). However, Her X-1 is probably closer to LMXBs regarding processes that might affect the orbital period, such as mass loss and/or transfer dominated by Roche lobe overflow rather than a stellar wind, and having negligible angular momentum residing in stellar rotation compared to that in the binary orbit. Even so, the periods for two of the three LMXBs mentioned above (Cyg X-3 and X1822−371) are increasing rather rapidly and therefore pose issues which are not pertinent to Her X-1, leaving EXO 0748−676 as the only LMXB exhibiting behavior possibly related to that observed in Her X-1.

On the other hand, Cen X-3 and similar high mass binaries are intrinsically different than Her X-1. Here the rotation of the companion star typically provides nearly nearly half of the total angular momentum in the system, and this reservoir of angular momentum must be taken into account when considering models for changes in the orbital period (cf. Kelley et al. 1983). In comparison the companion of Her X-1 is relatively compact, contributing only $\sim 2\%$ to the total angular momentum (assuming corotation). Therefore a simple model, in which the two stars comprising the binary are treated as point masses and only orbital angular momentum is considered, provides a reasonable approximation to the behavior of Her X-1.

For this simplified, analysis, we let m_1 be the mass of the neutron star, m_2 be the mass of the companion, $m = m_1 + m_2$ be the total mass of the system, a be the semimajor axis of the relative orbit, and Ω be the orbital angular velocity. Then the orbital angular momentum is given by $J = (m_1 m_2/m)a^2\Omega$. Kepler's third law may be used to remove explicit dependence of J on the semimajor axis, allowing the time derivatives of the remaining variables to be linked in a simple expression,

$$\frac{\dot{J}}{J} = \frac{\dot{m}_1}{m_1} + \frac{\dot{m}_2}{m_2} - \frac{\dot{m}}{3m} - \frac{\dot{\Omega}}{3\Omega} . \qquad (1)$$

We now consider several models of mass transfer and/or mass loss, using equation (1) to estimate the mass loss rate needed to sustain the observed $\dot{\Omega}$.

Case (*a*): *All mass lost from the companion is accreted by the neutron star.* In this case, $\dot{J} = 0$, $\dot{m} = 0$, and $\dot{m}_2 = -\dot{m}_1$. Using an eclipse duration of 0.232 days (DBP), and a mass ratio $m_2/m_1 = 1.68$ (Middleditch & Nelson 1976), a Roche-lobe model for the companion gives an orbital inclination for Her X-1 of 86°. Consequently, the mass function from the X-ray orbit yields stellar masses $m_1 = 1.3\ M_\odot$ (neutron star) and $m_2 = 2.2\ M_\odot$ (companion). Equation (1) then reduces to $\dot{\Omega}/\Omega = 0.94\ \dot{m}_1/M_\odot$, which indicates that mass transfer to the neutron star results in a decrease in the orbital period. From the value $\dot{\Omega}/\Omega = 1.32 \times 10^{-8}$ yr^{-1} calculated in § 2, we infer an accretion rate $\dot{m}_1 = 1.4 \times 10^{-8}\ M_\odot$ yr^{-1}. This is nearly an order of magnitude larger than the rate required to provide an X-ray luminosity of 2×10^{37} ergs s^{-1} (Lamb et al. 1973; London, McCray, & Auer 1981). Thus mass transfer alone cannot explain the observed change in orbital period of Her X-1. On the other hand, mass loss from the system will further diminish the orbital period provided it carries away enough angular momentum. We now consider two possible mechanisms that eject mass with high specific angular momentum.

Case (*b*): *Mass loss at the outer Lagrangian point* L_2. First we consider the extreme case in which all mass transferred from the companion is lost from the system, so that $\dot{m}_1 = 0$ and $\dot{m} = \dot{m}_2$. We assume that the material is lost in corotation at L_2, which lies $1.24a$ from the center of mass of the Her X-1 system. The associated loss of orbital angular momentum is given by $\dot{J}/J = 6.6\dot{m}/m$, and according to equation (1) the resulting change in orbital frequency is $\dot{\Omega}/\Omega = -16\dot{m}/m$. Consequently, the observed value of $\dot{\Omega}/\Omega$ reported in § 2 would require a mass loss rate $\dot{m} = -2.9 \times 10^{-9}\ M_\odot$ yr^{-1} for this case.

Since Her X-1 is not a contact binary, why should there be mass loss through L_2? Material arrives at the disk having relatively small angular momentum with respect to the neutron star, equivalent to a circular orbit with radius $0.073a$ (Begelman, McKee, & Shields 1983), and hence needs a large boost in angular momentum to raise it to L_2. Orbital torques on a nonaxisymmetric disk have been invoked to explain *removal* of excess angular momentum from the disk (Sawada et al. 1987), but the reverse mechanism to *add* angular momentum has little intuitive appeal. Even if such a mechanism could be invoked, X-ray photometry does not substantiate this model. Sonic mass flow through L_2 at the rate calculated above requires an accumulation of gas inside the associated critical Roche surface with mass density of approximately 10^{-10} g cm^{-3} (Pringle 1985), and consequently a column density of 10 g cm^{-2} through which both stars would have to be viewed once each orbit.

Case (*c*): *Magnetically channelled flow.* A wind emanating from the X-ray heated surface of the companion star provides another possible mechanism for loss of angular momentum in the Her X-1 system (Ruderman et al. 1989). The mass loss rate resulting from this wind may be comparable to the mass accretion rate onto the neutron star, although only a small fraction of the wind material is captured (London & Flannery 1982). According to equation (1), the specific angular momentum of this wind is so small (at least two orders of magnitude smaller than for material lost through L_2) that the orbital period should increase, even if the angular momentum is ultimately extracted from the orbit through tidal locking of the companion. A simple self-excited wind therefore cannot explain the period decrease observed in Her X-1.

If, however, the companion star possesses a magnetic field, the angular momentum carried away by the wind might be greatly increased. Mestel (1968) pointed out that magnetically channelled, centrifugally or thermally driven particle winds from rotating stars can yield significant angular momentum loss at modest mass loss rates because corotation of the flow extends out to the Alfvén radius. Subsequently, Patterson (1984) invoked magnetically channelled winds to explain the orbital evolution of catalysmic variables (CVs) and LMXBs, and Hellier et al. (1990) suggested that this mechanism is responsible for the period decrease in EXO 0748−676. According to London & Flannery (1982) and Ruderman et al. (1989), Her X-1 is expected to possess a wind with a mass flow rate comparable to the mass accretion rate; equation (1) then reduces to $\dot{J}/J \approx -\dot{\Omega}/3\Omega \approx -4 \times 10^{-9}$ yr^{-1}, assuming that the rotation of the companion is tidally locked to the orbital motion. The Alfvén radius of this wind would be roughly 7×10^{11} cm, requiring a magnetic field at the stellar surface of about 40 G (Mestel 1968).

A variation on this theme is to consider a magnetically channelled wind from the accretion disk. Cannizzo & Pudritz (1988) have shown that disk winds in the presence of equipartition-strength magnetic fields are highly efficient in removing angular momentum from CVs and, by extension, from disk-fed X-ray binaries. As a consequence of this efficiency nearly all the mass transferred to the disk is accreted by the neutron star, while the disk angular momentum is carried away by only a small fraction of the mass flow. In this way, the mass transfer rate and thus the rate of angular momentum deposition in the disk is fixed roughly by the value of the mass accretion rate inferred from the X-ray luminosity. But the rate of angular momentum loss needed to explain the observed value of $\dot{\Omega}/\Omega$ in Her X-1 significantly exceeds this limited deposition rate. Because we have found no acceptable mechanism for supplying angular momentum to the disk other than by mass transfer through L_1, we have not pursued this model further.

The discussion here does not even approximate a proper theoretical treatment of mass transfer and mass loss in the Her X-1 system. Our intention is only to present a rough, but quantitative examination of possible implications of the observations reported in this paper. Of these three simple models, only braking of the companion star by a magnetically channeled stellar wind provides a feasible mechanism for the angular momentum loss rate demanded by the observed values of $\dot{\Omega}/\Omega$ and the X-ray luminosity. Is there any independent observational evidence for such a wind? Both low- and high-dispersion *IUE* spectra of this system fail to establish the presence of either P Cygni profiles or even modest line shifts indicative of wind flows (Boyle & Howarth 1988; Boyle et al. 1986; Gursky et al. 1980). Mauche & Raymond (1987) have analyzed the physical conditions in catalysmic variables that do exhibit such evidence for winds. They find that emission line detection is probably marginal in CVs because of the high degree of ionization in the wind flows. The two order-of-magnitude higher X-ray luminosity associated with the Her X-1 system may consequently preclude spectroscopic detection of a wind, leaving this a possible mechanism for a steady loss of mass and angular momentum.

We turn now to the possibility that the orbital period change in Her X-1 was confined to the extended X-ray LOW state observed in 1983–1984. It is tempting to explain both of these phenomena by a sudden temporary increase in the rate of mass transfer through the inner Lagrangian point L_1. The consequent increase in column density of material near the orbital plane obscures our line of sight to the X-rays produced in the vicinity of the neutron star, resulting in the extended LOW state, and an associated loss of mass and angular momentum from the system could account for the change in orbital period.

There are several ramifications of this interpretation that are difficult to accept, however. For instance, if the decrease in orbital period is restricted to the 5–9 month interval of the extended X-ray LOW state, then the necessary rate of mass loss through L_2 (case *b*) must be roughly 10^{-7} $M_\odot$ yr^{-1}, or two orders of magnitude larger than the mass accretion rate needed to maintain the X-ray luminosity. Although such mass loss rates are not difficult to achieve during the evolutionary history of this system, turning this flow on abruptly (and for only a few months) may require rather special circumstances.

Another problem with this picture is that the Her X-1 system seems to have changed very little during the extended X-ray LOW state, except for the marked reduction in X-ray flux. In particular, heating of the companion was observed to persist during the extended LOW state (Delgado, Schmidt, & Thomas 1983; Mironov et al. 1986), so the scale height of a bloated disk must still have been sufficiently small to allow substantial illumination of HZ Her. Another indication of little change in mass transfer rate is the absence of significant variation in pulsation frequency inferred for the extended LOW state (Nagase 1989), indicating virtually no change in the mass accretion rate onto the neutron star. Furthermore, the phase of the 35 day cycle seems to have been maintained across the extended X-ray LOW state (Ögelman 1987), implying that the underlying 35 day clock was not disrupted by changes in the system.

We have suggested that continuous loss of mass and angular momentum from the Her X-1 system of a magnitude necessary to explain the observed decrease in orbital period may be a natural consequence of X-ray heating of the companion star driving a stellar wind in the presence of modest stellar magnetic field. By contrast, the interesting possibility of a discontinuous change in orbital period confined to the 1983–1984 extended LOW state runs contrary to the absence of change in other dynamical aspects of the system. It may be possible to decide whether or not the orbital period change was confined to the extended LOW state by using 1984 *EXOSAT* observations of Her X-1 to determine an orbital epoch directly following the extended LOW state.

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