Orbital Precession, Precessing Accretion Disks and Pulse Timing Residuals in Binary Systems with Mass Transfer

and

Hydrodynamic Stability of Jets Produced by Mass Accreting Systems

by

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Abstract

Part I:

We review the existing model for pulsed x-ray emission from the source Hercules X-1. A necessary part of this model is a precessing accretion disk which turns the source on and off with 35 day cycle. It is usually assumed that precession of the primary star in this binary system, Hz Hercules, slaves the disk to its precession rate. This model can account for the systems behavior in a qualitative manner. Precession of Hz Hercules with 35 day period requires precession of the binary orbit. Pulse arrival times from Herc X-1 have been analyzed for orbital precession. The inclusion of precession does not significantly improve the results obtained assuming a non-precessing orbit.

Part II:

Binary configurations like Herc X-1 can produce jets of material ejected perpendicular to the orbital plane. One such galactic binary system is SS433. On a much larger scale this type of system may produce extra-galactic jets whose observed emission is in the radio region of the spectrum. We have considered the fluid dynamical stability of such jets and the possible consequences of Kelvin-Helmholtz instability at the jet surface external medium interface.

The binary star system consisting of Hercules X-1 and Hz Hercules is an example of systems in which there is mass transfer from a primary star (Hz Herc) to a collapsed object (Herc X-1). Material in such systems forms an accretion disk around the collapsed object and material slowly spirals inwards as angular momentum is lost through turbulent and/or magnetic viscosity. Pulsed x-ray emission from Herc X-1 is produced as ionized material from the inner edge of the accretion disk is channeled along magnetic field lines to the polar caps of a rotating neutron star. The constant rotation of the neutron star and x-ray pulse rate of Herc X-1 provides a stable clock which can be used to determine orbital parameters of the binary system. One finds that the orbit is nearly circular with period 1.7 days and stellar separation is $\sim 4 \times 10^{11}$ cm; the neutron star's mass is $\gtrsim 1\ M_\odot$ and Hz Herc has a mass of approximately 2 $M_\odot$ (Giacconi et al. 1973). Additionally it is found that the pulsed x-ray emission has a 35 day on-off cycle with approximately 11 days on and 24 days off (Tananbaum et al. 1972). Optical observation of Hz Herc shows variation of 1.5 magnitudes on the 1.7 day orbital period but no 35 day variation (Bahcall and Bahcall 1972). This has been interpreted as a result of heating of Hz Herc by x-rays from Herc X-1 (Bahcall and Bahcall 1972; Forman, Jones, and Liller 1972).

The 35 day on-off cycle of the pulsed x-rays provides evidence for a tilted precessing accretion disk which occults the neutron star for 24 days and precesses with 35 day period (Katz 1973). Such an accretion disk can be created only if the mass is transfered with angular momentum inclined relative to the orbital angular momentum. This can occur if the spin axis of Hz Herc is inclined relative to the orbital axis, precesses with 35 day period driven by Herc X-1, and mass transfer is periodic (Roberts 1974). In this case the outermost part of the accretion disk is slaved to the precession of Hz Herc. Mass transfer can be periodic in a system with inclined primary as the size of the primaries Roch lobe is a minimum when the secondary (Herc X-1) crosses the equitorial plane of the primary (Avni and Schiller 1982). This implies mass transfer twice per orbit through the inner Lagrangian point. Since disk precession is opposite to the orbital motion, mass transfer occurs preferentially every 0.81 days, half the 1.62 day recurrence of identical accretion disk primary orientation (see Figure 1). Because the precessing disk cannot occult Herc X-1 as seen from Hz Herc, accretion disk parameters and orientation of the observer with respect to the orbital plane are constrained. The disk must be tilted about 30^{o} with respect of the orbital plane with width subtending an angle of about 37^{o} as viewed from Herc X-1, the outer edge of the accretion disk is at distance $> 1.6 \times 10^{11}$ cm from Herc X-1, and the observer's line of sight is about 9^{o} above the orbital plane (Gerend and Boynton 1976) - see Figure 2.

The fluid accretion disk precesses at a rate which is related to the forced precession rate, the transfer of angular momentum outwards from the inner portions of the disk, and the natural precession rate. An accretion disk acting under these driving torques behaves like a series of concentric rings which precess with different rates. The net result is a twisted accretion disk (Petterson 1975). In the Hercules system the natural precession rate of the disk outer edge is faster than the forced precession rate and is $\sim$ 17 days if the outer edge is at radial distance 2×10^{11} cm. In this case Herc X-1 is obscured before turn-on by the outer edge of the accretion disk and occulted at turn-off by inner portions of the disk. Since the outer portion of the accretion disk is force to precess with 35 day period rather than its natural 17 day period the outer edge of the disk nutates in addition to the average forced precession. It can be shown that disk tilt, θ, and angle of the line of nodes, ϕ, can be approximated by (Katz et al. 1982)

$$\theta \simeq \theta_o - \frac{\Omega_o \tan \theta_o}{2(\omega_* - \Omega_s)} \cos 2[(\omega_* - \Omega_s)t - \phi_o]$$

and

$$\phi \simeq \Omega_s t - \frac{\Omega_o}{2(\omega_* - \Omega_s)} \sin 2[(\omega_* - \Omega_s)t - \phi_o] + \phi_o .$$

In these expressions θ_o is the average disk tilt, Ω_s is the average forced precession frequency, Ω_o is the natural precession frequency - a function of radius, and ω_* is the orbital frequency. Note that $\Omega_o = - |\Omega_o|$ and $\Omega_s = - |\Omega_s|$ because precession is opposite to the direction of orbital motion, $\omega_* = |\omega_*|$.

Height of the center line of the disk relative to the orbital plane along the observer's line of sight is given by

$$h(t) = a \sin \phi \sin \theta$$

where a is the disk radius. Provided nutation is small

$$h(t)/a \sin \theta_o \simeq \sin (\Omega_s t + \phi_o) [1 - \frac{\Omega_o}{\omega_{.81}} \cos (\omega_{.81} t - \phi_o)]$$
$$- \cos (\Omega_s t + \phi_o) [\frac{\Omega_o}{\omega_{.81}} \sin \omega_{.81} t]$$

where $\omega_{.81} \equiv 2(\omega_* - \Omega_s)$ and has a 0.81 day period. Minimum h(t) corresponds approximately to the midpoint of the on state and turn-on occurs preferentially when h(t) is most rapidly varying. The behavior of h(t) is shown in figure 3 for $\phi_o = 0$, i.e., the line of nodes points towards the observer and the center line of the disk is in the orbital plane at eclipse center t = 0. The 11 day on state would begin when the center line of the disk is in the shadowed band. The horizontal arrows indicate two possible turn-on points on either side of the vertical arrow which is at eclipse center. In this example turn-on would occur preferentially at about 0.75 or 0.15 orbital phase relative to eclipse center. An analysis by Levine and Jernigan (1982) shows that a solid precessing ring mimics reasonably well the behavior of a fluid ring. Both Katz et al., and Levine and Jernigan claim that nutation can lead to preferential turn-on at orbital phase of about 0.3 and 0.7 relative to eclipse center. This behavior is suggested by the data (Boynton 1980). However, the tendancy for turn-on at these orbital phases is marginal (Levine and Jernigan 1982). Following h(t) over several precession periods suggests that turn-on moves in orbital phase as periodicities are not integer multiples of each other. The fact that closely spaced ($\sim$ 0.5 day apart) local minima and maxima exist in h(t) resulting from disk nutation suggest the possibility of turn-on followed by an absorption dip or weak turn-on followed by strong turn-on about 0.5 day later. Effects like these are seen in the data. However, the data also reveal so called anomolous absorption dips in the second binary orbit after turn-on. Disk nutation would only seem capable of producing absorption dips within the first binary orbit after turn-on. Recent results also show that turn-on varies by as much as 2 days from the 35 day average (Boynton, Crosa, and Deeter 1980). This behavior cannot be accounted for by nutation alone. It is possible that a combination of circulating structure on the disk edge and nutation can explain these and one other effect. Material is deposited with 0.81 day periodicity at the disk edge and increased disk thickness may be associated with this deposition. Crosa and Boynton (1980) argue that the Keplerian orbital period of about 15 hours at the disk edge when combined with scale height relaxation after mass transfer can explain absorption dips seen before eclipse. These pre-eclipse dips march to earlier orbital phase relative to eclipse center as the on cycle progresses. This behavior is produced in their model because material is deposited at the disk edge at earlier orbital phase as the on cycle progresses and circulates around the disk into the line of sight occulting Herc X-1 before eclipse at earlier orbital phase as the cycle progresses. It seems likely that a combination of disk nutation at 0.81 day period when linked to mass transfer effects at 0.81 day period will come closer to reproducing the observed effects as the two effects can be complimentary.

While these qualitative explanations for the complex behavior of Herc X-1 are plausible they are difficult to verify. Since the tidal torques acting on the system should have reduced precession of Hz Herc just as they are presumed to have circularized the orbit (Chevalier 1976), there is considerable reason to attempt to verify precession of Hz Herc. If Hz Herc precesses then the binary orbital plane must also precess with 35 day period. This orbital precession leads to x-ray pulse arrival times different from arrival times from a non-precessing orbit. The flight time of photons from a precessing non-nutating orbit is given by

$$\tau_p \simeq \frac{D}{c}\left(1 - 2\frac{D_{cm}a}{D^2}\left[\cos i\,\{\cos(\omega_* - \Omega_s)t\,\sin(\Omega_s t + \phi_o) + \cos\theta_o\,\sin(\omega_* - \Omega_s)t\,\cos(\Omega_s t + \phi_o)\} + \sin i\,\{\sin\theta_o\,\sin(\omega_* - \Omega_s)t\,\}\right]\right)$$

and for a non-precessing orbit ($\Omega_s = 0$) is

$$\tau_o \simeq \frac{D}{c}\left(1 - 2\frac{D_{cm}a}{D^2}\left[\cos i\,\{\cos\omega_* t\,\sin\phi_o + \cos\theta_o\,\sin\omega_* t\,\cos\phi_o\} + \sin i\,\{\sin\theta_o\,\sin\omega_* t\}\right]\right)$$

In these equations D_{cm} is the distance to the systems center of mass, $D = [D_{cm}^2 + a^2]^{1/2}$ where a is the distance of Herc X-1 from the center of mass, ω_* is the orbital frequency, $\Omega_s = -|\Omega_s|$ is the precession frequency, θ_o is the orbital tilt relative to the constant system angular momentum, and i is the inclination of the observer relative to the average orbital plane. The difference between flight times is

$$\Delta\tau \simeq -(a/c)(\theta_o^2/2)\cos i\,[\sin\omega_{1.62}t\,\cos(\Omega_s t + \phi_o) - \sin\omega_* t\,\cos\phi_o] + (a/c)\,\theta_o\,\sin i\,[\,\sin\omega_{1.62}t - \sin\omega_* t]$$

where $\omega_{1.62} \equiv \omega_* - \Omega_s$. For Herc X-1 $a \simeq 2.7 \times 10^{11}$ cm, $\theta_o \sim 0.5^o$ (we assume $L_{Hz\ Herc}/L_{orbit} \sim 0.02$ and that Hz Herc is tilted by 30^o), $i \simeq 9^o$, and we find that $\Delta\tau$ can be as large as 20 msec. Arrival time data has been analyzed assuming a precessing orbit and compared to analysis assuming a non-precessing orbit. While the fit was not significantly improved the amount of data was not sufficient to rule out precession of the orbit and Hz Herc. If more data becomes available in the future a better test of orbital precession can be performed.

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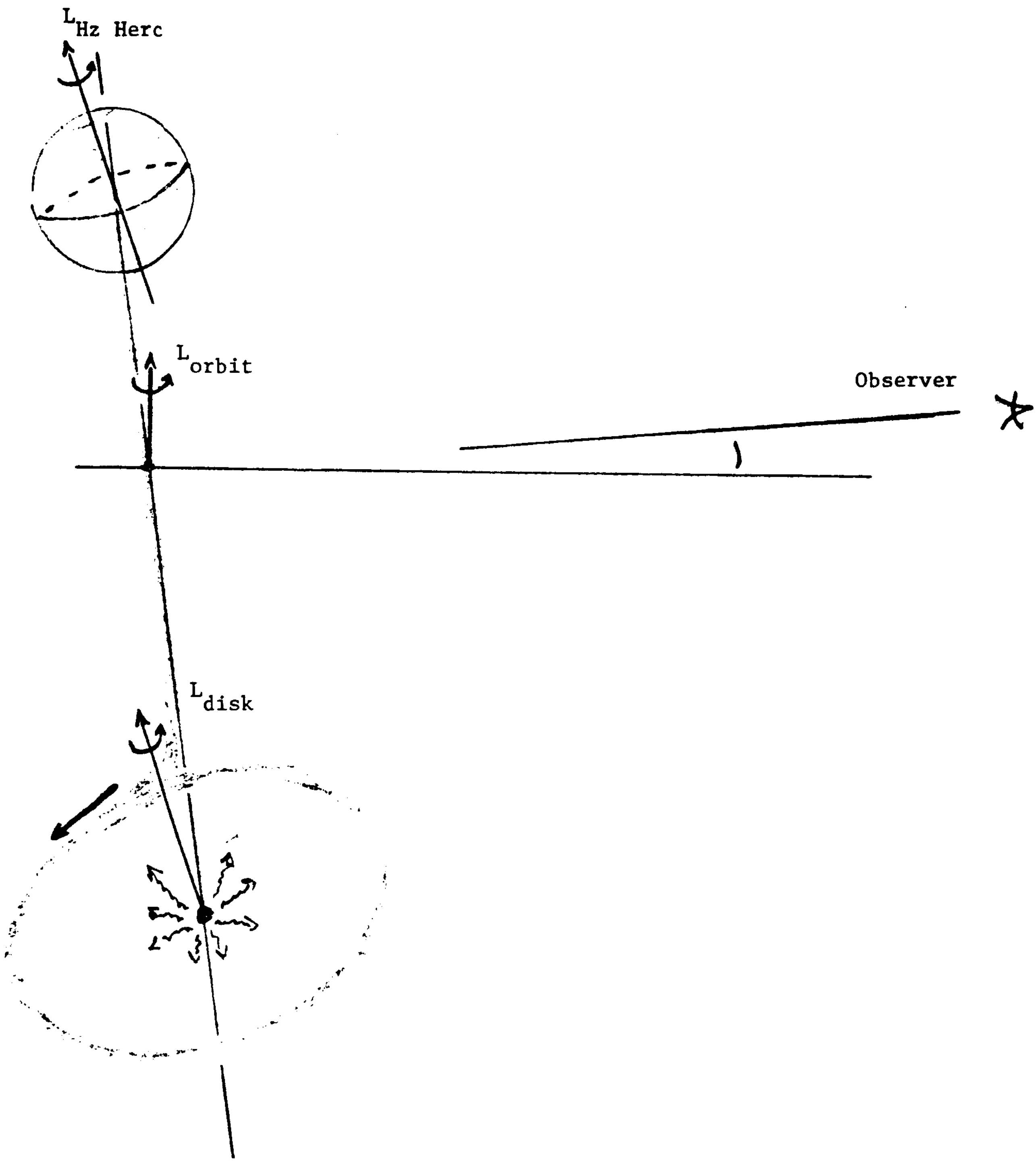


Figure 1: Herc X-1 crosses the orbital plane of Hz Herc and mass is transfered to the outer edge of the accretion disk. Precession is opposite to the direction of orbital motion.

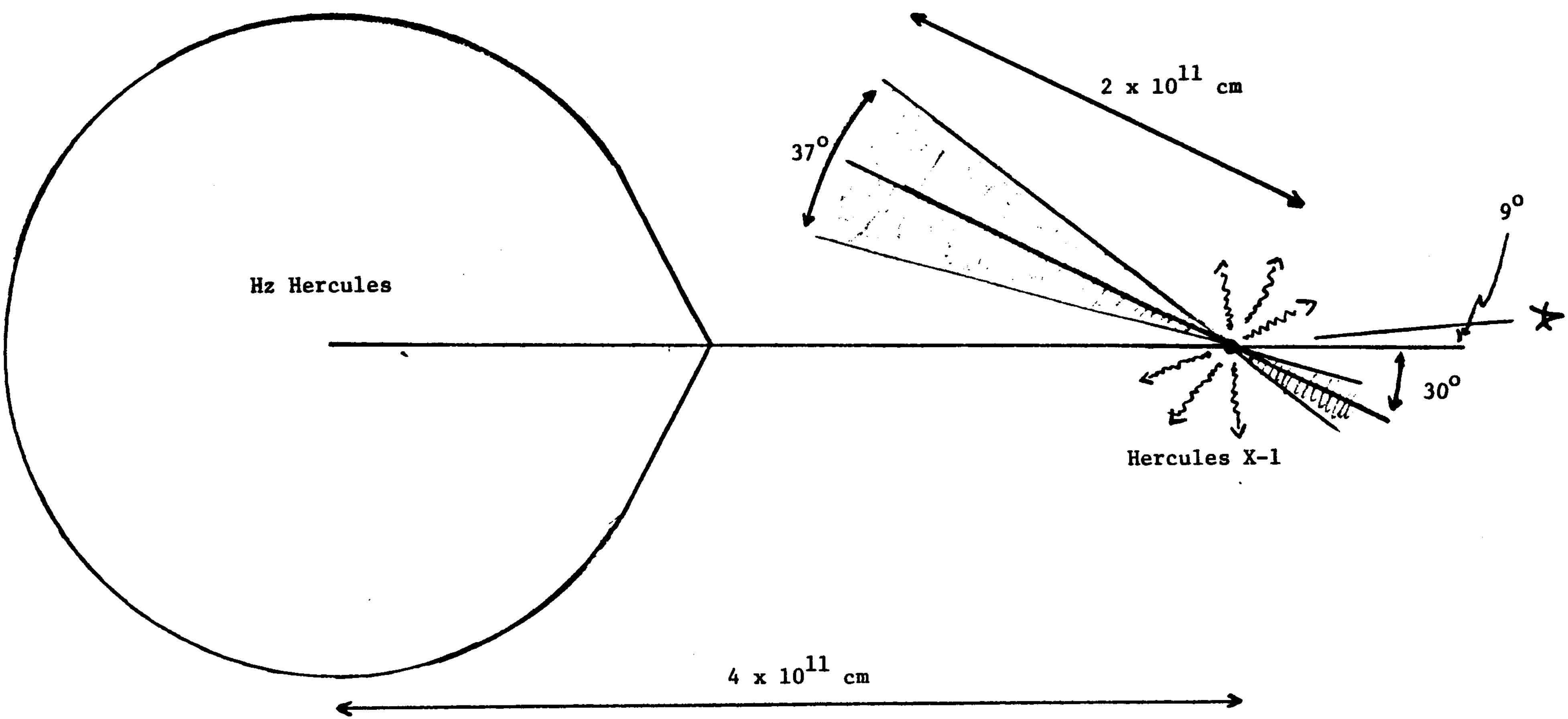
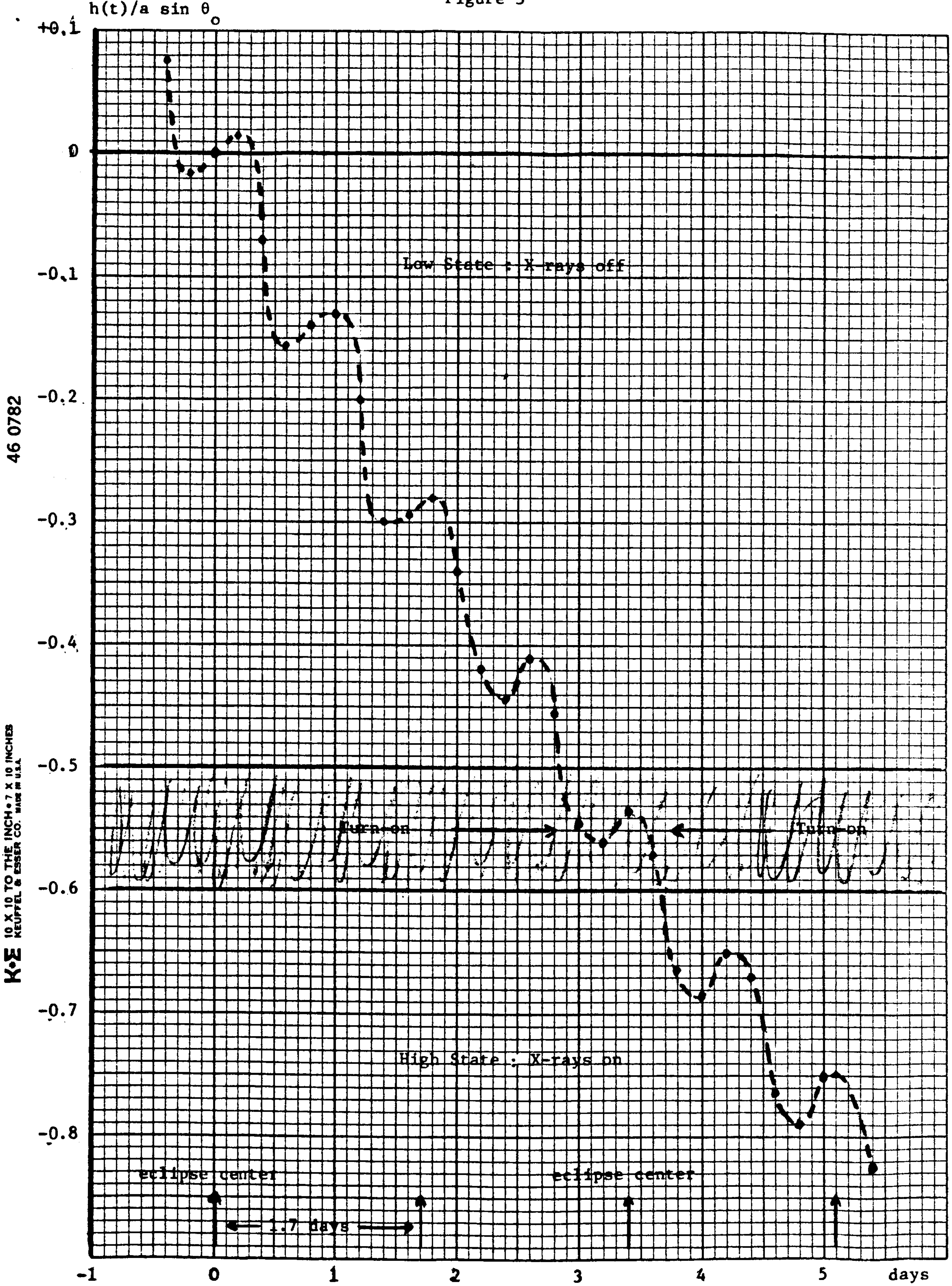


Figure 2: Accretion disk geometry implied by the optical observations of Hz Herc and the pulsed x-rays from Herc X-1.

Figure 5


h(t)/a sin θ_o
+0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
Low State : X-rays off
Turn-on
Turn-on
High State : X-rays on
eclipse center
eclipse center
1.7 days
-1
0
1
2
3
4
5
days
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