

DISCOVERY OF A PERIODIC PULSATING BINARY X-RAY SOURCE IN HERCULES FROM *UHURU*

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Received 1972 April 26

ABSTRACT

We have discovered a new pulsating X-ray source with a 1^d24 period in the constellation Hercules. Analysis of 5 months of data has shown the existence of periodic variations in the intensity of the source and correlated sinusoidal variations in the period of the 1^d24 pulsations. As in the case of the pulsating X-ray source Cen X-3, we interpret this effect as due to an occulting binary system, with the intensity changes due to occultation of the X-ray source by its companion and with the sinusoidal variations in the period of the 1^d24 pulsations due to the Doppler effect. The orbital period for the X-ray source is $1^d70017 \pm 0^s00004$, and the time of occurrence of the center of occultation is UT (1972 January 13.0772 $\pm$ 0.0003) $\pm$ $n(1.70017 \pm 0.00004)$. In addition, we have observed a longer-timescale cycle in which the source is bright and pulsing for approximately 9 days during which we can observe the 1^d7 occulting, followed by approximately 27 days during which the source is not detected above background on individual 20-s scans.

I. INTRODUCTION

As previously reported (Schreier *et al.* 1972), we have observed from *Uhuru* a periodic pulsating X-ray source in Hercules, 2U 1705+34, which shows two distinct levels of intensity. The presence of both regular pulsations and distinct variations in average intensity led to the immediate conjecture as to its similarity to the occulting binary Cen X-3.

We have now ascertained the periodicity of the intensity changes between the two levels and the presence of cyclic variations of the pulsation period with the same 1^d7 period. In these two major features, then, the source is similar to Cen X-3 and should be regarded as the second confirmed example of a class of X-ray-emitting occulting binaries. In addition, however, the Hercules source exhibits a 36-day cycle involving extended times when the source does not emit X-rays at its high level.

II. OBSERVATIONS

In 1971 November we observed a previously unreported pulsing X-ray source in the constellation Hercules. Figure 1 shows a histogram of counts observed in 0^s096 intervals during the central 30 s of a 100-s observation of this source. The continuous curve is a minimum χ^2 fit to the pulsations of a sine function, its first and second harmonic, plus a constant, modulated by the triangular response of the collimator. The period determined from this fit is $1^s2368 \pm 0^s0006$. The data show that at least 80 percent of the power is pulsed when the source is in this high-intensity state, which is observed at approximately half the intensity measured for Cen X-3.

Our ability to locate this new X-ray source was limited by the failure of the *Uhuru* star aspect sensors in 1971 November. However, by observing the source with spin-axis orientations that included in the scan band strong, well-located sources such as Sco X-1 and Cyg X-1, we were able to obtain an approximate location for the source. Within this location box, we had previously obtained a location for the X-ray source 2U 1705+34 (Giacconi *et al.* 1972). Although this is a relatively weak source, we are confident that it is in fact the Hercules pulsating source, particularly because we find individual sightings of this weak source at least 50 percent pulsed with a period consistent with

SOURCE IN HERCULES (2U1705+34)

November 6, 1971

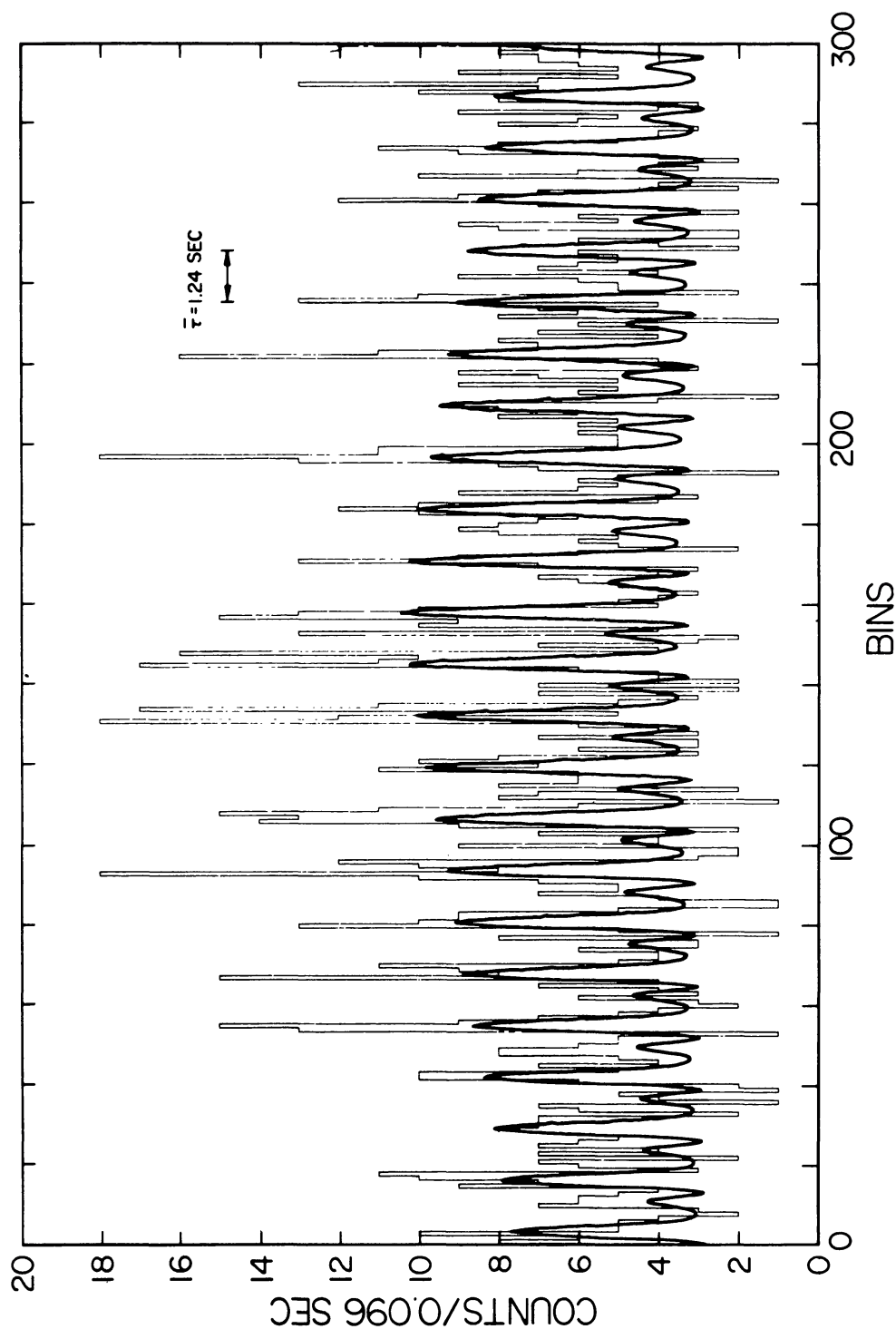


FIG. 1.—The counts accumulated in 0.096-second bins from Hercules X-1 during the central 30 seconds of a 100-second pass on 1971 November 6. The heavier curve is a minimum χ^2 fit to the pulsations of a sine function, its first and second harmonics plus a constant, modulated by the triangular response of the collimator. The functional fit is systematically below the peak counting rate partly due to the sharpness of the pulsing and partly due to the minimum χ^2 technique.

1^s24. The centroid for the source location is $\alpha(1950) = 17^{\text{h}}05^{\text{m}}30^{\text{s}}$, $\delta(1950) = 34^{\circ}52'$, while the corners of the 90 percent confidence location box are given as

$$\begin{aligned} \alpha &= 17^{\text{h}}13^{\text{m}}18^{\text{s}}, & \delta &= 34^{\circ}33'; & \alpha &= 16^{\text{h}}57^{\text{m}}30^{\text{s}}, & \delta &= 35^{\circ}31'; \\ \alpha &= 16^{\text{h}}57^{\text{m}}18^{\text{s}}, & \delta &= 35^{\circ}15'; & \alpha &= 17^{\text{h}}13^{\text{m}}06^{\text{s}}, & \delta &= 34^{\circ}18'. \end{aligned}$$

We observed two distinct intensity levels in our 1971 November observations of the Hercules source, as can be seen in the upper portion of figure 2. We then began to look

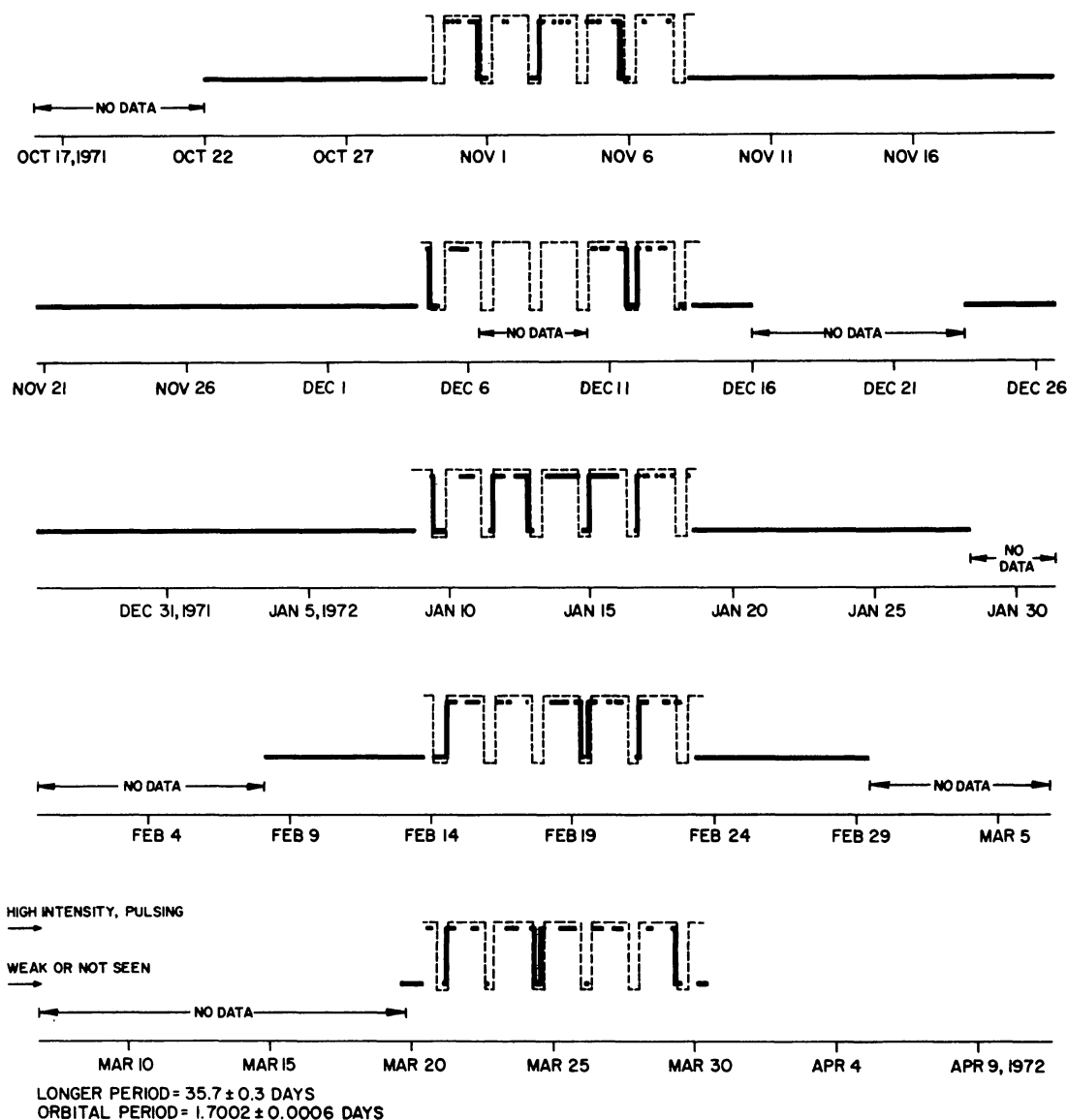


FIG. 2.—The heavier lines represent schematically the observations of Hercules X-1 as either high-intensity, pulsed sightings or as weak or not observed sightings. Short-term breaks are due to blocking of the source by the Earth or due to dropouts in Quick Look data transmission. Intervals where the satellite was oriented so as not to scan the Hercules source are marked no data. The lighter dashed curve shows a single 1.700-day period fit to all of the observations. Each row in the figure has a duration of 35.7 days and the regular occurrence of the 9-day high-intensity pulsed intervals demonstrates the 35.7-day cycle discussed in the text.

for a periodicity in the intensity changes as had been reported for Cen X-3 (Schreier *et al.* 1972). Figure 2 shows the results of approximately 5 months of almost continuous observations of the Hercules source. In the figure we have represented the Hercules observations schematically either as high-intensity pulsed sightings or as weak or not observed sightings. The heavier curve gives the actual observations, with short-term breaks due to blocking of the source by the Earth or due to dropouts in Quick Look data transmission. Intervals where the satellite was oriented so as not to scan the Hercules source are marked as "no data."

Data in figure 2 such as those from 1972 January 9–18 which shows several high states, low states, and transitions were used to determine a 1^d7 intensity cycle. The lighter dashed curve shows a unique periodic 1^d700 fit to all of the intensity observations. We estimate average durations of $1^d43 \pm 0^d08$ for the high state, $0^d24 \pm 0^d06$ for the low state, and of less than 0^d025 for each transition, with the period being $1^d7002 \pm 0^d0006$.

In the case of Cen X-3, we have pointed out that there are times at which the source remains in its low emission state for days; these extended lows have not yet exhibited any predictability. However, as seen in figure 2, the Hercules data show a regular pattern for this extended low-intensity state. From the data in figure 2 we determine a duration of $35^d7 \pm 0^d3$ for this new cycle. For $8^d9 \pm 0^d3$ the source is intense, pulsing, and exhibits the 1^d7002 intensity period. It then remains weak or off for $26^d8 \pm 0^d3$. The phase of this cycle is such that the center of the 9-day intense state occurs at UT (1972 February 18.8 ± 0.5) $\pm n(35.7 \pm 0.3)$. The probability that randomly occurring extended low-intensity states could produce the pattern observed is less than 1 part in 10^9 .

Examining all of the *Uhuru* scans of the Hercules region, we find no intense, pulsing sightings except those shown in figure 2. Observations in 1971 January do show the source to be at a low but observable intensity, with definite pulsations during an expected high state. Other observation times correspond to predicted low states, and the source is not seen. Thus, the 35^d7 cycle may have had a somewhat different behavior before 1971 November with a lower intensity during the high states.

With the evidence that the pulsating X-ray source Hercules X-1 is a component of a binary system with an orbital period of 1^d7 , we were led by our knowledge of Cen X-3 to look for Doppler variations in the 1^d24 pulsation period. The technique of following the phase of the pulsations from sighting to sighting has been described in detail in our earlier papers (Giacconi *et al.* 1971; Schreier *et al.* 1972). In figure 3 we show the phasing analysis for 3 days of data obtained in 1972 January. Also shown is the sine-function fit to the data. If we assume that the observed variations in arrival time of the pulses are due to orbital motions of the source, then the amplitude of the sine curve directly measures the projected radius of the orbit which is 13.19 ± 0.03 light-seconds. The projected velocity computed for this radius using a period of 1^d700 is 169.2 ± 0.4 km s $^{-1}$.

The average pulsation period determined from this sine fit is $1^d237772 \pm 0^s000001$. While the phasing technique does not give the period uniquely, but rather a set of discrete periods, there is strong evidence for the value given. This is the only value for the period which is consistent with the period determined directly from the 100-s observation in 1971 November. Furthermore, the sets of periods determined in 1971 December, 1972 January, 1972 February, and 1972 March are consistent with one another to a precision small compared to the spacing of adjacent possible periods. If the period were changing from month to month, the probability that these sets of periods would be consistent is less than 1 percent. Since we have not yet analyzed production data for the other observations, we can not presently discuss the possibility of period changes smaller than 0.1 ms.

By comparing the phases of the Doppler curve shown in figure 3 and a similar analysis done for the 1971 December data, we independently determine the occultation period as $1^d70017 \pm 0^d00004$. In addition, we find that the zeros of the sine function coincide with the centers of the low and high states of this cycle.

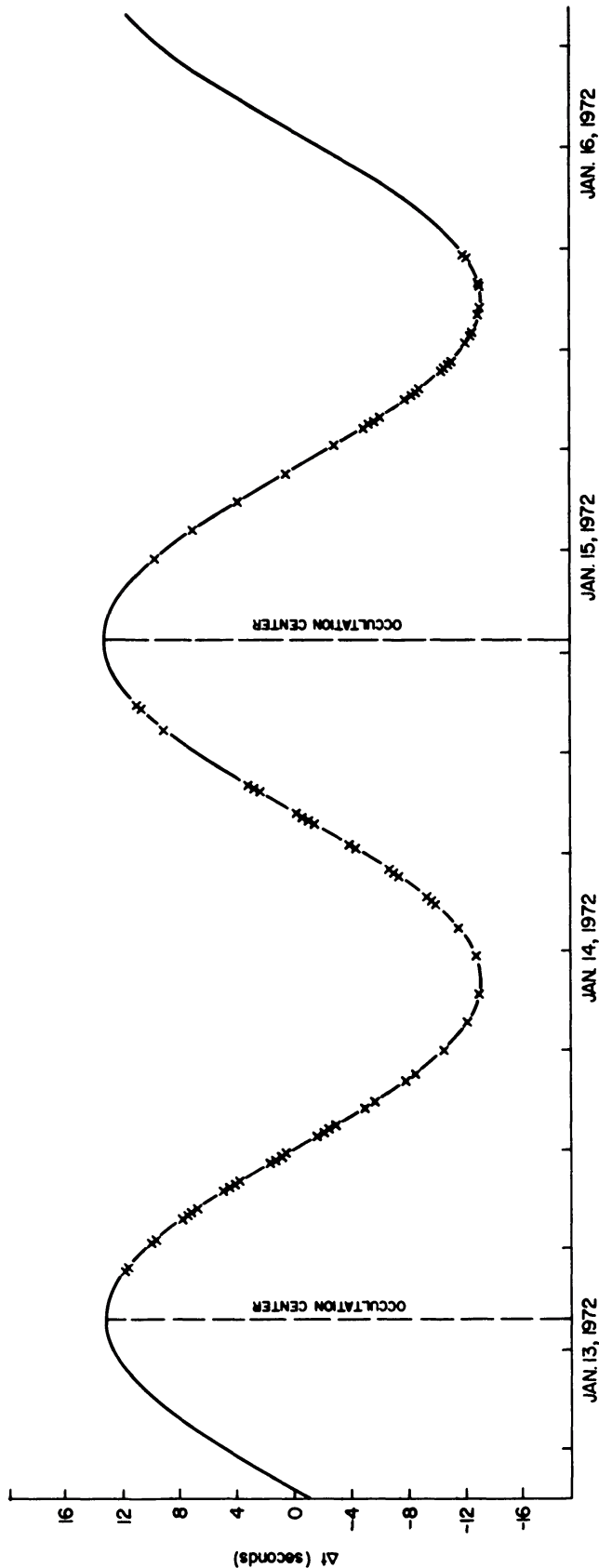


FIG. 3.—The difference Δt between the time of occurrence of a pulse and the time predicted for a constant period is plotted as a function of time. A best fit function and the values of the parameters are given. $\Delta t = t_n - j_n \tau^*$; $\Delta t = at + b \sin [2\pi T^{-1}(t - t_0)]$; $\tau^* = 1.237772 \pm 0.000001$; $a = 0 \pm 0.0000001$; $b = 13.19 \pm 0.03$ sec.

III. DISCUSSION

The preceding data show that the dominant features observed in Cen X-3 are also found in the Hercules source; there exists a periodic 1^d700 intensity cycle with sharp transitions between two intensity states, and a sinusoidal variation in the 1^s24 pulsations, consistent with the same period and phased so that the zeros of the period variation coincide with the centers of the low- and high-intensity states. Thus, we conclude that the physical mechanism is an occulting binary system as proposed for Cen X-3, whereby the X-ray pulsations emanate from a compact object in a close orbit about another body. Using this model, we may compute from the observational data the orbital radius and velocity of the compact object as well as the mass function. In table 1 we summarize the relevant observational and derived parameters for the two sources.

It can be seen that the Doppler velocity of 169 km s⁻¹ for Her X-1 is less than half that for Cen X-3, and thus the mass function is decreased by a factor of about 20. With a mass function of 0.85 $M_{\odot}$, we would not necessarily expect the system to be very luminous optically. However, the location of Hercules 35° off the galactic plane may facilitate an optical identification.

It has been pointed out by R. E. Wilson (1972) and others that for close binaries, the size of the Roche lobe of the occulting object is determined by the mass ratio. Although sophisticated techniques exist to calculate this dependence (e.g., Wilson and Devinney 1971), we use the approximate relation (Plavec 1968)

$$R_L/D = 0.38 + 0.2 \log (M_2/M_1) ,$$

where R_L is the radius of the Roche lobe, D the separation of the binary components, and M_1 and M_2 the masses of the X-ray source and occulting star, respectively. We also use the classical expression

$$R^2/D^2 = \cos^2 i + \sin^2 b \sin^2 i ,$$

TABLE 1
PARAMETERS

Observed Parameters	Centaurus X-3	Hercules X-1
τ (average pulsation period in seconds).....	4.843496±0.000007 4.842185±0.000001 4.842176±0.000012	1.237772 ±0.000001
$\Delta\tau$ (half-amplitude of period variation in seconds).....	0.006717±0.000005	0.0006986±0.0000014
T (orbital period in days).....	2.08712 ±0.00004	1.70017 ±0.00004
Low duration.....	0.476 to 0.500	0.18 to 0.30
Each transition.....	0.035 ±0.007	0.005 to 0.025
High duration.....	1.541 to 1.517	1.51 to 1.35
ϕ_T (phase of eclipse: low center)	UT 1971 June 29.583±0.001	UT 1972 Jan 13.0772±0.0003
P (long-term period in days)...	?	35.7±0.3
(Up duration).....	?	8.9±0.3
ϕ_p (phase long term: high center).....	?	UT 1972 Feb 18.8±0.5
Derived Parameters	Centaurus X-3	Hercules X-1
$v \sin i = (\Delta\tau/\tau)c$ (km s ⁻¹).....	415.1±0.4	169.2±0.4
$r \sin i = (T/2\pi) v \sin i$ (cm)....	(1.191±0.001)×10 ¹²	(3.95±0.01)×10 ¹¹
$M_2^3 \sin^3 i / (M_1 + M_2)^2 =$ $(2\pi/T)^2 (r \sin i)^3 / G$ (grams)...	(3.074±0.008)×10 ³⁴ ≈15 $M_{\odot}$	(1.69±0.01)×10 ³³ ≈0.85 $M_{\odot}$
e (eccentricity).....	≤0.05	≤0.1

where R is the radius of the occulting object, i the orbital inclination, and b the phase angle of the occultation duration. If we assume from the sharpness of the occultation that the obscuring region is no larger than its Roche lobe (Wilson 1972), we can determine upper estimates for the masses M_1 and M_2 for a given inclination. At 90° inclination, M_1 ranges from 0.22 to $3.0 M_\odot$ and M_2 from 1.2 to $3.2 M_\odot$ as b varies from 31.8° to 25.4° . These values for b correspond to 0^d30 and 0^d24 estimated limits for the maximum occultation duration observed for Her X-1. The range of values for the occultation duration given in table 1 extends somewhat lower than 0^d24 , since for Her X-1 as well as for Cen X-3 the duration of the occultation is variable. For Cen X-3, the measurements are precise enough to require the X-ray source to be significantly less than $1 M_\odot$. A small rotating neutron star that is accreting mass from its companion seems a plausible model for the X-ray source (e.g., Sofia 1972).

The most apparent difference between Her X-1 and Cen X-3 as seen from table 1 is the presence of the 36-day cycle for the Hercules source. The data currently available indicate that if Cen X-3 also has a regular cycle for these extended lows, the period must be considerably longer; furthermore, the cycle must be more involved than a single pair of high-low states.

Several possibilities have been suggested for explaining the 36-day effect for Hercules. One involves a three-body system with a highly eccentric orbit to account for the 75 percent off-time for the source. This seems unlikely due to geometrical considerations and the lack of an observed effect on the 1.47 Doppler curve. A second possibility is pulsation of the central star with a 36-day period. The extended lows would occur when the X-ray source is sufficiently embedded in the atmosphere of the central star to have the X-rays absorbed. One objection to this model is that the radius of the central star as calculated for classical objects such as Cepheids with a 36-day period is considerably larger than the orbital radius shown in table 1. A third suggestion for the 36-day period involves instabilities of the atmosphere of the central star near its Roche lobe. This model assumes accretion onto the X-ray star as the energy source for the X-rays; when the Roche lobe is no longer filled, the energy source is effectively turned off until the atmosphere of the central star again fills the Roche lobe. A fourth possible mechanism involves precession of a pulsar beam such that we are in the path of the beam for 9 out of 36 days.

Further analysis of data involving the X-ray light curves and spectra during transitions may allow us to choose among the various models. In this regard, it should be noted that Her X-1 shows qualitatively the same spectral behavior as Cen X-3, with a substantial low-energy cutoff that appears to vary, and a very flat overall spectrum. Given the remarkable similarity of the two pulsating binary sources Cen X-3 and Her X-1, we find it attractive to assume that the physical mechanisms for the two are the same and that the 36-day cycle for Her X-1 and the extended lows of Cen X-3 will eventually be understood in terms of a single mechanism.

We would like to thank Wallace Tucker for useful discussions. This research was sponsored under NASA contract NAS5-11422.

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