

EVIDENCE FOR THE BINARY NATURE OF CENTAURUS X-3 FROM *UHURU* X-RAY OBSERVATIONS

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ABSTRACT

Analysis of data spanning a year of observations of the pulsating X-ray source Cen X-3 from *Uhuru* has revealed the existence of periodic variations in intensity of the source and correlated sinusoidal variations in the period of the 4^s8 pulsations. We interpret this effect as due to an occulting binary system. The changes in intensity are then due to occultation of the X-ray source by a large massive companion, and the sinusoidal variations in the period of the 4^s8 pulsations are due to Doppler effect. The orbital period of the X-ray source is $2^{\circ}08712 \pm 0^{\circ}00004$. The time of occurrence of the center of occultation is $\text{JD}(2,441,132.081 \pm 0.001) \pm n(2.08712 \pm 0.00004)$. Physical parameters for the system are derived. Evidence for the existence and nature of an extended atmosphere surrounding the massive occulting object is discussed.

I. INTRODUCTION

In a previous letter (Giacconi *et al.* 1971) we have reported the discovery of periodic X-ray pulsations from Cen X-3. Over 70 percent of the X-ray flux was found to be pulsed with a period of approximately 4^s8. The average intensity was observed to change by a factor of 10 within 1 hour during a day-long observation. The regular nature of the pulsations set the source apart from the variable pulsating sources, such as Cyg X-1 and the source in Circinus, 2U 1516-56 (Schreier *et al.* 1971a; Margon *et al.* 1971).¹

Since the discovery of its pulsing properties, we have continued analyzing observations of Cen X-3 from *Uhuru* taken between 1971 January and December. The study of these additional data has led to the discovery that Cen X-3 undergoes regular changes in intensity between two distinct levels with a period of 2 days. Furthermore, the period of the short pulsations (4^s8) undergoes continuous variations with the same 2-day cycle, indicating the existence of a physical connection between these two effects.

We have adopted the working hypothesis that we are dealing with an eclipsing binary system consisting of a compact object and a large massive companion. We find that all our present observational data are consistent with this interpretation. We can then derive detailed physical parameters describing the mass of the system, the orbital radius and velocity, and also some information about the atmosphere of the large companion.

II. INTENSITY VARIATIONS

In examining the entire set of observations from 1971 January to 1971 December we were struck by the existence of two distinct levels of intensity at which the source would appear. The transitions between high and low levels, when they could actually be observed, were always found to occur within about 1 hour.

In 1971 May we obtained a continuous and detailed set of observations of Cen X-3 spanning an entire week. The data are shown in Figure 1. The intensities shown represent the observed counting rates above background. Since the source pulsates, we have defined the intensity as the average counting rate over each transit containing several 4^s8 periods. The observed high-level intensity corresponds to an absolute counting rate of 0.25-0.35 counts cm⁻² s⁻¹ in the 2-6-keV energy range. Three low-intensity states are observable starting at days 126.02, 128.12 and 130.2, respectively. The low-level in-

¹ The 2U notation for sources refers to *The Uhuru Catalog of X-Ray Sources* (Giacconi *et al.* 1972).

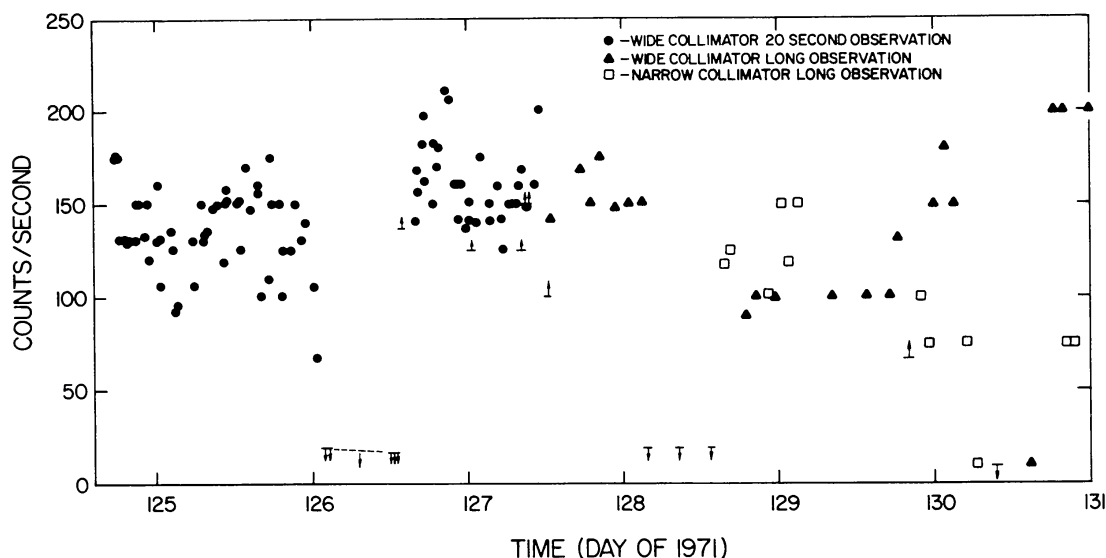


FIG. 1.—The observed intensity from Cen X-3 averaged over several 4 $\times$ 8 cycles is shown as a function of time. The different symbols refer to sightings of different duration as noted. The data have not been corrected for elevation in the field of view of the detector.

tensity is approximately $0.02\text{--}0.035\text{ counts cm}^{-2}\text{ s}^{-1}$ (2–6 keV). The regular nature of the intensity variations clearly suggests the presence of a periodic phenomenon, with the low-intensity state comprising about one-quarter of the period.

When we examine the bulk of the data obtained between 1971 January and 1971 December, we find this behavior to be always present, as shown in Figure 2. We can fit all the observations with a periodic function as shown. The unique period obtained for this function is $2^{\text{d}}08710 \pm 0^{\text{d}}00015$. The low, high, and transition states are of $0^{\text{d}}488 \pm 0^{\text{d}}012$, $1^{\text{d}}529 \pm 0^{\text{d}}012$, and $0^{\text{d}}035 \pm 0^{\text{d}}007$ duration, respectively. The probability that the observed transitions are due to randomly occurring events is negligible.

We wish to note, however, that the variations of the average intensity from Cen X-3 are more complex than outlined above. First, the average intensity during any given “high” state can vary by as much as 30 percent, in times shorter than 1 minute. Also, there appear to be times at which the source remains in its low emission state for days. In particular, Cen X-3 was scanned for a day or more on 1970 December 30–1971 January 1, February 10–13, February 22–23, March 12–13, and 1971 March 19–22. During all the above observations, the intensity from Cen X-3 appeared to be less than $0.03\text{ counts cm}^{-2}\text{ s}^{-1}$ in the 2–6-keV range. We found, however, no instance in all of our data in which the source was observed at its high emission level except in accordance with the predictions of the periodic fit function discussed above.

III. PULSATION-PERIOD ANALYSIS

An absolute determination of the period of the 4 $\times$ 8 pulsation was obtained during long scans of the source, by fitting the data with a sinusoidal function via a minimum- χ^2 technique. A typical fit to the data is shown in Figure 3. We have available 27 long-duration ($\geq 100\text{ s}$) sightings of Cen X-3 during 1971 April, May, and June, to each of which this technique was applied. The resulting values for the pulsation periods are shown in Table 1. The scatter of these values is not consistent with statistics, indicating real changes in the values of the period of about $0^{\text{d}}02$. These changes occur in successive days and do not indicate a long-term trend. With the exception of an anomalously high

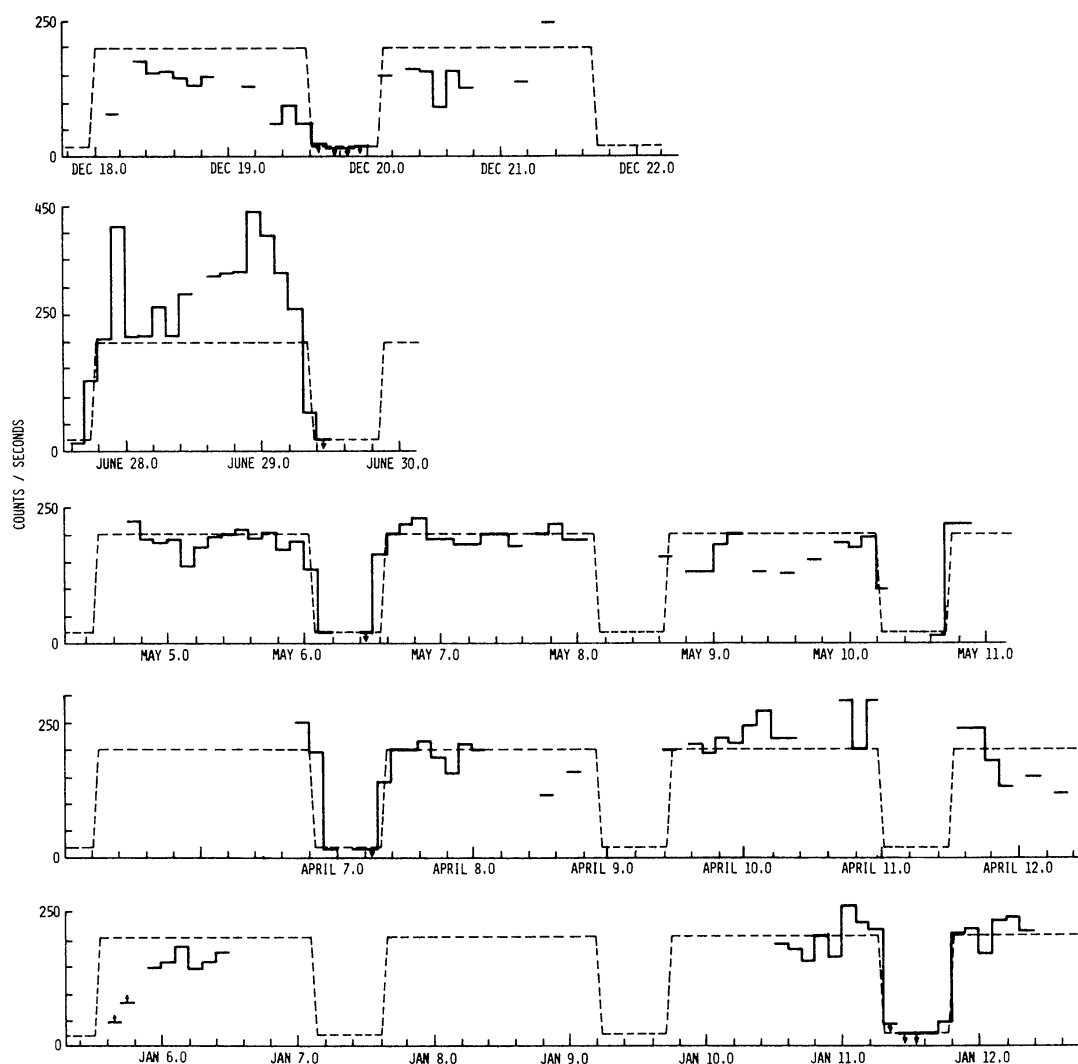


FIG. 2.—The observed intensity from Cen X-3 averaged over 0^d1 intervals and corrected for elevation in the field of view is plotted as a function of time. Statistical errors are not shown and are typically of the order of 1 percent. Also plotted is the average intensity predicted by the light curve.

value found for the period in 1971 January 11–12, which we now believe to be in error, all values range from 4^s832 to 4^s853, oscillating about an average value of 4^s842.

It can be seen from Figure 3 that a large part of the X-ray emission is pulsed. In all 27 long passes, with the source at its high-intensity level, 80–90 percent of the power was pulsed. In the low-intensity level, we can place an upper limit of about 20 percent on the amount of power pulsed.

In order to study the period changes in more detail, the phase of the pulsations was followed from sighting to sighting during those times when the satellite scanned the source every 720 s. The method was described in our earlier paper. This phasing analysis has been applied to three sets of data in January, May, and June. In all cases where 20,000 s or more of data were analyzed, changes of period were noted. In the longer observations, it became clear that the transitions were more continuous than had previously been thought, and that the discrete-period values determined in the earlier paper were the result of straight-line approximations to short sections of a continuous

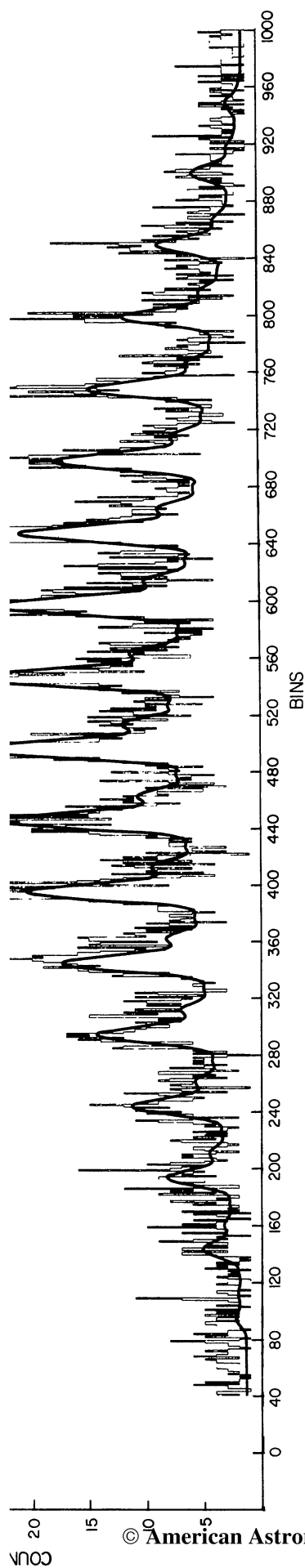


FIG. 3.—The counts accumulated in 0.096 bins from Cen X-3 during a 100-s pass on 1971 May 7 are plotted as a function of bin number. The functional fit obtained by minimizing χ^2 is also shown.



COUNTS

©

ITS/0.096 SEC

TABLE 1
PULSATION PERIOD OF CENTAURUS X-3

DATE (1971) (1)	LONG SIGHTINGS τ (sec) (2)	PHASING ANALYSIS $\tau = \tau_0 + A \cos(2\pi/T)(t - t_0)$			
		τ_0 (sec) (3)	A (sec) (4)	t_0 (day of '71) (5)	T (days) (6)
Jan 5-6*	4.8368 $\pm$ 0.0004 $\rightarrow$ 4.8449 $\pm$ 0.0005				
Jan 11-12†	4.8703 $\pm$ 0.0002 $\rightarrow$ 4.8726 $\pm$ 0.0005				
Jan 5-12	...	4.843255 $\pm$ 0.000007 (4.843496)	0.00668 $\pm$ 0.00015	11.0022 $\pm$ 0.0077	2.08712 $\pm$ 0.00011
April 8.16	4.832 $\pm$ 0.010				
8.29	4.845 $\pm$ 0.006				
8.59	4.834 $\pm$ 0.011				
8.74	4.838 $\pm$ 0.006				
8.79	4.848 $\pm$ 0.007				
9.64	4.839 $\pm$ 0.004				
9.99	4.837 $\pm$ 0.003				
10.22	4.839 $\pm$ 0.004				
10.27	4.844 $\pm$ 0.003				
10.34	4.847 $\pm$ 0.004				
10.51	4.853 $\pm$ 0.004				
11.86	4.838 $\pm$ 0.003				
12.11	4.838 $\pm$ 0.003				
May 4-7	...	4.842398 $\pm$ 0.000001 (4.842185)	0.006717 $\pm$ 0.000005	125.7923 $\pm$ 0.0002	2.08707 $\pm$ 0.00025
May 7.53	4.848 $\pm$ 0.005				
7.73	4.850 $\pm$ 0.004				
7.80	4.838 $\pm$ 0.005				
7.85	4.843 $\pm$ 0.004				
8.06	4.848 $\pm$ 0.004				
8.80	4.836 $\pm$ 0.004				
8.86	4.834 $\pm$ 0.003				
8.98	4.839 $\pm$ 0.003				
9.35	4.843 $\pm$ 0.003				
9.57	4.842 $\pm$ 0.004				
9.71	4.851 $\pm$ 0.005				
9.77	4.852 $\pm$ 0.003				
June 28-29	...	4.842435 $\pm$ 0.000012 (4.842176)	0.006699 $\pm$ 0.000029	180.0605 $\pm$ 0.0009	2.0885 $\pm$ 0.0035
June 30.72	4.822 $\pm$ 0.002				
30.86	4.844 $\pm$ 0.004				

NOTES TO TABLE 1

The values of the period determined from each of the 100-s sightings at the times shown in column (1) are given. Note that the periods corresponding to the January 5-6 (marked with an asterisk) and 11-12 (marked with a dagger) observations have been obtained by a different technique. Since long passes were not available, a χ^2 fit to the entire set of 20-s observations allowed us a criterion to choose between discrete possible periods. The high values of the period shown for January 11-12 are due to a choice from the χ^2 fits with a 95 percent confidence. The alternative choice results in a period consistent with all others shown. In column (3) the periods obtained from the phasing analysis are shown. The numbers in parentheses are corrected for the Earth's orbital motion. In the remaining columns we give the best-fit values of the parameters.

curve. In fact, all the data currently available are consistent with a 2-day sinusoidal variation in the pulsational period. In Figure 4a we show a phasing analysis of two days of data obtained in May. Also shown is the best fit function of the form

$$\Delta t \equiv t_n - j_n \tau^* = at + b \sin(2\pi/T)(t - t_0), \quad (1)$$

where Δt is the difference in seconds between the time t_n at which a peak of a pulse is observed and the predicted time of occurrence $j_n \tau^*$ assuming an integral number of trial periods τ^* , t and t_0 are expressed in days, T is the occultation period in days, b is the amplitude of the oscillation in seconds, and a is a quantity which measures the fractional deviation of the average period of the pulsations from the trial period.

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 39.75 ± 0.04 light-seconds.

From the formula above, we can by differentiation derive an expression for the actual pulsation period dependence on time of the form

$$\tau = \tau_0 + A \cos(2\pi/T)(t - t_0), \quad (2)$$

where $\tau_0 = (1 + a)\tau^*$ is the average period, $A = \tau^*b(2\pi/T)$ is the amplitude of the period variations, and the other quantities have been previously defined. A plot of this function for the same data is shown in Figure 4b.

In Figure 4c we show the observed intensity values as well as a segment of the average light curve derived previously. The zeros of the period function are seen to coincide with the centers of the low and high states. We see the period of the 4^s8 pulsations increasing as the object enters the low state and decreasing as it emerges. Thus, both the sign and the phase of the period variation are what would be predicted by Doppler effect. The values of the best-fit parameters derived from applying the phasing analysis to data in January, May, and June are shown in Table 1. It should be noted that a period of $2^d08712 \pm 0.00004$, independently derived from the phasing analysis by comparing phases of the Doppler curves, is consistent with the $2^d08710 \pm 0^d00015$ derived from the intensity variations.

There appears to be a decrease of 1 part in 4000 in the average period of pulsation from 1971 January to 1971 May which cannot be explained in terms of the Earth's motion about the Sun. This period change must be occurring at the source, although we cannot yet determine whether any secular trend exists.

IV. DISCUSSION

We may summarize the preceding observational data on Cen X-3 as follows: (1) There exist two distinct average intensity levels differing by a factor of 10 and repeating with a period of $2^d08710 \pm 0^d00015$; (2) there are times when the source remains at its low level for extended periods, but there are never high-level states when a low is predicted; and (3) the 4^s842 pulsation period shows a sinusoidal variation occurring every $2^d08712 \pm 0^d00004$ and with null points of variation coinciding with the centers of the high and low states to within $0^d003 \pm 0^d006$.

We conclude that a single physical mechanism is responsible for both changes in the period of the pulsations and the changes in intensity. The time of occurrence of the null point of period variation coinciding with the center of the low state is

$$\text{JD } (2441132.081 \pm 0.001) \pm n(2.08712 \pm 0.00004).$$

On the basis of the above, we adopt the working hypothesis that we are observing an occulting binary system. The short-period (4^s84) X-ray pulsations originate from a pulsating or rotating compact object. This X-ray source orbits a large occulting object.

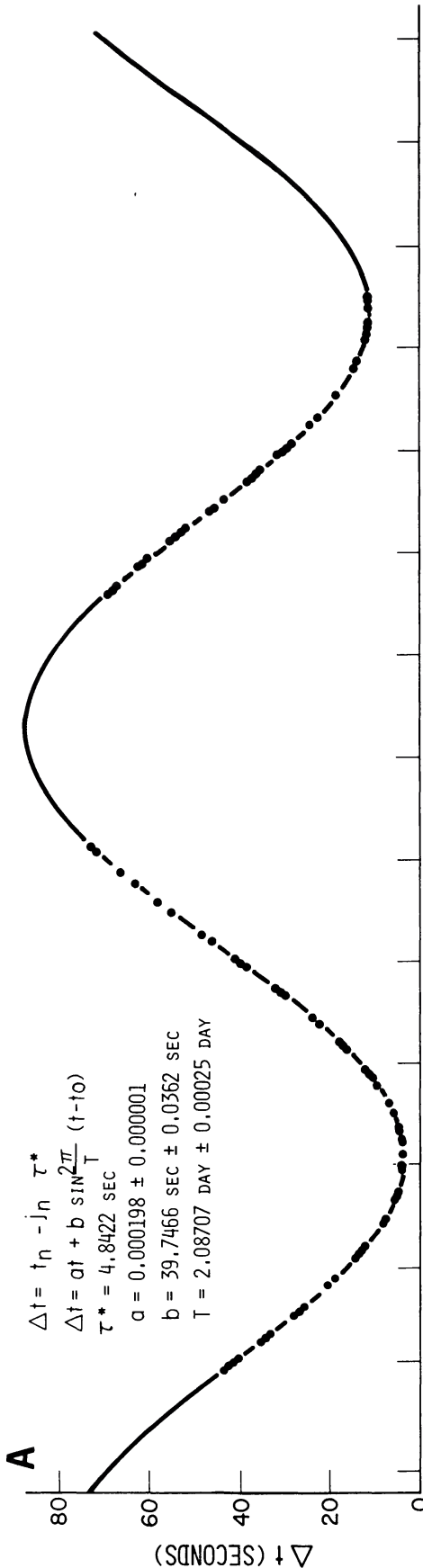


FIG. 4.—(a) The difference Δt between the time of occurrence of a pulse and the time predicted for a constant period is plotted as a function of time. A best-fit function and the values of the parameters are given. (b) The dependence of the pulsation period τ on time as derived from the best-fit phase function above is shown and the values of the parameters given. (c) The intensity observed and the light curve predictions are shown for the same set of data. Note the coincidence of the null points of the period function with the centers of the high- and low-intensity states.

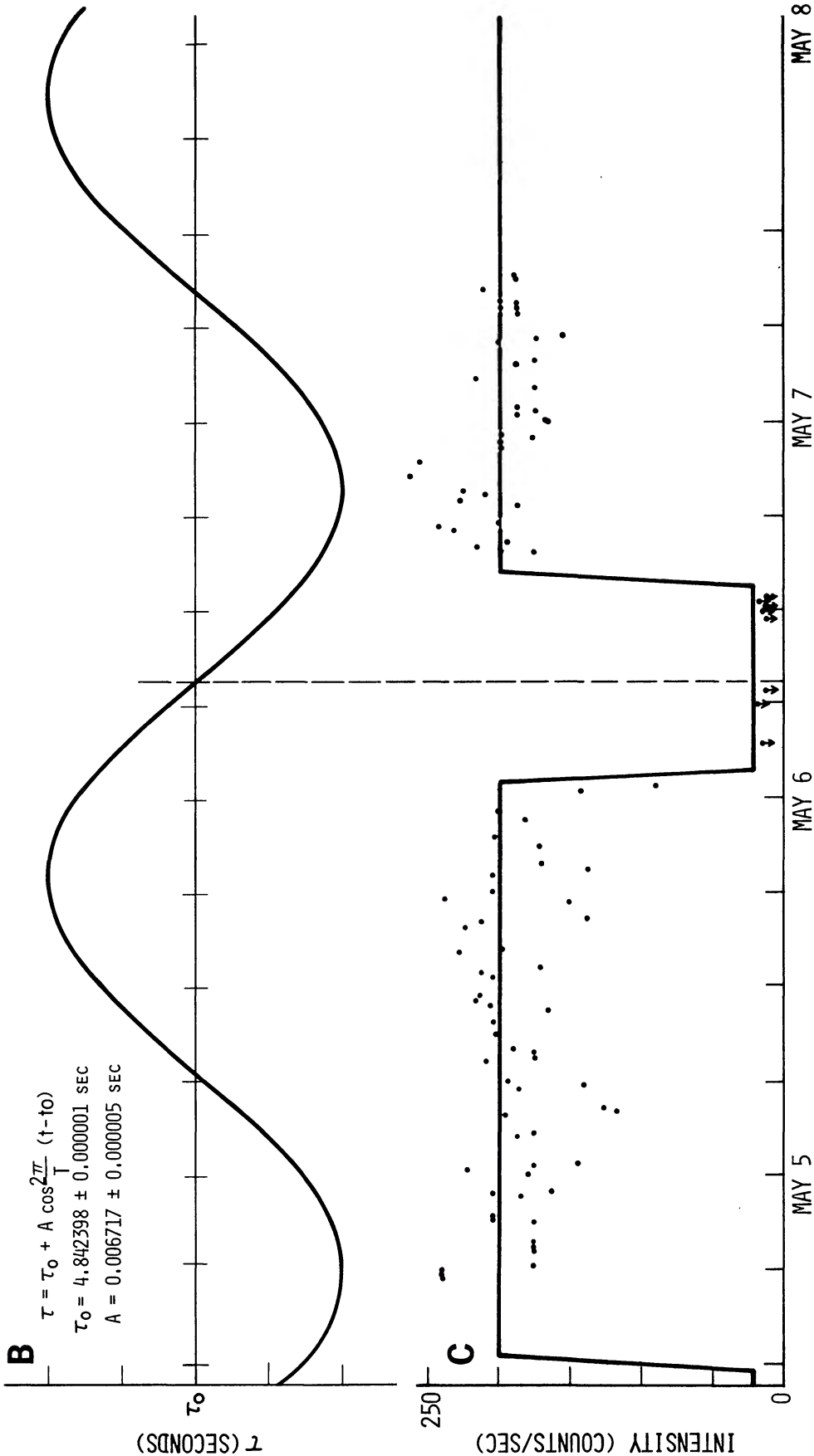


FIG. 4.—Continued

The cyclic variations in the average intensity are due to occultation, and the cyclic changes in the pulsation period are due to Doppler effect.

The agreement between our trial sinusoidal fit and the measured phase shown in Figure 4 implies that the orbit is circular to within our statistical accuracy. We estimate an upper limit on the eccentricity of 0.05. We can then proceed to compute the various parameters of the system from the measured quantities. If i is the inclination of the orbit, r its radius in the center-of-mass system, R the radius of the central occulting object, M and m the masses of the objects, v the orbital velocity, c the speed of light, and G the gravitational constant, then

$$v \sin i \equiv \frac{Ac}{\tau_0} = 415.1 \pm 0.4 \text{ km s}^{-1},$$

$$r \sin i \equiv \frac{T}{2\pi} v \sin i = (1.191 \pm 0.001) \times 10^{12} \text{ cm},$$

$$\frac{M^3 \sin^3 i}{(M + m)^2} \equiv \frac{(2\pi)^2}{GT^2} (r \sin i)^3 = (3.074 \pm 0.008) \times 10^{34} \text{ g}.$$

Considering, in addition, that the occulted fraction of the orbit is one-quarter of the total orbital period, and assuming that the radius of the X-ray emitting object is negligible, we can write that

$$\sin i = \frac{r}{R} (1 + m/M) \sin 45^\circ; \quad \text{wrong relation}$$

thus the inclination must satisfy $45^\circ < i \leq 90^\circ$.

Although we cannot measure the inclination independently, we can use this range to place limits on the several parameters; thus,

$$415 \text{ km s}^{-1} < v < 588 \text{ km s}^{-1},$$

$$1.19 \times 10^{12} \text{ cm} < r < 1.69 \times 10^{12} \text{ cm},$$

$$3.07 \times 10^{34} \text{ g} < \frac{M^3}{(M + m)^2} < 8.81 \times 10^{34} \text{ g},$$

$$0.84 \times 10^{12} \text{ cm} < R < r(1 + m/M).$$

From the existence of periodic pulsations of 4.8 we had previously concluded that Cen X-3 is a collapsed object of radius less than 10^9 cm. Thus, the assumption that its size is negligible with respect to the radius of the orbit and that of the massive central star seems reasonable. If we assume that the mass of the compact source is $1 M_\odot$, the mass of the companion ranges from 17 to $46 M_\odot$.

The radius of the occulting object cannot immediately be equated to the radius of a star. The occultation might be due to a tenuous atmosphere occupying a region much larger than the stellar dimensions. If we assume, however, that the radius of the star is of comparable dimensions to the occulting disk, then the range of mean density for this star is between 0.0015 and 0.01 g cm^{-3} . Thus, the values we find for the radius, mass, and mean density of the central object are reasonable for massive main-sequence stars and for B0-type supergiants. However, considerations of tidal instability would seem to argue against giant and supergiant stars.

We do have evidence which seems to indicate the existence of an atmosphere. This stems from the observation of the gradual nature of the occultation, which occurs over about 1 hour. The effect cannot be due to gradual occultation of the X-ray source which we believe to be compact. Thus, we explain the effect on the basis of progressively in-

creasing absorption by an extended atmosphere. We would then expect that the spectrum of Cen X-3 should exhibit progressively more absorption at low energies as the occultation proceeds, and we have preliminary indications that this is indeed the case. The existence of the effect requires that the atmosphere exhibit a strong dependence of density on radius. In the assumption of an exponential atmosphere, we estimate a scale height of 5×10^{10} cm at the outer radius of the occulting region. The density in this region would be on the order of 10^{12} hydrogen atoms cm^{-3} . There also appears to be some indication that the duration of the occulted state varies. This might be due to expansion and contraction of the atmosphere.

It is clear from the persistence of X-ray emission even during occultation that an additional source of X-rays must be postulated to exist in the system. Since the level of intensity observed between peaks of the 4.8 pulsations is also comparable, it is attractive to consider that the X-ray emission from the compact source may be close to 100 percent pulsed, and that the emission from a second quasi-constant source may explain the interpulse level, the emission observed during occultation, and the emission observed during those times in which the pulsating component seems to have disappeared. Further analysis of the energy spectrum of the radiation observed in these different states may establish if, indeed, the assumption of a unique source is valid, and help to differentiate between various physical processes which may give rise to this emission. A plausible process would appear to be the slow radiative cooling of the gas surrounding the system, which is heated by the pulsing source.

We believe that our data prove the binary nature of Cen X-3. We do not yet know in detail the origin of the 4.8 pulsations. The absence of rapid changes in period allows as a clock mechanism either rotation or pulsation of a compact star. The energy source for the X-rays is also not known. Nuclear burning and accretion have been considered by various authors (Blumenthal *et al.* 1972; Prendergast and Burbidge 1968; Shklovsky 1967; Zel'dovich and Shakura 1969; Cameron and Mock 1967). The presence of a close binary companion makes it very probable that accretion is taking place.

The position of Cen X-3 has been refined to R.A.: $11^{\text{h}}19^{\text{m}}0 \pm 0^{\text{s}}.4$, δ : $-60^{\circ}19'2 \pm 3'$ sufficiently precisely to attempt an intensive search for an optical candidate. We would expect this optical candidate to be quite luminous as is implied by the large mass of the system. It should be noted, however, that there is no reason in principle to expect that the visible light emission from the system, which is probably dominated by the central massive object, should exhibit either 4.8 pulsations or a 2-day period photometrically. The object should appear as a spectroscopic binary with a velocity of a few tens of kilometers per second.

The recent discovery that the optical candidate for Cyg X-1 is a spectroscopic binary of 5.6 period (Bolton 1971; Webster and Murdin 1971) in conjunction with our data on Cen X-3 greatly strengthens the view that a class of galactic X-ray sources may be associated with binary systems. The observation from *Uhuru* (Schreier *et al.* 1971b; Giacconi *et al.* 1972) of a 1.25 period pulsating X-ray source in Hercules (2U 1702+35), which also appears to show two distinct levels of intensity, may provide a third candidate for this class of objects.

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