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OBSERVATION OF CENTAURUS X-3 BY *HAKUCHO*

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ABSTRACT

The binary X-ray pulsar Cen X-3 was observed by the X-ray astronomy satellite *Hakucho* between 1981 March 21–26. A pulsation period of 4.8317231 ± 0.0000004 s and an orbital epoch of JD $2{,}444{,}686.44760 \pm 0\overset{d}{.}00005$ were obtained from the pulse-timing analysis. The long-term spin-up rate in the pulsation period of Cen X-3 between 1977 and 1981 shows a decrease by a factor of 5 from that in 1975. The orbital period of $2.0871061 \pm 0\overset{d}{.}0000002$ averaged between 1979 and 1981 exhibits a small but significant decrease. The present result confirms the trend of a steady decrease of the orbital period. In this paper, possible mechanisms for the decrease of the pulsar spin-up rate and the decrease in the orbital period of Cen X-3 are discussed.

Subject headings: pulsars — X-rays: binaries

I. INTRODUCTION

Ever since the discovery of pulsations from Cen X-3 (Giacconi *et al.* 1971), variability in the pulsation periods of X-ray stars has been of great importance to our understanding of the accretion process and the internal structure of neutron stars (Ghosh and Lamb 1979; Joss and Rappaport 1980; Lamb, Pines, and Shaham 1978). The long-term decrease in the pulsation period of Cen X-3 was first discovered by *Uhuru* observations, and the rate of period change was found to vary with time (Schreier and Fabbiano 1976; Fabbiano and Schreier 1977). Subsequent observations gave an average rate of $\dot{P}/P = -2.8 \times 10^{-4}$ yr^{-1}, and the result was interpreted in terms of the torques exerted by the matter accreting onto the neutron star (Fabbiano and Schreier 1977; Rappaport and Joss 1977). Further observations by *Ariel 5* (Tuohy 1976), *COS B* (van der Klis, Bonnet-Bidand, and Robba 1980), and *SAS 3* (Kelley *et al.* 1982) confirmed the spin period decrease.

In addition, changes in the orbital period of Cen X-3 were also discovered by *Uhuru* observations (Fabbiano and Schreier 1977). The period was found to decrease on average but fluctuate significantly about this average.

These changes in the pulsation period and the orbital period are good tools in understanding neutron stars and their environment. In this paper, we report a new result on the spin-up rate and a change in the orbital period of Cen X-3 derived from the *Hakucho* observation.

II. OBSERVATION AND DATA ANALYSIS

The observation of Cen X-3 was carried out with the FMC and the CMC (fine and coarse modulation collimators) detectors on board *Hakucho* between 1981 March 19 and April 2. The present analysis is limited to the data obtained by the FMC-2 between March 21 and 26. During this period, Cen X-3 was in a high state and was continuously monitored with the FMC-2 in the energy range 1–22 keV. The FMC-2 is a Xe-filled proportional counter with an effective area of 83 cm^2 and a field of view of $5\overset{\circ}{.}7$ FWHM aligned with the spin axis direction. Details of the satellite and the detectors are given elsewhere (Kondo *et al.* 1981).

Data were acquired typically for 20–40 minutes during each orbit, excluding the period of the Earth occultation and the Brazilian anomaly. After March 27, the intensity of Cen X-3 went below our detection limit, and no pulsations were observed. The pulse profile during this observation was similar to the one observed

TABLE 1

BEST-FIT ORBITAL PARAMETERS

Parameter	Value
P_0	4.8317231 ± 0.0000004 s
A	39.664 ± 0.007 s
P_{orb}[a]	$2.0871061 \pm 0^d.0000002$
T_0	JD 2,444,686.44760 $\pm 0^d.00005$

NOTE.—All quoted uncertainties represent single parameter 1 σ confidence limits.

[a] This orbital period is calculated by combining our orbital epoch with that of *SAS 3* in 1979 (Kelley *et al.* 1982).

by *COS B*, showing one peak with a small hump on the decay slope of the peak (van der Klis, Bonnet-Bidand, and Robba 1980).

a) *Pulsation Period*

The best-fit orbital parameters were determined by a minimum χ^2 fit of the pulse arrival times to a function of the form

$$t_n = t_0 + P_0 n + A \cos\left[\frac{2\pi}{P_{orb}}(t - T_0)\right],$$

where t is time, t_n is the observed epoch time of the nth pulse, A is the half-amplitude of the orbital Doppler effect, P_{orb} is the binary period, and T_0 is the mid-eclipse time. In this analysis, the eccentricity of the orbit was taken to be zero, since it was found to be negligibly small for purposes of the present analysis ($e = 0.0008$; Fabbiano and Schreier 1977). Table 1 gives the best-fit values of the orbital parameters. Twenty-nine data points of the pulse period are shown in Figure 1, after correcting for the heliocentric motion of the Earth. The best-fit Doppler curve is also shown in Figure 1. In Figure 2, the present result is compared with the pulse periods thus far obtained (see Joss and Rappaport 1980, and references therein). It is clear from this figure that the long-term spin-up rate of Cen X-3 is not constant. These data further confirm those of *COS B* by van der Klis, Bonnet-Bidand, and Robba (1980). From 1976 to 1981, the average spin-up rate is $\dot{P}/P \approx -1 \times 10^{-4}$ yr^{-1}, a decrease by a factor of 5 in comparison to the rate of $\dot{P}/P \approx -5.5 \times 10^{-4}$ yr^{-1} reported by *COS B* from 1974 to 1976 (van der Klis *et al.*).

b) *Orbital Period*

Because of the short span of the present observation, the orbital period cannot be determined accurately with the present *Hakucho* data alone. Combining our result with the latest observational results of *SAS 3* in 1976 and 1979 (Kelley *et al.* 1982), we can obtain average orbital periods of $2.0871148 \pm 0^d.0000001$ and $2.0871061 \pm 0^d.0000002$ from 1976 to 1979 and from 1979 to 1981, respectively, by dividing the time between eclipse centers by an integer number of orbital periods. Figure 3 shows the average orbital period over the indicated baseline from 1976 to 1981 in comparison with the previous data since 1971. Even excluding the first five points of data before 1973, the observations consistently indicate a small but significant decrease in the orbital period. The long-term decrease in the orbital period averaged over 8 yr between 1973 and 1981 is $\dot{P}_{orb}/P_{orb} \approx -2.4 \times 10^{-6}$ yr^{-1}. This value is ~ 3 times smaller than the earlier result obtained from *Uhuru* observations (Fabbiano and Schreier 1977). Because of long separation between observations and the short duration of these observations, it is not clear whether changes in the orbital period on shorter time scales exist or not.

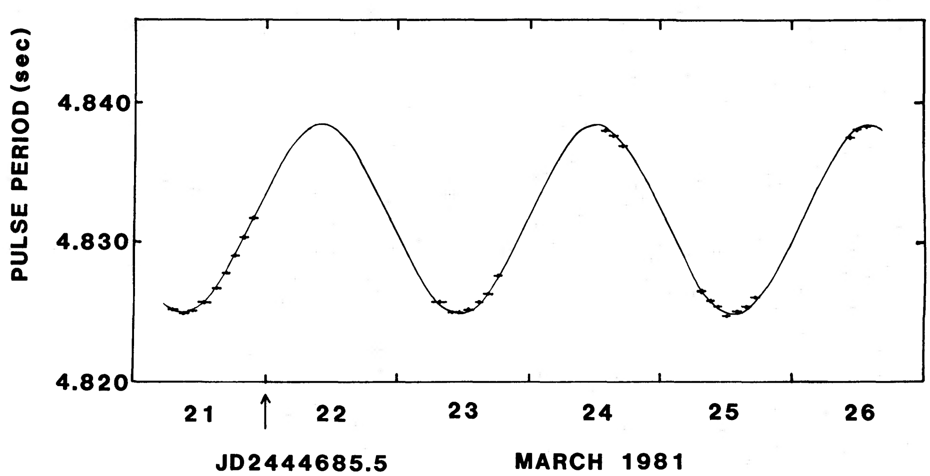

FIG. 1.—Doppler curve of the pulsation period and the best-fit orbit for Cen X-3 between 1981 March 21–26

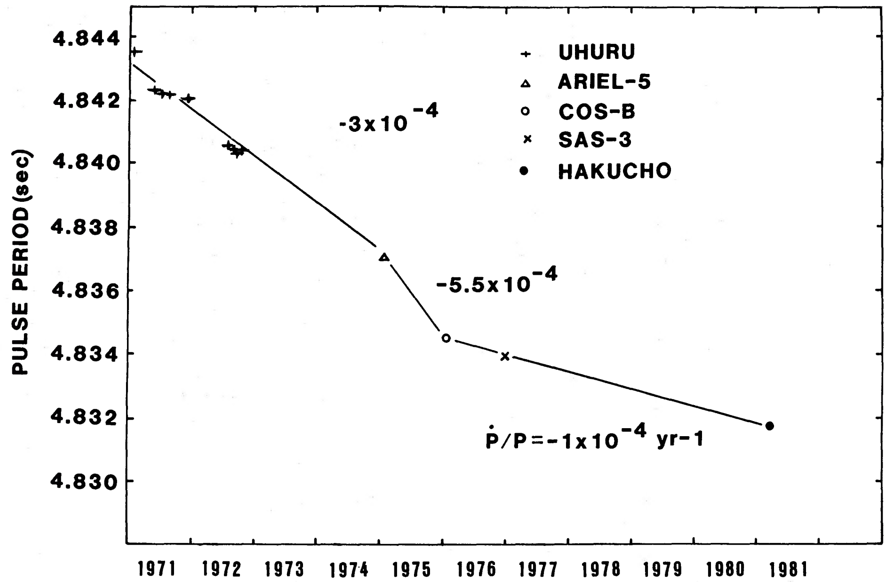

FIG. 2.—The long-term behavior of the pulsation period of Cen X-3. The *Uhuru*, *Ariel 5*, *COS B*, and *SAS 3* data are from Fabbiano and Schreier (1977), Tuohy (1976), van der Klis, Bonnet-Bidand, and Robba (1980), Joss and Rappaport (1980), and Kelley *et al.* (1982), respectively.

III. DISCUSSION

The long-term behavior in pulse period from many X-ray pulsars has been observed by various satellites. Vela X-1, GX 301-2, and Cen X-3 results have been further extended by *Hakucho* observations (Nagase 1981; Oda *et al.* 1982). The presently available data of Cen X-3 span the past decade. The secular decrease in the pulse period may be understood in terms of the torques exerted by the matter accreting onto the neutron star. Cen X-3 is believed to be a disk-fed system, even with the presence of a stellar wind from its O-type companion star (Osmer *et al.* 1975). Many theoretical works on these accretion torque have been reported (Ghosh and Lamb 1979; Joss and Rappaport 1980, and references therein). These calculations predict a spin-up rate expressed as $\dot{P}/P \approx -3\times10^{-5} f \cdot P \cdot (L_{37})^{6/7}$, where L_{37} is the X-ray luminosity of the source in units of 10^{37} ergs s^{-1} and the dimensionless function f is of order of unity in the case of a neutron star (Rappaport and Joss 1977). In Table 2, we summarize the reported luminosity of Cen X-3 from 1971 to 1981, including this work. Although the observational windows were extremely short, the luminosity range of 2–6×10^{37} ergs s^{-1} is sufficient

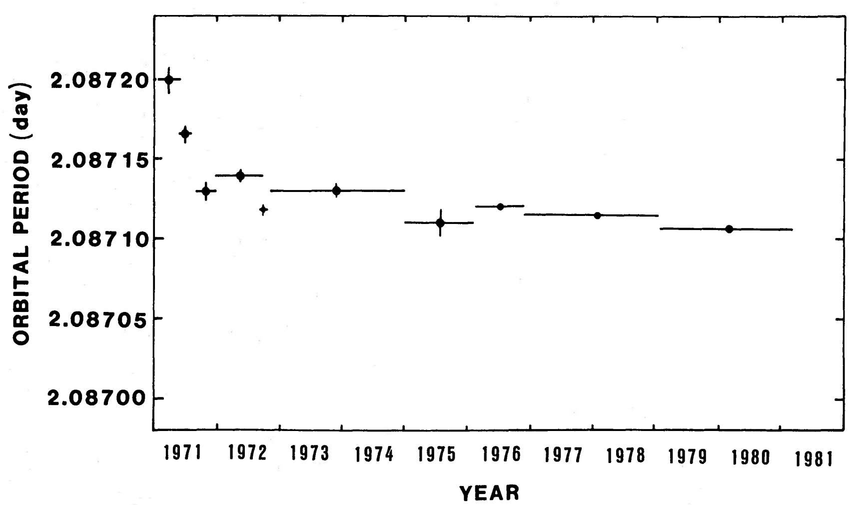

FIG. 3.—Orbital period history of Cen X-3 from 1971–1981. References for these observational results are the same as for those in Fig. 2.

TABLE 2

OBSERVED LUMINOSITY OF CEN X-3

Satellite	Luminosity (ergs s^{-1})	Time	Reference
Uhuru	3×10^{37}	30^d during 1971	Osmer *et al.* 1975
Ariel 5	2×10^{37}	during 1975	Holt *et al.* 1978
COS B	$4–6\times10^{37}$	30^d in 1976	van der Klis, Bonnet-Bidand, and Robba 1980
SAS 3	4×10^{37}	1977	Bradt, Doxsey, and Jernigan 1979
Hakucho ...	3×10^{37}	6^d in 1981	this work

NOTE.—For these calculations, we assumed a distance of 8 kpc to Cen X-3.

to explain the order of magnitude of the change in pulsation period of Cen X-3. However, there appears to be no significant relation between $\dot{P}/P$ and the observed luminosity. A similar behavior (change in $\dot{P}/P$ independent of luminosity) was noted for the case of Vela X-1 (Nagase 1981).

The existence of a long-term decrease of the orbital period is clearly discernible in Figure 3. This result further confirms that of the *Uhuru* and *Ariel 5* observations (Fabbiano and Schreier 1977; Tuohy 1976). The possible mechanisms were discussed previously by Fabbiano and Schreier (1977). It is clear that losses due to gravitational radiation are insufficient to explain the change in the orbital period of Cen X-3 (Will 1976). Mass exchange from the main star to the neutron star is also insufficient. The mass transfer rate required for the observed orbital decay is calculated to be $3.5\times10^{-7}\ M_\odot\ yr^{-1}$ which corresponds to a luminosity of $\sim10^{39}$ ergs s^{-1}, much higher than that observed.

Spectroscopic observation indicates that the primary star is an early-type giant or supergiant of spectral type O with a P Cygni profile (Osmer *et al.* 1975). It is therefore reasonable to expect the mass loss from this system to be $\sim4\times10^{-6}\ M_\odot\ yr^{-1}$ (Fabbiano and Schreier 1977). However, simple mass loss by the stellar wind from the main star cannot explain the decrease of the orbital period. To reduce the angular momentum of the system by the stellar wind, we need the coupling between the stellar wind and the magnetic field. If we assume the distance to the Alfvén surface is to be the binary separation, we need several hundreds gauss in magnetic field on the surface of the primary star. This value is much stronger than that expected as an early-type star (Shibazaki 1982). The tidal circularization time scale of $\dot{P}_{orb}/P_{orb}=-2\times10^{-5}\ yr^{-1}$ which was suggested by Lecar *et al.* (1976) and reexamined by Fabbiano and Schreier (1977) is adequate to explain the observed rate. Recently Shibazaki pointed out that Cen X-3 is now in an unstable nonsynchronous phase, spiraling into the main star with the tidal braking time scale (Shibazaki 1982; Lecar, Wheeler, and McKee 1976). The rather small value of changes in the orbital period of Her X-1 ($|\dot{P}_{orb}/P_{orb}|<2\times10^{-8}\ yr^{-1}$; Deeter, Boynton, and Pravdo 1981) may be understood in this context because of a much longer time scale of the tidal circularization which is expected from Her X-1 (Lecar *et al.* 1976). The secular decrease of the orbital period cannot be explained by other effects, such as apsidal motion or the presence of the third body.

In conclusion, the present results show that the long term spin-up rate of Cen X-3 is variable by as large as a factor of 5, while the observed luminosity remained within a factor of 3. The long-term change of the orbital period of Cen X-3 is evident from the observational results of *SAS 3*, *COS B*, and these *Hakucho* results.

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