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DISCOVERY OF PERIODIC X-RAY PULSATIONS IN CENTAURUS X-3 FROM *UHURU*

R. GIACCONI, H. GURSKY, E. KELLOGG, E. SCHREIER, AND H. TANANBAUM
American Science & Engineering, Inc., Cambridge, Massachusetts 02142
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ABSTRACT

A search for X-ray sources exhibiting pulsating characteristics similar to the ones recently discovered in Cyg X-1 by Oda *et al.*, and confirmed by Holt *et al.*, has revealed the existence of periodic pulsations in the X-ray emission from Cen X-3.

The pulsations are of large amplitude, comprising at least 70 percent of the total flux from the source. The period is approximately 5 s. Due to the amplitude of the effect and the long period, we are able to establish that the period and phase of the pulsations are maintained for several hours. In addition, two very remarkable events are observed to occur during a 1-day interval. The first is a change in the intensity of the source by a factor of 10 occurring in approximately 1 hour. The second is a decrease and then an increase in the period of the pulsations, corresponding to about 0.02 and 0.04 percent, each change of period occurring in a time of about 1 hour. The magnitude of the changes, and the short time interval in which they take place, are quite different from any observed in radio pulsars. In addition, we see evidence for changes of the period by about 1 percent occurring over a time span of 3 months. Present data are inconclusive about the presence of faster pulsations from the source. The X-ray spectrum shows evidence of substantial absorption below 3.8 keV.

I. EXPERIMENTAL DATA

Centaurus X-3 was first observed by Chodil *et al.* (1967) in May, 1967 at a flux of 0.7 photons $cm^{-2}\,s^{-1}$ in the energy range of 2–9.5 keV. It was then observed on two occasions by Cooke and Pounds (1971) at 0.18 counts $cm^{-2}\,s^{-1}$ in June 1968 and in November 1968, and then in April 1969 at about 0.9 counts $cm^{-2}\,s^{-1}$ in the energy range 1–12 keV. Thus, the source was known to be highly variable and, in addition, peculiar spectral features were observed. *UHURU* locates a source at $\alpha(1950)\ 11^h20^m\!.4 \pm 1^m\!.1$, $\delta(1950) - 60°29' \pm 5'$. Due to the apparent agreement on location, variability, and spectral features, we believe this source is the previously reported Cen X-3.

We have observed Cen X-3 in the 1–20-keV energy range from *UHURU* on several occasions in January and April 1971. A brief description of the instrumentation of the satellite is given elsewhere (Giacconi *et al.* 1971). On January 11 and 12, the observations were carried out with a spin rate of about $0.°5\ s^{-1}$; thus, the source was in the field of view of the $5° \times 5°$ detector for 20 s every 720 s. On April 10 and 12, the observations were obtained at a spin rate of about $0.°07\ s^{-1}$, resulting in 150 s exposure in the $5° \times 5°$ detector and 15 s in the $\frac{1}{2}° \times 5°$ detector. We have analyzed a total of seventy-four sightings on January 11 and 12, two of the 150-s scans on April 10 and 12, and six of the 15-s scans obtained from April 9 to April 12.

We find that the intensity of the source indeed varies very considerably on time scales of days, minutes, and seconds. The long-term behavior can be illustrated by the data obtained on January 11 and 12 and shown in Figure 1. In a time of approximately 1 hour Cen X-3 changes its intensity in the 2–6-keV range from 2.4×10^{-2} counts $cm^{-2}\,s^{-1}$ to 2.4×10^{-1} counts $cm^{-2}\,s^{-1}$, corresponding roughly to the high and low levels previously observed. Particularly remarkable are the nearly constant levels before and after the flare that we observe. The postflare fluctuations in intensity may be due to wobble of the spacecraft axis, since the data have not been corrected for minor aspect variations. At the preflare level, however, one can observe a short increase in intensity that cannot be explained in terms of attitude corrections.

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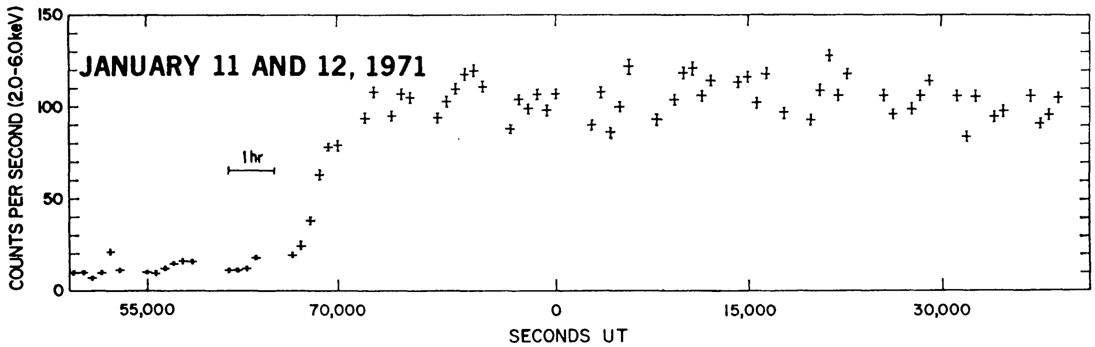

FIG. 1.—Average counting rate from Cen X-3 in the 2–6-keV energy range as a function of time observed on 1971 January 11 and 12. Error bars reflect only counting statistics. Missing data are due to occultation of the source by the Earth. Data are not corrected for aspect.

During the April observations the flux was about 3×10^{-1} counts cm^{-2} s^{-1}. The short-term fluctuations of the source are illustrated by the data shown in Figure 2. In the 150-s exposure several peaks and valleys occur with great regularity, immediately suggesting a periodic phenomenon. A χ^2 fit to the data with a sinusoidal function, and its first and second harmonic plus a constant, yields the curve also shown in Figure 2. The period of the fundamental frequency resulting from this fit is 4.832 ± 0.004 s.

In order to study both the period and the phase of the pulsations over as large a span of time as possible, we have analyzed the data obtained on January 11 and 12 after the intensity had reached 50 percent of the postflare value. Preflare intensities correspond to so few counts accumulated in each pass that, although we are able to ascertain that pulsations were occurring, we are not able to measure accurately the period and phase under those conditions.

The postflare data, on the other hand, are of sufficient quality to warrant a much more elaborate analysis. The data consist of 20-s sightings, spanning three or four periods of the pulsations, separated by about 720 s, corresponding to about 145 periods. If we measure the phase in each successive sighting, the period can be determined with great precision, but not uniquely since different assumed numbers of intervening pulses can equally well fit the data. In order to remove this ambiguity, we fit to each sighting a function of the same form as the one previously used to fit the April data and illustrated in Figure 2. We then determine the period which minimizes the sum of all the individual χ^2's. From this analysis we obtain a period of 4.876 ± 0.015, which is sufficiently precise to allow us to determine uniquely, at the 95 percent confidence level, the number of pulsations intervening between successive acquisitions.

We can now refine this result by following the phase of the pulsations from sighting to sighting. The functional fit to each of the postflare acquisitions determines the time of occurrence of a peak T_n, measured from some arbitrary T_0, the time of the first acquisition. We then subtract from each T_n the largest $J_n\tau$ (where J_n is an integer and τ is a fixed trial period) giving a positive residue. The resulting $\Delta T_n = T_n - J_n\tau$ equals a constant if the trial period is correct. If the true period is not correct, but is constant, we expect $\Delta T_n =$ constant $\times J_n$, that is, we should be able to fit a straight line through the data. Deviations from linearity indicate a change in the true period. The results of the analysis are shown in Figure 3. We note that the data can be fitted by a straight line for about 30000 s, but that before and after this time span, two straight lines of different slope are required. We find that the period at the onset of the postflare observation is 4.8713 ± 0.0002 s during about 9000 s. It then changes within an hour to 4.8703 ± 0.0002 which persists for about 28000 s. The period then again changes within about an hour to 4.8726 ± 0.0005 which persists for 19000 s until the end of the observation. It

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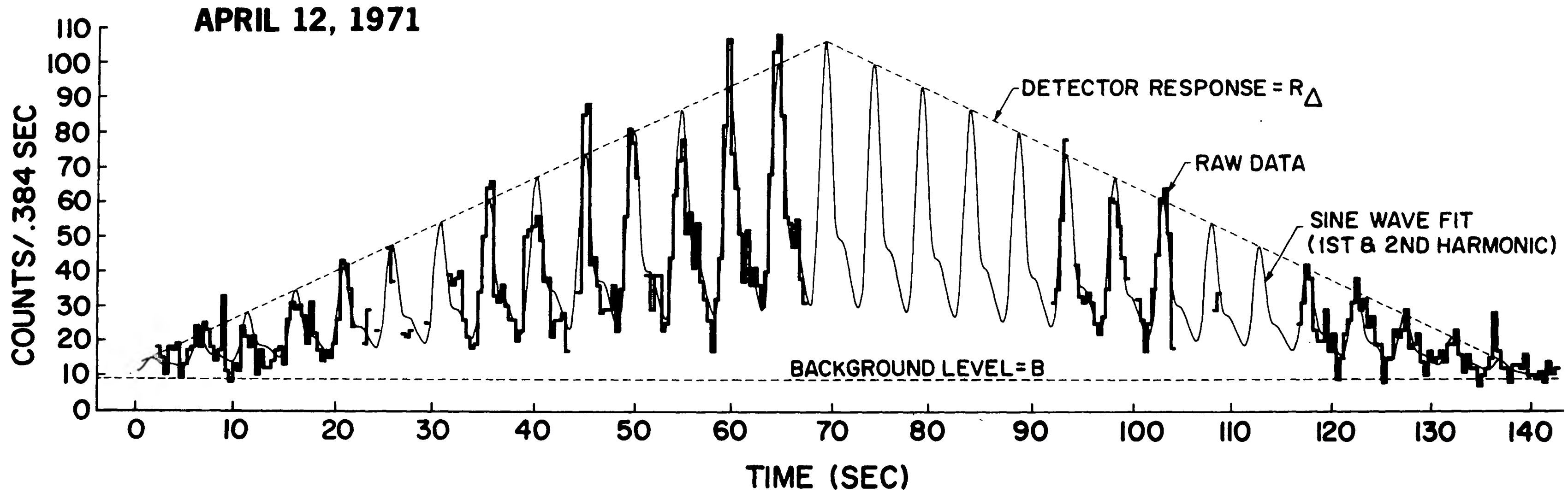

FIG. 2.—Histogram shows counts accumulated in 0.384-s intervals in the 2–6-keV energy range as a function of time on 1971 April 12. Missing portions of the data are due to quick-look transmission dropout. The spacecraft spin rate during this observation was about 0°.07 s^{-1}. The sinusoidal function fit to the data is shown as the continuous curve and is given analytically by the function $f = B + R_\Delta[A_0 \sin(\omega t + \phi_1) + A_1 \sin(2\omega t + \phi_2) + A_2 \sin(3\omega t + \phi_3) + C]$.

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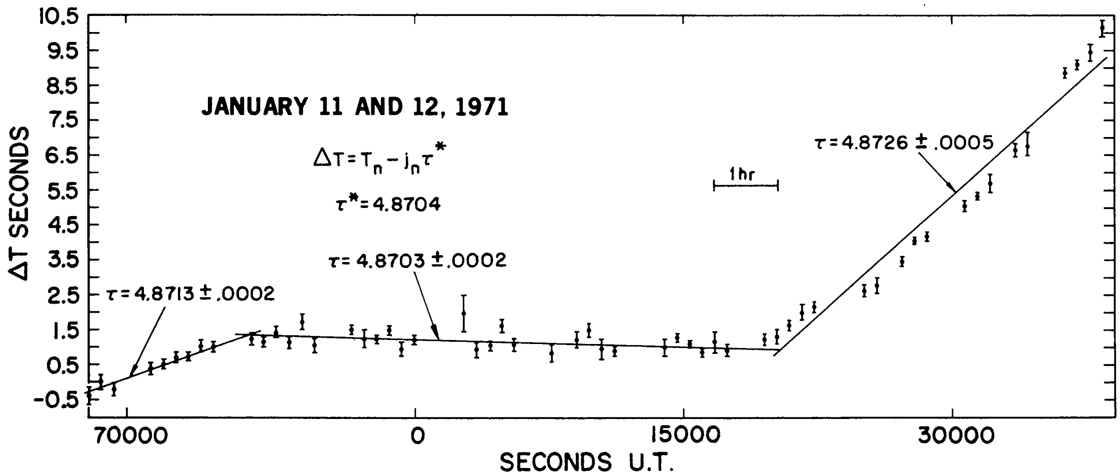

FIG. 3.—Phase of pulsations from sighting to sighting on 1971 January 11 and 12. A trial period (τ^*) of 4.8704 was used in determining the residual (ΔT) and the number of periods (Jn) from an arbitrary initial time to the time of occurrence of the first peak in each source sighting. The data are fitted to three straight lines of different slopes indicating periods as shown.

should be noted that the data, in this last 19000 s, show evidence of significant shifts in phase, while the period appears to remain constant.

In Table 1 we summarize the values of the period we find in the different observations.

The most remarkable feature of the data is the very large changes in period occurring in very short times on January 11 and 12. The period first decreases by about 1 ms, then increases by 2.3 ms, each change occurring in less than 1 hour. It also appears that in 3 months between January and April 1971 the period has decreased on the average by about 30 ms, corresponding to about 0.6 percent change.

We have examined the data for evidence of pulsations occurring in shorter time periods. A Fourier analysis of the January data very clearly indicates the presence of a fundamental periodic component at about 4.8 s and a strong component corresponding to the first harmonic at about 2.4 s. No significant higher-frequency components appear in the power density spectrum, although it should be noted that the data were obtained with 0.384 s integration time. Also, a fit to the January and April data, with the previously described function, yields a reasonable χ^2 of about 1.2 $\pm$ 0.1 per degree of freedom. A fit to the data obtained during six 15-s passes in April, with 0.096 s integration time, yields a χ^2 of 1.1 $\pm$ 0.1. This indicates the absence of either periodic or aperiodic faster components of the pulsations containing a large fraction of the emitted power, unless they occur in a time scale short compared to our integration time of 0.096 s.

TABLE 1

PERIODS OBSERVED FOR CENTAURUS X-3

Date (1971)	Seconds (UT)	τ
January 11......	68000–77000	4.8713±0.0002
January 11–12...	77000–19000	4.8703±0.0002
January 12......	19000–38000	4.8726±0.0005
April 10.........	29400 (150-s observation)	4.847 ±0.004
April 12.........	9700 (150-s observation)	4.832 ±0.004

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The shape of the pulse is indicated by the functional fit to the data shown in Figure 2. The pulse is characterized by a fast rise and a slower decay, or shoulder, possibly due to the presence of an interpulse. From the functional fit shown in Figure 2, we can determine that at least 70 percent of the emitted power is pulsed with a very large duty cycle.

Finally, the spectrum of emission of Cen X-3 is shown in Figure 4. The best fit to the data occurs with either a blackbody spectrum with temperature of about 3.3×10^7 ° K or a thermal bremsstrahlung spectrum with $kT = 15.7 \pm 1.4$ keV and a cutoff of 3.8 keV.

II. DISCUSSION

From the above, we believe we have established the existence of X-ray pulsations from Cen X-3 with a 5-s period. Large variations of the period (both increases and decreases), corresponding to $\Delta\tau/\tau$ of about 2×10^{-4} and 4×10^{-4}, are observed to occur in times of the order of 1 hour or shorter. A decrease of 0.6 percent in the period is observed to have occurred between the January 11–12 and the April 10–12 observations. We have investigated the possibility that these effects might be due to errors or shifts in the time base and evaluate the maximum possible error to be one part in 10^5, while the effects we observe are about 40 times and 800 times larger. These changes in period might, of course, be due either to an intrinsic property of the source or to relative motions of the source with respect to the observer. Orbital motions of the satellite, or seasonal

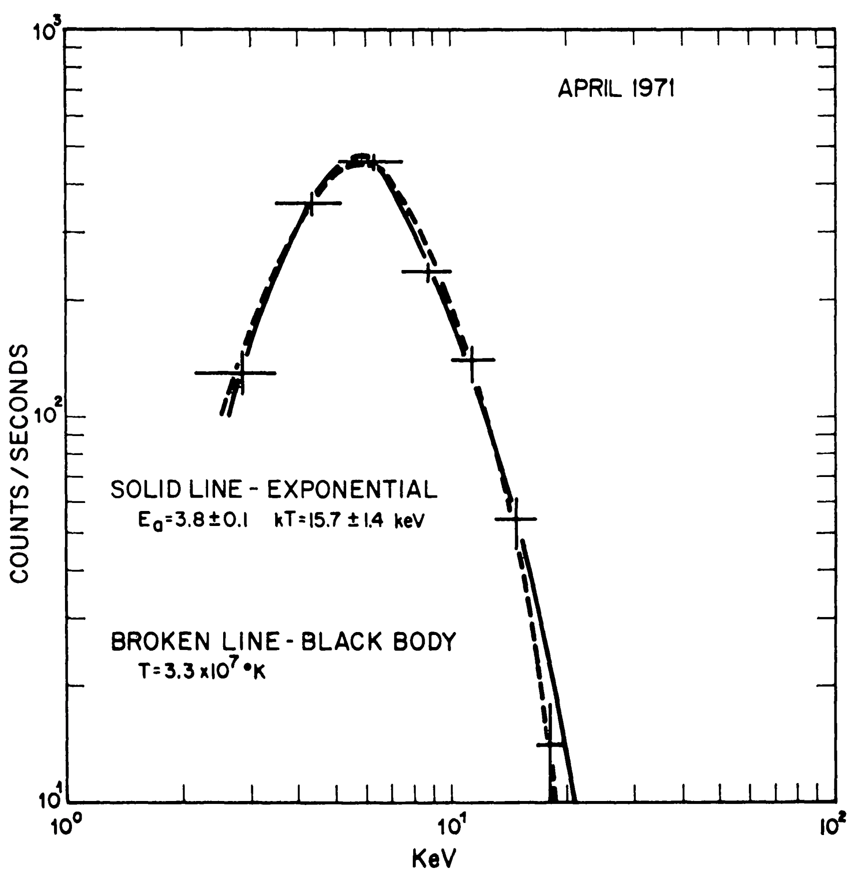

FIG. 4.—Spectrum of Cen X-3. *Crosses*, counting-rate data and error bars in seven energy channels from 2 to 20 keV. *Solid curve*, best-fit thermal-bremsstrahlung spectrum with an effective temperature of 15.7 keV and an exponential cutoff energy E_a of $\sim$3.8 keV folded through the detector response function. *Dashed line*, best-fit blackbody spectrum with a temperature of 3.3×10^7 ° K.

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TABLE 2

DATA ON X-RAY PULSARS

	Star		
Parameter	NP 0532*	Cygnus X-1†	Centaurus X-3
Period τ (seconds)	0.033	0.073 or 0.292 1.1 or 1.3 Possibly >5	4.87
$\Delta\tau/\tau$	-10^{-8} (1969 Sept 28±1)	?	-2×10^{-4} 1971 Jan 11, 77000 $+4\times10^{-4}$ 1971 Jan 12, 19000 -6×10^{-3} 1971 Jan 11 & 12–April 10 & 12
Optical or radio pulsar	Yes	None observed	?
Supernova remnant	Yes	$<10^{-2}$ Crab brightness in optical; $<10^{-4}$ Crab in radio at 11 cm	?
Fraction of X-ray power pulsed 2–6 keV	?	~20%	~70%
Variation in average emitted power	None observed	Factors of 2–4 in 1 hr	A factor of 10 in 1 hr
L_X, luminosity at the source (ergs s^{-1})	$\sim10^{36}$	$\sim3\times10^{36}$ if at 1 kpc	$\sim10^{36}$ if at 1 kpc
Spectral shape	Power law	Power law	Blackbody or thermal bremsstrahlung with severe cutoff

* Hewish (1970).
† Kristian (1971), Hjellming (1971), Oda *et al.* (1971), Holt *et al.* (1971).

effects, cannot explain the observed phenomena. Orbital motions of the source about another star could not explain the abrupt period variations in January, but might explain the long-term decrease from January to April. We conclude that at least the abrupt increases and decreases in the period are taking place at the source.

We know at least three stars which are pulsating mainly in the X-ray region: NP 0532, Cyg X-1, and Cen X-3. (We have also observed X-ray pulsations from 1 ASE 1516−57 [Lup X-1], but have not yet fully analyzed the data.) Some of their properties are summarized in Table 2.

It appears, from the shortness of the period of pulsations and from the extreme variability in short times, that the X-ray emitting regions in these sources are quite small, of the order of 10^9 cm or less. The large power emitted and the apparent regularity of the pulsations suggest that all these objects may be collapsed rotating stars with strong magnetic fields. The obvious differences between them, however, are so great that it seems likely that different types of stars will be required to explain their characteristics. For instance, Cen X-3 has a period longer than any known pulsar and some 150 times longer than NP 0532, yet emits X-rays at almost the same rate as NP 0532 (if at 1 kpc). While the data on NP 0532 are believed to fit a rotating-neutron-star model, Tucker (1971) has suggested that if Cen X-3 is a white dwarf rotating close to instability, several features of its emission could be explained. Cygnus X-1 may require yet a different explanation. The rapidly accumulating observational material on the X-ray emission from these pulsating objects has opened a new technique for detailed study of the physical properties of stars near the endpoint of their evolution.

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Note added in proof.—The November 1968 observation of Cen X-3 was carried out by A. MacGregor, F. Seward, and I. Turiel, and reported in *Ap. J.*, **161**, 979–986 (1970). The intensity of the source was 0.8 photons cm^{-2} s^{-1} in the 2–10-keV range.

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