THE ASTROPHYSICAL JOURNAL, 166:L1–L7, 1971 May 15

X-RAY PULSATIONS FROM CYGNUS X-1 OBSERVED FROM *UHURU*

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Received 1971 March 22

ABSTRACT

We have observed from *Uhuru* large-amplitude X-ray pulsations from Cyg X-1, which occur several times a second with a duration of less than a fraction of a second. The amplitude of the pulsations at times exceeds 25 percent of the average source intensity. The pulsations do not occur at random. Although we cannot within our data uniquely determine their period, we find that the data are consistent with a period of 73 milliseconds. In addition to fine-scale time variations, the average X-ray intensity from the source changes by factors of 2 over times of the order of 10^3 seconds. We conclude that we have discovered a pulsating X-ray star, whose characteristics are quite different from those of NP 0532.

Previous communications (Giacconi *et al.* 1971; Tananbaum *et al.* 1971) have reported briefly on the *Uhuru* instrumentation and on some results obtained from the orbiting X-ray observatory on the location of Cyg X-1. The observations had been carried out on 1970 December 21 and 27 and on 1971 January 4. We have further examined the same set of data from the point of view of obtaining a more detailed description of the time variability of Cyg X-1 over periods ranging from a few seconds to several hours. In order to examine the variability of a source over time intervals of a few seconds, we utilize the data from the broad field of view detector (5° × 5° FWHM). Because of the slow rate of spin of the satellite (approximately one rotation per 720 seconds) a source remains in the field of view of the detector for about 20 seconds. The sampling period for this detector is normally 0.384 seconds. The data from four passes on Cyg X-1 are shown in Figure 1. The expected response of the counter to a point source is a triangular-shaped distribution. The distributions shown in Figure 1 show much larger departures from this expected response than can be accounted for by random statistical fluctuations. This was to us an unexpected and surprising discovery, particularly in view of the amplitude of the variations which appear to be as large as 25 percent of the average source intensity over times as short as a few seconds. None of the previously known variable X-ray sources had been observed to exhibit such rapid and large variations in intensity except the X-ray pulsar in the Crab Nebula, NP 0532. Even in the case of the Crab Nebula, the X-ray pulsed emission constitutes only a small fraction of the observed average flux, and the average flux itself does not appear to vary over periods of minutes or hours. In the case of Cyg X-1 the data of Figure 1 show large pulsations in times of the order of seconds, and the average intensity of the source varied by a factor of 2 on successive acquisitions separated by about 800 sec.

We ascertained that this behavior was not due to instrumental effects by noting the absence of pulsations or large time variations in Sco X-1 and Cyg X-3, and by examining the spectral distribution of the counts from Cyg X-1 in one of the passes as shown in Figure 2. We note that the same features of the pulsations appear clearly in seven different energy channels which constitute a semi-independent set of data. Intrigued by these unexpected results, we decided to perform additional observations on Cyg X-1 with increased time resolution. The data from the narrow field of view of the detector (0°.5 × 5°

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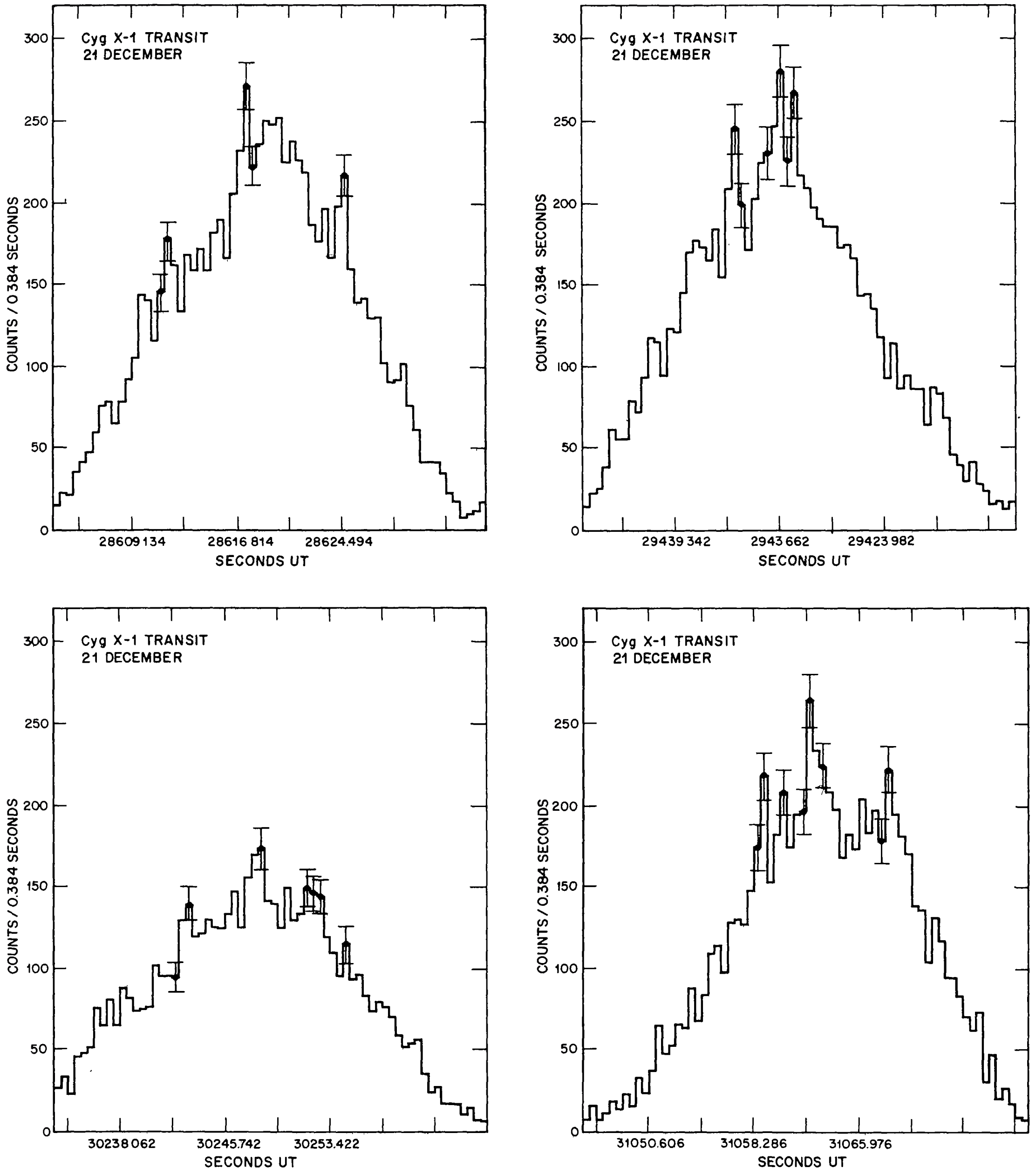

FIG. 1.—Counts accumulated in the energy region 2.4 to 6.9 keV every 0.384 sec in the 5° × 5° FWHM detector during four transits of Cyg X-1. Expected statistical fluctuations are shown in a few instances. The times shown are UT in seconds on 1970 December 21. Cyg X-1 was essentially in the center of the field of view during each pass.

FWHM) are transmitted every 0.096 seconds. However, the source remains in the field of view for only 2 seconds and thus does not allow a sufficiently long observation time to determine the characteristics of the source. We have, however, the capability in *Uhuru* to cross-couple the detector banks and their respective electronics on command from the ground. Thus, we can receive data from the large field of view of the detector on a given source for a period of 20 seconds with a time resolution of 0.096 seconds.

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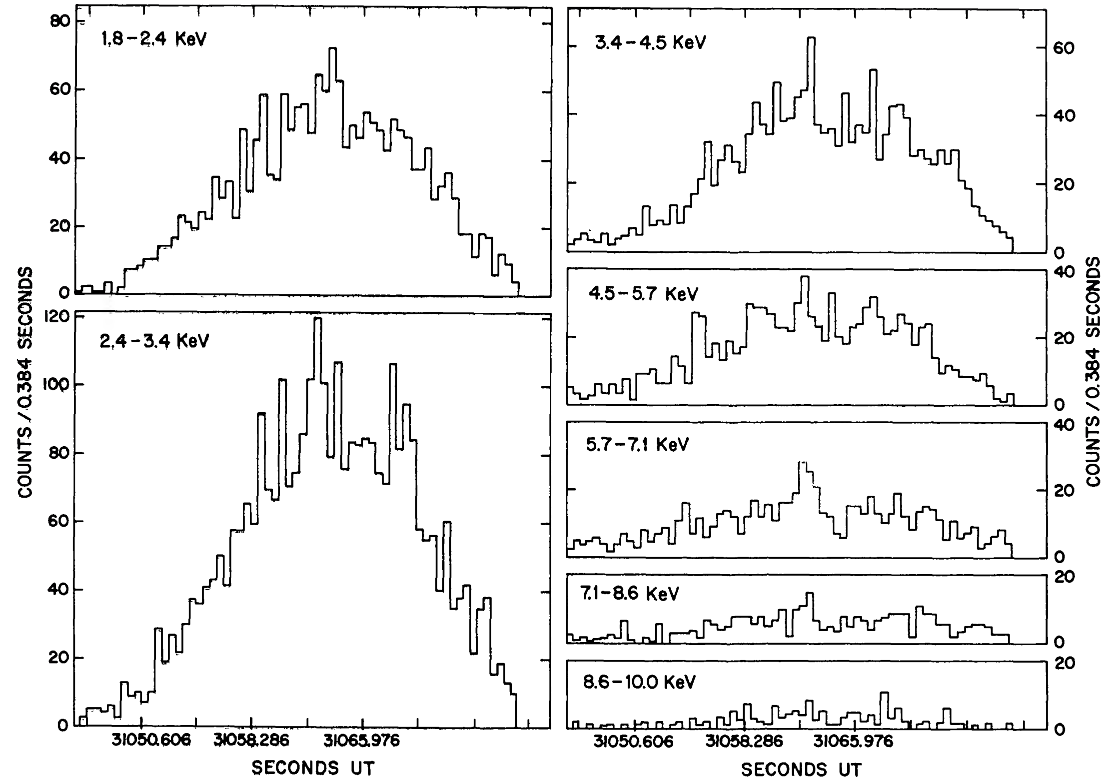

Fig. 2.—Counts accumulated in 0.384 seconds in several channels of pulse height corresponding to the energies indicated in the figure during one transit of Cyg X-1. The data were obtained on 1970 December 21 during one of the passes shown in Fig. 1.

This observational mode was used on 1971 March 6 for about a day. Real-time data were telemetered to the ground during each pass over Quito, Ecuador, for about 10 minutes and were relayed by telephone link to NASA's Goddard Space Flight Center, and later to AS&E. In this fashion we observed Cyg X-1 once per orbit when not occulted by the Earth, and five passes were available for the present analysis. The data from three such passes are shown in Figure 3. We can observe again, but in finer detail, the main features of Cyg X-1 variability, namely, the rapid pulsations with a time scale of fractions of a second. We see as well large variations of the average intensity.

Some of the data give a distinct impression of the presence of a periodic pulsation. For example, the data in Figure 2 show a series of "spikes" separated by 1.4 seconds. More impressive are the data in Figure 3*c* in which "spikes" appear almost regularly every third interval (0.288 seconds). These features were verified by simply folding the data modulo a trial period. We tested the data further for periodicity by performing autocorrelations and Fourier analyses on individual source acquisitions.

However, at first no consistent pattern of periodicity emerged. Different sets of data seemed to show different periods. In fact, this is the impression one has from the primary data themselves. It was also bothersome that the periodicity that seemed to be present was almost precisely three sampling intervals. This was puzzling until we realized that the true frequency of the underlying pulsation might be higher than the sampling rate of the telemetry. In this case one would get a beating between two frequencies, and a complex pattern of pulses could emerge that could vary on a time scale of 20 seconds, which is our maximum source transit time. For example, if the X-ray

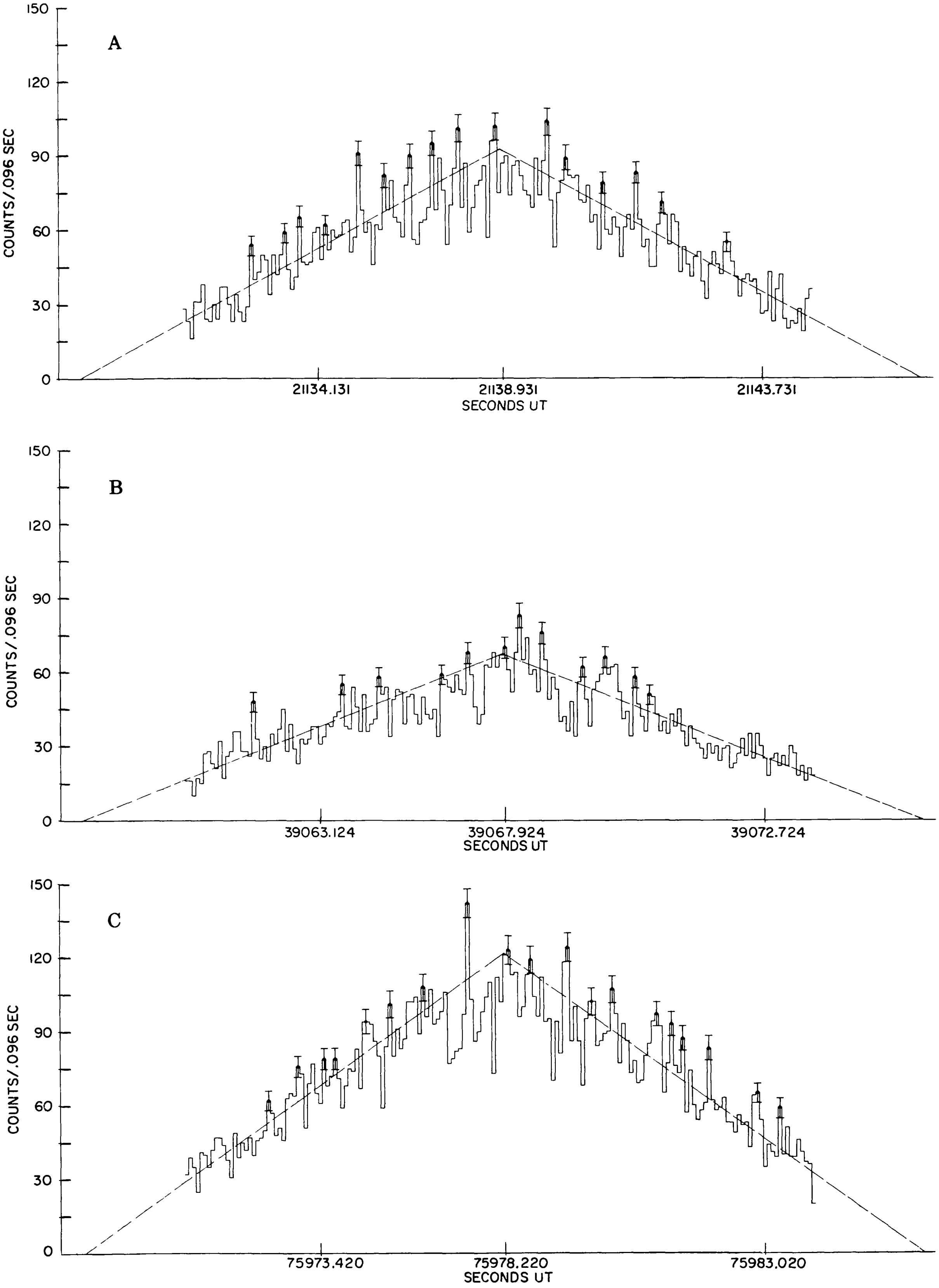

Fig. 3.—Counts accumulated in 0.096 seconds in several passes on Cyg X-1 on 1971 March 6. The data in the three scans *a*, *b*, and *c* were obtained at the UT times shown. Expected statistical fluctuations are shown in a few instances. Cyg X-1 was essentially in the center of the field of view during each pass. Dashed line represents the triangular response of the detector normalized to the total observed counts.

intensity were pulsating with a period about two-thirds of the sampling time, at least one pulse would appear in each sampling interval and two pulses would appear in every third interval. In this case the data would appear periodic with a period of three sampling intervals. Clearly the exact sequence of a train of excess pulses depends critically on the period of the pulsations, the phase of the initial pulse, and the pulse width. In fact, one can show that the relation between the true period of pulses, τ, and the period of the beats, k, is

$$\tau(n \pm mT/k) = T\,, \qquad n, m = \text{arbitrary integers,}$$

where T is the width of the sampling interval.

We then attempted to interpret the Fourier analyses by using this relation. These analyses, obtained by using the Cooley-Tukey algorithm, showed sharp, statistically significant peaks at a variety of frequencies for each of the five scans with 0.096-sec resolution and seven scans with 0.384-sec resolution. These frequency peaks repeat from scan to scan, and we are able to observe statistically significant peaks at a fundamental beat frequency and its harmonics to the eighth order. Thus, the probability that this result might be due to random pulsations is negligibly small. Using the above-quoted formula to deduce the actual period, we obtain about 73 ms as the true period of the pulsations.

Fourier analyses of simulated data have given us further confidence in the correctness of this interpretation. Data with random spikes will yield significant peaks in the Fourier spectrum but at random positions, while data with regular pulses with a period of about 73 ms yield spectral peaks at regular positions as we see them in the *Uhuru* Cyg X-1 data. We analyzed in the same fashion data obtained when observing Sco X-1 and also data obtained during calibration, when the accumulated counts are produced by an onboard radioactive source. In neither set of data were statistically significant frequency peaks present.

Based on the above interpretation, we can also estimate the amplitude of the pulses. If the pulse period is 73 ms, the beat that appears in each third sampling interval is caused by one excess pulse present in that interval. The χ^2 excess indicates that these beat pulses must contain about 15 percent of the counts recorded in a sampling interval, which in turn implies that about 20 percent of the total power in the source appears in the periodic pulses.

We must point out that this simple interpretation of our data is not unique. In particular, we cannot exclude the possibility that the time period is a multiple of 73 ms in the range up to 292 ms, or that a much more complex pattern of emission from the source may be degraded by our coarse time resolution. The *Uhuru* data are clearly quite limited for this type of investigation. The relatively poor time resolution makes it difficult to establish a precise value of the amplitude, shape, or period of the pulsations. When combined with the short acquisition time (20 seconds), it means that we cannot determine if the effect is truly periodic over long time intervals and, in particular, we cannot establish whether phase is conserved from one acquisition to the next. Hence, it is essential that the results be confirmed by continuous observations made with finer time resolution, such as should be possible with balloons or sounding rockets.

Evidence for long-term variability for the X-ray flux of Cyg X-1 has been discussed by several authors (e.g., Byram, Chubb, and Friedman (1966); Grader *et al.* 1966; Overbeck and Tananbaum 1968; Tananbaum *et al.* 1971). Evidence was reported for variations of intensity by factors of 2 to 4 over periods of weeks to years.

The present observations clearly are consistent with the view that the intensity of Cyg X-1 varies by large factors in short periods of times and, in fact, the long-term variability previously observed may have been due to sampling of the source at high- and low-intensity levels. On the other hand, our results are not consistent with the previous report by Friedman *et al.* (1969), who placed an upper limit of 6 percent on a pulsed component of Cyg XR-1 in the range from 0.008 to 4 seconds. This discrepancy might partly be understood in view of the much lower statistical precision of their measurement.

Measurements by several groups have established some of the characteristics of the Cyg X-1 source. An upper limit of about 1 kpc on the distance has recently been determined on the basis of the detection of a turnover of the spectrum at low energy (Gursky *et al.* 1971). An upper limit of $1\overset{\prime}{.}4$ on the angular size of the X-ray source has been placed by Floyd (1969). Spectral measurements by several groups have established a power-law spectrum $dN/dE \approx 1.5E^{-1.7}$ from 0.5 to 100 keV. This object has therefore an X-ray luminosity of about 3×10^{36} ergs $\sec^{-1}$ in this energy range. An upper limit on the radio emission from the object of 0.01 flux units at 11 cm has been obtained by Hjellming (1971). We are not aware of any reported upper limit placed on the pulsed radio emission from Cyg X-1, although it has not been detected in the extensive searches for galactic pulsars. The present measurement places very severe constraints on the physical conditions of the source. The occurrence of rapid pulsations requires that at least 25 percent of the emission occur in a region of linear dimension smaller than 10^8 cm. The existence of variations in intensity by factors of 2 in 800 seconds requires that at least 50 percent of the emission occur in a region smaller than 1 a.u. The existence of persistent 70-ms pulsations compels us to invoke stellar rotation as the underlying timing mechanism, almost independently of whether these pulsations remain rigorously periodic over very long times or persist only for several tens of seconds at a time. Further, the rapid rotational period requires that the rotating star be a collapsed object, such as a neutron star or a black hole. Clearly, many of the characteristics of Cyg X-1 are similar to those of the Crab Nebula pulsar NP 0532. The most outstanding difference is, of course, the absence of a supernova remnant surrounding Cyg X-1, as shown by the quoted upper limit on radio emission at 11 cm which corresponds to about 10^{-4}–10^{-5} of the radio emission from the Crab at that wavelength. We are then driven to the conclusion that either Cyg X-1 was not formed in a supernova explosion or that, for some reason, the radio emission from the remnant is either absent or undetectable. If we accept the current view of the relation between age and rotational period in rotating collapsed objects, Cyg X-1 cannot be too old. Its period is the shortest known next to NP 0532 and is only slightly shorter than the period of the Vela pulsar PSR 0833, which would imply an age of between 10^3 and 10^5 years. This makes it unlikely that a possible remnant might have expanded away from Cyg X-1 and by now be undetectable. We are then left with the question of whether a collapsed star can be formed without a supernova explosion or whether we can invoke peculiar choices of parameters to avoid the production of copious radio emission as discussed by Colgate and White (1966) and by Leblanc and Wilson (1969).

The fact that an X-ray pulsating star can exist without a detectable supernova envelope makes it more plausible to invoke similar objects to understand the nature of X-ray stars such as Sco X-1 and Cyg X-2, as has recently been suggested by several authors, including Tucker (1969), and Coppi and Ferrari (1970).

We would like to acknowledge the assistance and cooperation of the Control Center and the Data Center at Goddard Space Flight Center of NASA in maneuvering the spacecraft and in making quick-look data available to us in a very rapid fashion for this special event. We are grateful to S. Rappaport and R. Doxsey for making available to us the results of analysis and simulations performed (independently) by them on our data, utilizing computer facilities of the Massachusetts Institute of Technology. We have benefited greatly from a series of illuminating discussions with B. Rossi and W. Tucker on the physical nature of Cyg X-1 which took place from the onset of this analysis. We are grateful to B. Coppi for discussing with us several details of his theory of X-ray emission from pulsars.

This work was supported by NAS 5-11092. M. Oda was supported in part by funds from the University of Tokyo.

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