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# Monitoring Cen X-3 with BATSE

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**Abstract**

The eight uncollimated BATSE Large Area Detectors (LAD's) provide the ability to monitor pulsed hard x-ray sources on a nearly continuous basis. Using data from the LAD's, the pulse timing and pulsed flux of the 4.8 second period binary x-ray pulsar Centaurus X-3 has been analysed over a two month period. The methods and initial results of this analysis, which includes both data folded on-board GRO and 1.024 second resolution discriminator rates folded on the ground, are presented.

## 1. Introduction

One of the objectives of the Compton Gamma ray Observatory's Burst and Transient Source Experiment (BATSE) is the long-term monitoring of x-ray pulsars. As a exploration of BATSE's pulsar monitoring capabilities, this paper presents the initial results of a timing analysis of the x-ray pulsar Centaurus X-3.

Pulsations from Cen X-3 with a period of 4.8 seconds were first observed in Uhuru data in 1971 [1]. Further analysis of the Uhuru data revealed that the source was a member of a binary system [2]. This was demonstrated both by 2.087 day period doppler signatures in the detected pulse period, and eclipses with the same period. Since that time a considerable body of observations has accumulated, including observations by Uhuru [3], Cos-B [4], SAS 3 [5], Heao 1 [6], Hakucho [7], Tenma [8], Ginga [9], Röntgen on Kvant [10], and Art-P on Granat [11]. To this body of observations BATSE promises to add a nearly continuous data set spanning several years.

BATSE has eight uncollimated Large Area Detectors (LAD's) placed on the corners of the Compton Gamma Ray Observatory spacecraft [12]. Cen X-3 (or any other source) is continuously viewed by four of these detectors during the portion of each orbit that it is unocculted by the Earth. Each LAD consists of a .5 inch thick by 20 inch diameter NaI(Tl) scintillator coupled by a light integration chamber to three 5 inch photo-multiplier tubes. The useful energy range of the LAD's is from 20 keV to 1 MeV. The data types from these detectors relevant to pulsar analysis are summarized in Table 1.

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| Data Type | Energy Channels | Time Resolution | Accumulation Time per day |
|---|---|---|---|
| Folded On-Board | 16 | Period/64 | 5000-10000 sec |
| DISCLA | 4 | 1.024 sec | 50000-86400 sec |
| CONT | 16 | 2.048 sec | 50000-86400 sec |

**Table 1.** Data from the BATSE LAD's that is useful for pulsar analysis.

The BATSE hardware can fold data on-board for periods specified in integral numbers of microseconds. The result of this folding is 64 phase resolved count spectra each with 16 energy channels. Due to scheduling competition with other pulsars, and due to telemetry competition with burst data, typically only 5000 to 10000 seconds of this data type is acquired per day for Cen X-3. The DISCLA data contains the four discriminator rates for each of the LADS with 1.024 second time resolution. The CONT data contains 16 channel count spectra for each of the LADS with 2.048 second time resolution. Useful data of each type is available at all times the source is visible, except for times of SAA passage, solar flares, and other interfering events.

In the analysis presented here we begin by studying the lowest DISCLA energy channel (20-60 keV). This data is used to establish the history of Cen X-3's intensity and rotational phase. High intensity portions of the folded on board data are then examined using the phase ephemeris developed from the DISCLA data. The CONT data, which contains additional spectral information, has not yet been analysed.

## 2. DISCLA Analysis

The DISCLA data used in this analysis consists of the counting rates from the eight BATSE LADS in the 20-60 keV energy deposit range sampled every 1.024 seconds. The data set analysed covers the period from Truncated Julian Date (TJD) 8369 to TJD 8433 (23rd April to 26th June 1991). These rates are typically between 1000 and 2000 counts per second. In this energy range the sky is brighter than the Earth's atmosphere. This contrast imposes a modulation at the spacecraft orbital period (5600 seconds) of 500-1000 counts per second. Excursions from these typical rates are caused by solar flares, gamma-ray bursts, and atmospheric electron events. And of course, buried in these rates is the few counts per second periodic signature of Cen X-3.

The first step taken in the DISCLA processing was to filter the data and form a linear combination of the rates from individual detectors. Data was rejected from periods when Cen X-3 was occulted by the Earth. Data was also rejected during periods when solar flares, gamma ray bursts, or other events caused rapid variations in the counting rates. The rates were then summed over the detectors exposed to Cen X-3, with a weighting for each detector given by the cosine of the angle between the detector's normal and the source direction. This weighting roughly mimics the detector response, and produces a linear combination that is fairly insensitive to reorientations of the Compton GRO spacecraft. In this first step of processing the time-tags associated with each rate were reduced to the geocenter, thereby eliminating any further need for the spacecraft ephemeris.

The linearly combined rates were then "pulse folded" using a technique simular to that employed by Deeter et al. [13] in timing analyses of Vela X-1. The data were divided into segments 300 seconds long which were individually fit to models of the form:

$$R(t) \;=\; B_0 + B_1 t + B_2 t^2 \;+\; \sum_{k=1}^{3} [C_k \cos 2\pi k\phi + S_k \sin 2\pi k\phi] \tag{1}$$

where $R$ is the model rate, the quadratic in time $t$ represents the background rate, $\phi$ is a provisional model of the pulsar's rotational phase, and the pulsar light curve is parameterized by the first three harmonics of the observed pulse shape. Due to the 1.024 second resolution of the DISCLA rates, little additional information could be obtain by including higher harmonics. These $\chi^2$ fits to this nine parameter model used variances calculated from the individual detector rates by assuming Poisson statistics. Data segments with a $\chi^2$ per degree of freedom greater than 1.4 were rejected from further analysis. For the remaining segments sufficient information was recorded to allow the calculation of the $\chi^2$ associated with the model in equation (1) for an arbitrary set of parameters.

A further step was then employed that resulted in a $\chi^2$ fit to the remaining data over intervals of approximately 10000 seconds. The resulting fit was to a model of the form

$$R \;=\; B(t) \;+\; \sum_{k=1}^{3} [C_k \cos 2\pi k(\phi + \delta\phi) + S_k \sin 2\pi k(\phi + \delta\phi)] \tag{2}$$

where $B(t)$ is the background model and $\delta\phi$ is a correction to the model of the pulsar's rotational phase applied above. The pulsar light curve is assumed to be constant over each interval. For each 300 second segment within an interval the background was again modeled as a quadratic,

$$B(t) = B_0^i + B_1^i t + B_2^i t^2 \quad for \quad \tau^i < t < \tau^{i+1} \tag{3}$$

where $\tau^i$ are the segment boundaries. The model however was constrained to be continuous in value and slope at the boundaries of adjoining segments. These interval fits were obtained from the previous segment fits using a sequential estimation technique known as Square-Root Information Filtering (SRIF) [14]. Only the estimates of the pulsar light curve harmonic amplitudes and their associated errors were retained from these interval fits.

The parameterized light curves obtained from the interval fits were then correlated with a template to obtain a Cen X-3 pulse intensity and phase offset for each interval. The template used is shown in Figure 1. This resulted from folding data from TJD 8369.9 to 8370.5, subtracting the mean, and normalizing to obtain a mean square value of one.

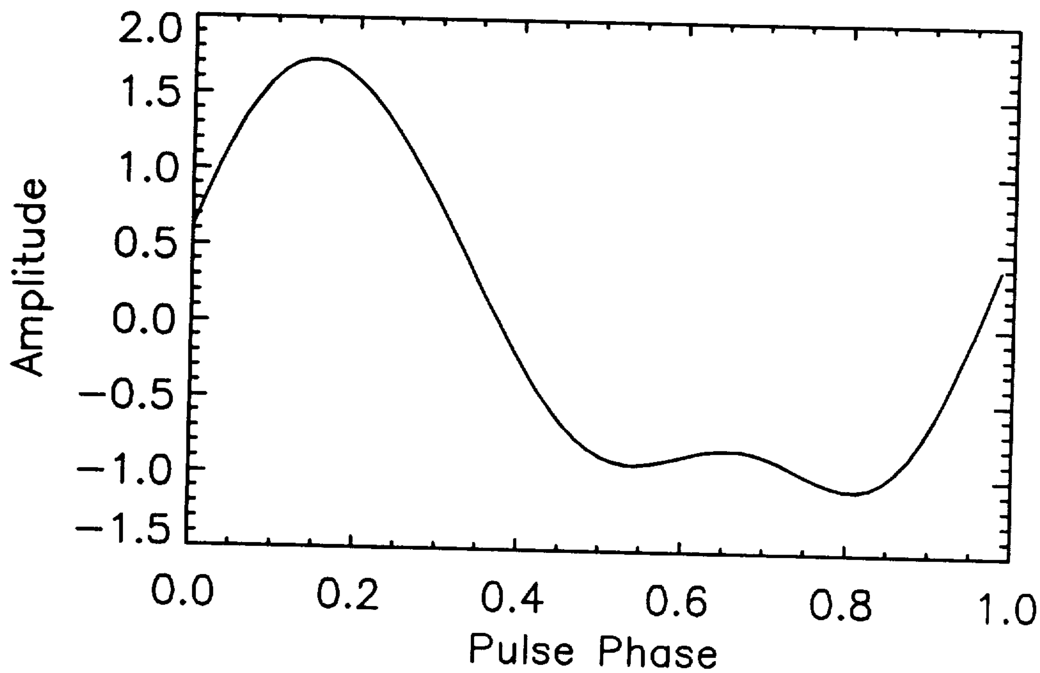


**Figure 1.** The pulse template used for Cen X-3 timing. This was derived from data in the interval TJD 8569-8574.

## 3. Results

In the calculation of pulsar phases for the folding of the DISCLA data the planetary ephemeris DE200 was used in conjunction with the Cen X-3 binary system ephemeris given in Table 2. This binary ephemeris was based on orbital elements found by Murakami et al. [7] and the orbital period derivative derive by Kelley et al. [5]. It was found necessary to make an adjustment to the orbital phase. This adjustment, which was consistent with the quoted ephemeris errors, was determined from data in the period TJD 8370-8374, and is reflected in the mid eclipse epoch given in Table 2.

| | |
|---|---|
| Epoch of mid Eclipse | $t_{\pi/2}$ = JD 2448370.1470 ± .0005 |
| Binary Period | $P_{orb}$ = 2.0870686 days |
| Period rate of change | $\dot{P}_{orb}$ = $-1.02 \cdot 10^{-8}$ |
| Projected semi-major axis | $x$ = 39.664 sec |

**Table 2.** Cen X-3 binary ephemeris adopted from Murakami et al. and Kelly et al. with an adjustment in orbital phase.

The data was initially folded with a pulse frequency of 0.20747 Hz. Phase residuals from the template correlation were then fit and the interval fits recalculated. After several iterations the following total phase model was arrived at:

$$\phi + \delta\phi = -0.2350 + 17925.701442\Delta t - 0.03355982\Delta t^2 + 0.0003579274\Delta t^3 \quad (4)$$

where $\Delta t$ is the time elapsed in days since JD 2448370.5 in the pulsar timescale.

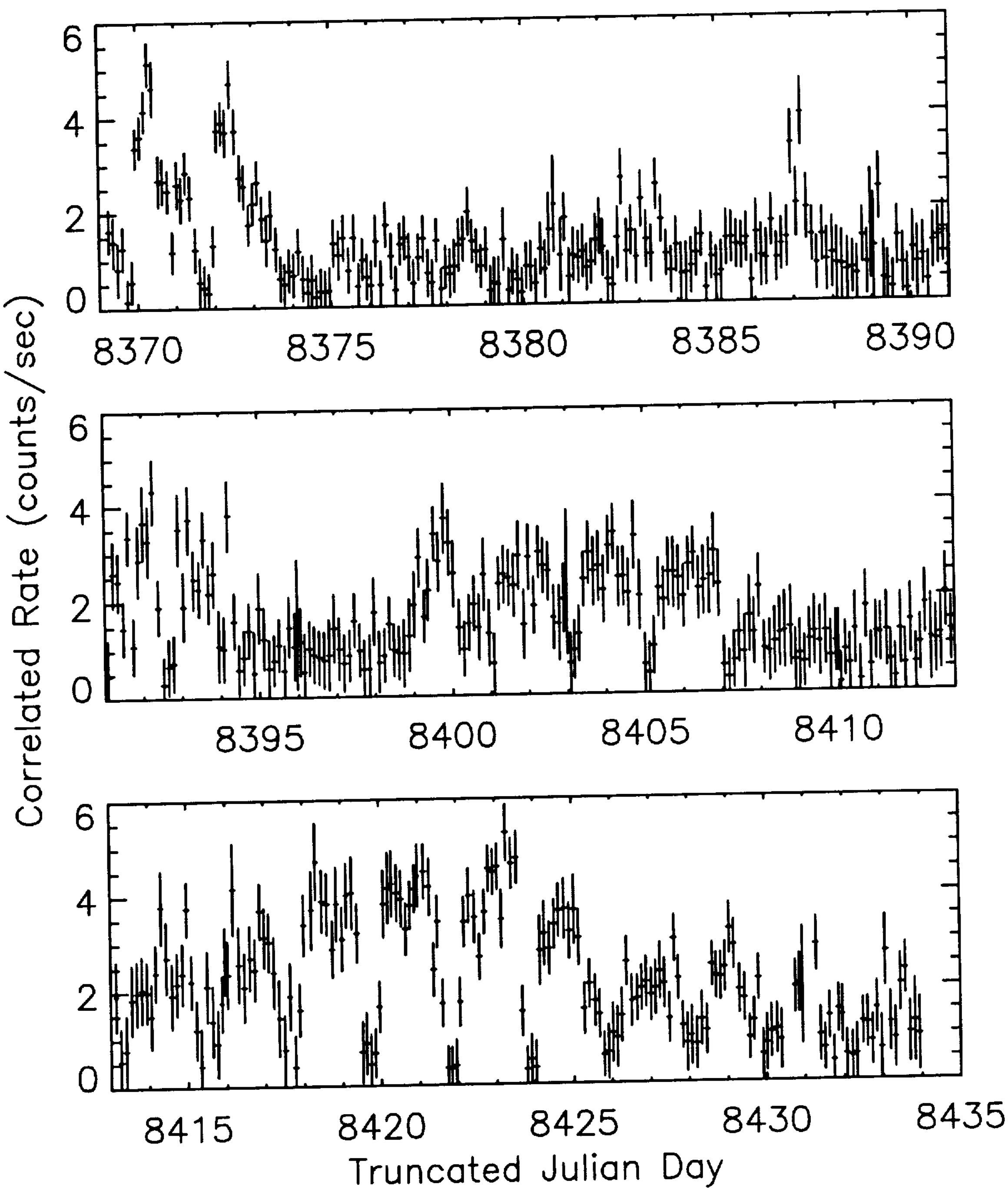


**Figure 2.** The Intensity history of Cen X-3 obtained by correlation of the folded rates with a pulse template.

The intensity history of Cen X-3, as determined from the 10000 second interval template correlations, is show in Figure 2. Several high intensity periods are visible, the most notable being from TJD 8369 to 8384, from TJD 8399 to 8407 and from TJD 8413 to TJD 8430. During these periods the eclipses are clearly visible. The phase residuals relative

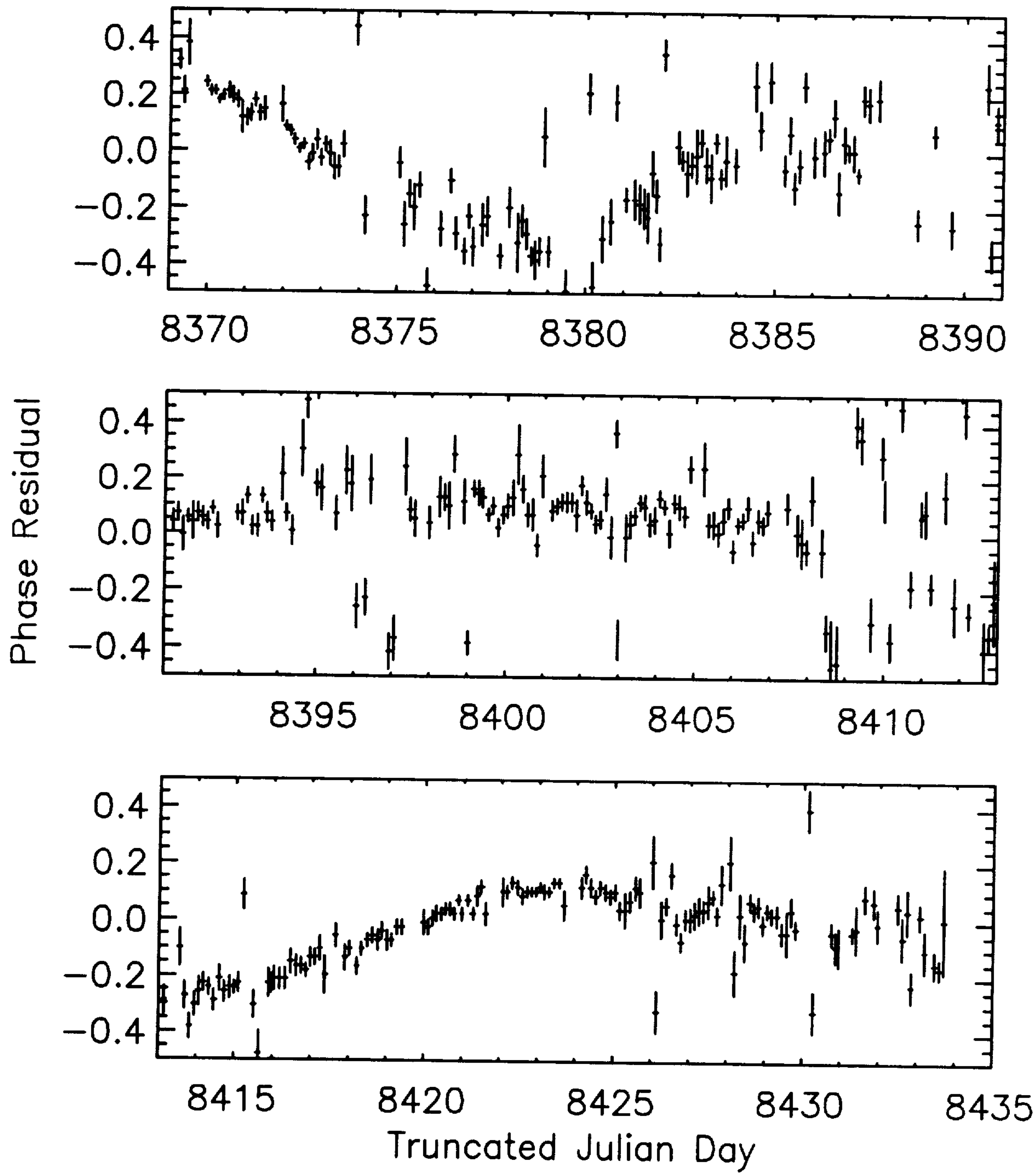


**Figure 3.** The phase residuals of Cen X-3 relative to the model given in equation (4) obtained by correlation of the folded rates with a pulse template.

to the model in equation (4) are shown in Figure 3. In order to eliminate the majority of intervals when no signal was detected, phase points are only shown if the intensity to intensity error ratios is greater than 1.5. The connectivity of the phase points is clear in the intervals of high intensity. In the intervals from TJD 8388 to 8390 and from TJD 8408 to 8413 however, it appear that no signal from Cen X-3 has been detected, and it is possible that the phase slips by a cycle. During the interval from TJD 8399 to 8407 the phase residuals appear to have a periodic signature which suggest a possible need for orbital parameter corrections. However the same signature is not present in the other intense intervals. A possible explanation that needs to be investigated is a variation of pulse shape with orbital phase within this or other intervals. The total observed phase in these three period of high intensity were fit with a quadratic model resulting in the periods and period derivatives given in Table 3.

| Epoch (JD) | Period (sec) | Period Rate ($10^{-10}$ sec/sec) |
|---|---|---|
| 2448372.0 | 4.8199422(10) | 2.06(29) |
| 2448403.5 | 4.8201772(5) | −0.01(6) |
| 2448421.0 | 4.8200583(3) | −1.00(3) |

**Table 3.** Cen X-3 pulse period and derivative at selected epochs. Errors on the last digit are given in parentheses.

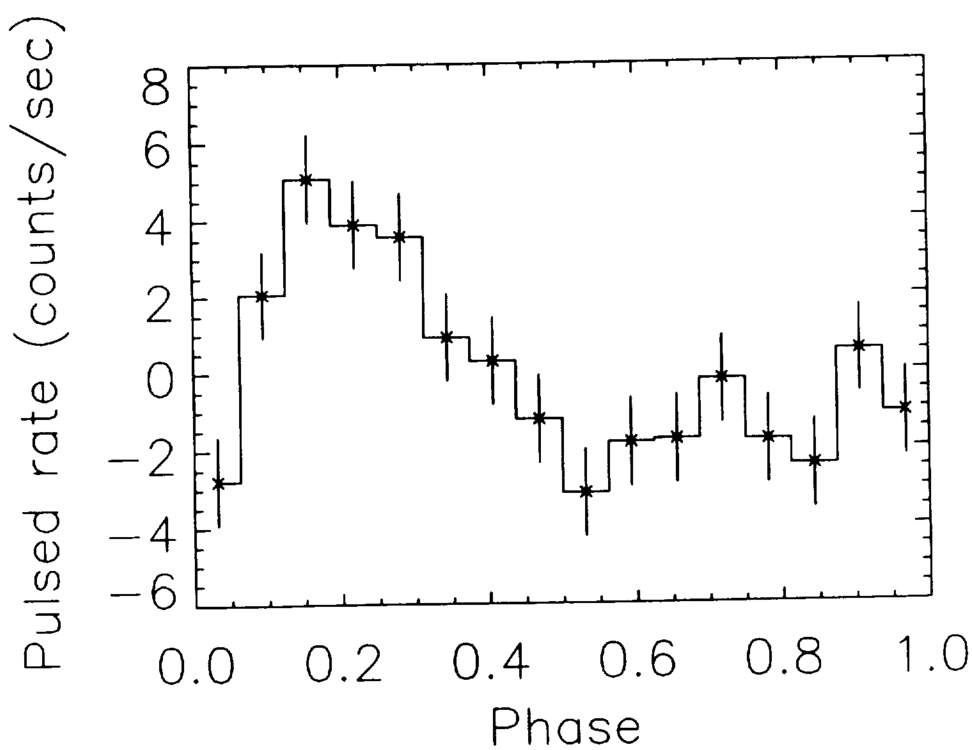


**Figure 4.** The light curve of Cen X-3 in the 20 to 60 keV energy band for the period TJD 8399-8407 based on folded-on-board data.

## Folded-on-board Data Analysis

The folded-on-board data analysis is described by Wilson et al. in these proceedings. The analysis of the folded-on-board data from Cen X-3 is still in its early stages. An example of the light curves obtained from the folded on board data is shown in Figure 4. For this light curve data in the 20 to 60 keV range from the high intensity period from TJD 8399 to 8407 was folded using the period and period derivative given in Table 3. Data was included only for Cen X-3 orbital phases in the range from .1 to .9. The total accumulation time of the included data was 23369 seconds. Significantly greater pulse shape information is available in the folded-on-board data than in the DISCLA. However due to counting statistic the full hardware resolution of 64 phase bins is not useful and is not shown in the figure.

## Conclusion

The uniqueness of BATSE from the standpoint of pulsar observation is its ability to view in all directions continuously. This ability makes BATSE an excellent instrument for the long term monitoring of x-ray pulsars. This is particularly true for the longer period pulsars which may be studied exclusively with the continuously available DISCLA and CONT data.

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