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LETTER

Letter to the Editor

A possible 13.81 d period of the X-ray binary 4U 1700-377

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Abstract. We report the results of a temporal analysis of CGRO BATSE and RXTE ASM All-Sky monitor X-ray light curves of the high mass XRB 4U 1700-377. In addition to the known orbital period of 3.41 d we found evidence for the existence of a second periodicity of about 13.81 d in the light curves of both satellites. We suggest that this new period might be due to the free precession of the neutron star.

Key words: X-rays: stars

1. All-sky monitor data

The X-ray source 4U 1700-377 was first detected by UHURU in 1970 (Jones et al. 1973). The accreting compact object in the X-ray binary is eclipsed every 3.41 d by its companion star, which was optically identified as the O7f star HD 153919 (Penny et al. 1973). The X-ray spectrum and the optical mass function indicate that 4U 1700-377 is a neutron star, although no (persistent) X-ray pulsations have been observed (Gottwald et al. 1986).

We examined All-Sky monitor X-ray light curves from the CGRO satellite (launched in April 1990) and the RXTE satellite (launched in December 1995). All data which are presented are public data provided as an on-line service from the Laboratory for High Energy Astrophysics (LHEA) at NASA/GSFC. The BATSE experiment (sodium iodide scintillators, energy range 20 keV to 1 MeV) on the CGRO satellite was designed to detect gamma-ray bursts and search the sky for other transient emission. This experiment uses eight independent detectors, one at each corner of the satellite, resulting in a continuous view of those parts of the sky not blocked by the Earth. Using Earth occultations BATSE provides long term flux histories for bright X-ray sources (given as one-day-averages). Fig. 1a shows the X-ray time series of 4U 1700-377 measured by the BATSE experiment.

The ASM instrument on the RXTE satellite consists of three wide-angle shadow cameras equipped with proportional counters (energy range 2 keV to 10 keV). Every day a bright X-ray source dwells a few times (typically 5 - 10) in the cameras field-of-view. Fig. 2a displays the ASM X-ray time series of 4U 1700-377.

Table 1. Period estimates

instrument	P_0 estimate [a] 10^5 sec	χ^2_{red}
CGRO BATSE	2.94812 ± 0.00038	16.2
RXTE ASM	2.9483 ± 0.0012	51.1

[a] test period that corresponds to maximum χ^2_{red} for epoch folding with 15 phase bins.

2. Temporal analysis

We have applied the epoch folding technique (Leahy 1983) to perform a period search in the X-ray light curves of both satellites (s. Table 1). The corresponding χ^2 statistics clearly show the known 3.41 d periodicity, which is believed to originate from X-ray source occultations by the companion (s. Fig. 1b and 2b).

Due to the lower statistical quality of the CGRO BATSE data, more fluctuations appear in the regime of small test periods ($P < 5 \cdot 10^5$ sec). For increasing test periods, however, this perturbation dies out and the 3.41 d multiples ($P_1 = 2 \cdot P_0$, $P_2 = 3 \cdot P_0$, $P_3 = 4 \cdot P_0, \ldots$) dominate the χ^2 distribution (s. Fig. 1b). In addition to these multiples, a small peak occurs very close to the P_3 peak ($\approx 1.2 \cdot 10^6$ sec) and close to the P_7 peak ($\approx 2.4 \cdot 10^6$ sec).

A detailed view of the P_3 regime in the CGRO BATSE χ^2 distribution (s. Fig. 3a) clearly shows a second broad peak at $P_{new} = (1.1936 \pm 0.0019) \cdot 10^6$ sec ($\approx$ 13.81 days), located close to the third multiple peak at $P_3 = (1.1792 \pm 0.0018) \cdot 10^6$ sec ($\approx$ 13.65 days). The peak which is located close to the P_7 peak in Fig. 1b is the first multiple of the P_{new} oscillation (at $2 \cdot P_{new} \approx 2.39 \cdot 10^6$ sec). The χ^2_{red} amplitude of 2.87 for the P_{new} test period yields an a-priori false alarm probability of $2.391 \cdot 10^{-4}$ for wrongly indicating periodic behaviour (for comparison, false alarm probabilities of 10% and 1% corre-

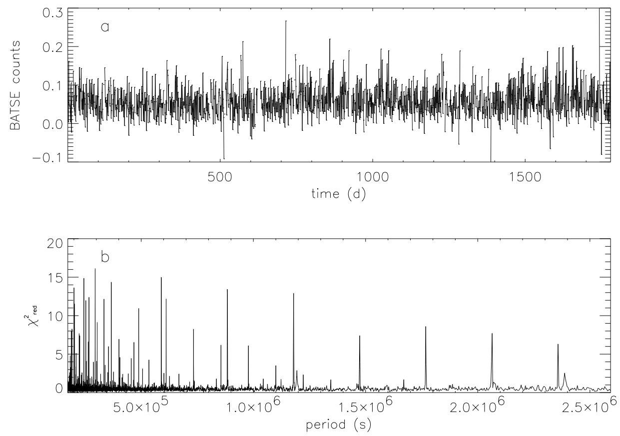

Fig. 1. **a** CGRO BATSE All-Sky monitor light curve ($T_{\rm tot,BATSE}$ = 1780 d, zero is JD 2448370.0), **b** epoch folding χ^2 statistic (15 phase bins).

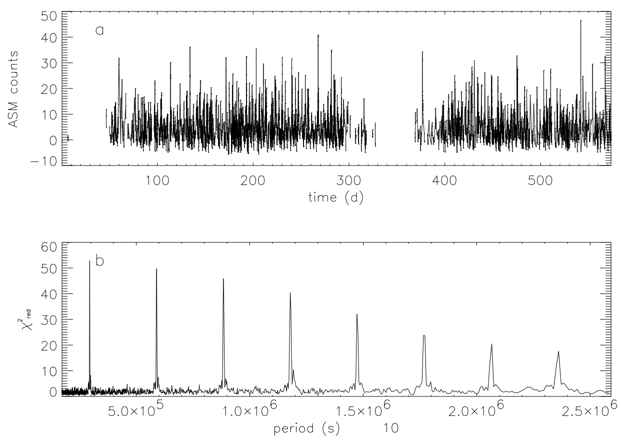

Fig. 2. **a** RXTE ASM All-Sky monitor light curve ($T_{\rm tot,ASM}$ = 573 d, zero is JD 2450088.613), **b** epoch folding χ^2 statistic (15 phase bins).

spond to $\chi^2_{\rm red}$ values of 1.51 and 2.08, respectively). Following the relatively high $\chi^2(P_{\rm new})$ amplitude, we deduce that the second periodicity is a statistically significant feature in the CGRO BATSE χ^2 distribution.

The spike-like structure at $\approx 1.22 \cdot 10^6$ sec in Fig. 3a is a P_3 sidelobe, produced by yearly gaps in the CGRO BATSE time series ($P_{\rm spike} = P_3 + 4.4 \cdot 10^4$ sec). We have checked other CGRO BATSE All-Sky monitor light curves (Vela X-1, Cyg X-1, etc.) and we have found no evidence for any systematic origin (i.e. from the satellites sampling pattern) of the discovered $P_{\rm new}$ periodicity.

The corresponding epoch folding plot for the RXTE ASM light curve (s. Fig. 3b) provides the P_3 multiple and also shows strong evidence for the second periodicity. The $\chi^2_{\rm red}$ amplitude of 10.13 for the $P_{\rm new}$ test period corresponds to an even lower false alarm probability compared to the CGRO BATSE results.

The estimated peak width of the P_3 multiple peak in the CGRO BATSE χ^2 statistics is $\Delta P_3 = 2150 \pm 319$ sec which is in good agreement with the expected value of $\Delta P_{3,\rm th} = 4 \cdot P_0^2/T_{\rm tot,BATSE}$ = 2258 sec from epoch folding theory. The $P_{\rm new}$ peak width is expected to be $\Delta P_{new,\rm th} = P^2_{\rm new}/T_{\rm tot,BATSE}$ = 9263 sec. The estimation meets the theoretical peak width of ΔP_{new} = 9214 ± 1344 sec.

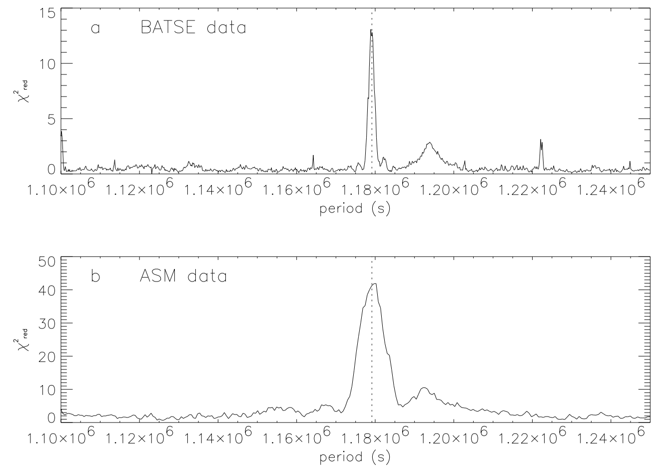

Fig. 3. Detailed $\chi^2_{\rm red}$ distribution of the P_3 regime a) for the CGRO BATSE data and b) for the RXTE ASM data, respectively (the dotted line denotes $P_3 = 1.179 \cdot 10^6$ sec).

In case of the peaks in the RXTE ASM χ^2 statistics, the estimated width $\Delta P_3 = 7772 \pm 910$ sec also fits the expected value of $\Delta P_{3,\rm th} = 4 \cdot P_0^2/T_{\rm tot,ASM}$ = 7013 sec. The $P_{\rm new}$ peak width is expected to be $\Delta P_{new,\rm th} = P^2_{\rm new}/T_{\rm tot,ASM}$ = 9263 sec. The estimation meets the theoretical peak width of ΔP_{new} = 9214 ± 1344 sec. Though hampered by the P_3 overlap (see below), the estimated value $\Delta P_{\rm new} = (26.5 \pm 5.7) \cdot 10^3$ sec confirms the theoretical peak width $\Delta P_{\rm new,th} = 28.7 \cdot 10^3$ sec.

Please note that, although the period estimates of P_3 and $P_{\rm new}$ nearly equals each other, the corresponding peak widths differ significantly ($P_{\rm new} \approx P_3 = 4 \cdot P_0$ yields $\Delta P_{new,th} \approx (4 \cdot P_0)^2/T_{\rm tot} = 4 \cdot \Delta P_{3,th}$).

As the temporal baseline $T_{\rm tot,ASM}$ = 573 d of the RXTE ASM observation is only 32% compared to $T_{\rm tot,BATSE}$ = 1780 d of the CGRO BATSE time series, all periodicity peaks in the ASM χ^2 statistics are 3.1 times broader compared to the corresponding peaks in the BATSE χ^2 distribution. This yields an overlap of the two ASM χ^2 peak structures (s. Fig.3b). The P_3 - $P_{\rm new}$ separation has just begun and will improve with increasing RXTE observation length.

The pulse profiles of the discovered $P_{\rm new}$ periodicity exhibit no double structures which indicates that $P_{\rm new}$ is no multiple, but the main period (s. Fig. 4b and Fig. 5b). Both pulse profiles show little influence of the nearby P_3 and, in addition, both pulses show a single peak-like structure at phase ≈ 0.8 with a duration of roughly two phase bins, corresponding to 1.84 days.

The temporal behaviour of both X-ray satellite time series is composed of a 3.41 d periodic oscillation and an additional 13.81 d periodicity which causes 'bright states' of 4U 1700-377 when both oscillators maxima are phase coherent. Therefore, in the case of 'in-phase' oscillations, every fourth 3.41 d pulse appears to be brightened (s. Fig. 6). The periods $P_{\rm new}$ and P_3 differ 1.25% which yields about 78 $P_{\rm new}$ cycles or ≈ 1090 days for

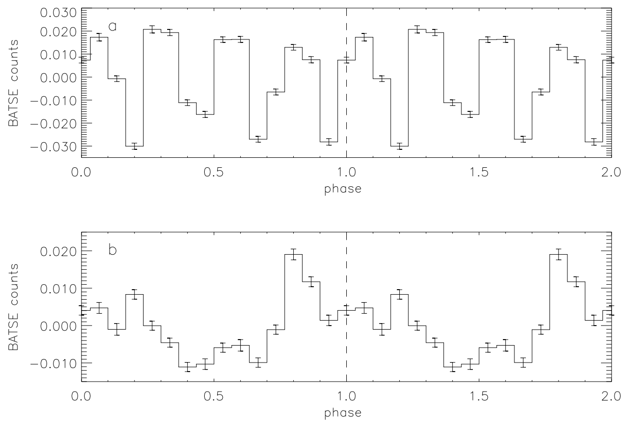

Fig. 4. Folded pulse profiles for a) P_3 and b) P_{new} (CGRO BATSE data with subtracted mean, 15 phase bins, zero is JD 2448369.0).

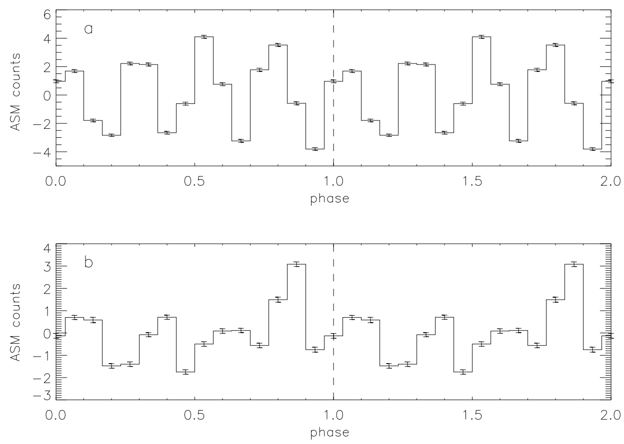

Fig. 5. Folded pulse profiles for a) P_3 and b) P_{new} (RXTE ASM data with subtracted mean, 15 phase bins, zero is JD 2448369.0).

the beat period. As the P_3 oscillation consists of four subpulses (s. Fig. 4a and Fig. 5a), every 272 days 'bright states' occur.

3. Discussion

Using the HEASARC CGRO BATSE and RXTE ASM online archives, we have found strong evidence for the existence of two periodicities, modulating the X-ray light curves of 4U 1700-377. The known orbital period of P_0 = 3.41 d and its multiples dominate the temporal behaviour of both All-Sky light curves. The newly discovered period of P_{new} = 13.81 d modulates the dominating orbital structure.

In the light of the discovered second periodicity we derived the following system geometry: The rotational axis of the neutron star is not aligned with the perpendicular direction of the orbital plane of the binary. This slant yields a free precession of the neutron star (with the period P_{new}). Following this hypothesis, it is only possible to detect X-ray pulsations during a passage of the precessing neutron stars' rotational axis through the line-of-sight (which corresponds to the 'bright state'). The requirements for such a passage are, first, that the X-ray source is not eclipsed by the companion and, second, that the direction of the slanted rotational axis allows an observation of the spinning neutron star. This model of a X-ray pulsar assumes a tilted magnetic field axis in respect to the rotational axis and is valid for both, pencil-beam and fan-beam X-ray emission geometries.

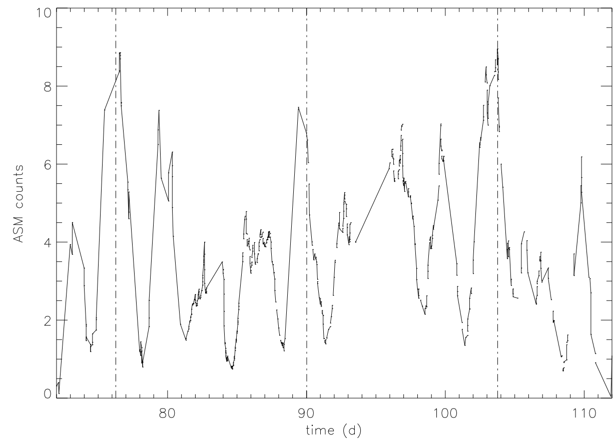

Fig. 6. RXTE ASM X-ray light curve (detail of Fig. 2a, a triangle filter with a 1d baseline has been applied to the time series due to clarity reasons). The vertical lines indicate 13.81 d oscillation maxima.

Possible X-ray pulsations with a period of 67.4 sec were discovered by the X-ray satellite Tenma (Murakami et al. 1984). The pulsations were observed only during a bright flare of 4U 1700-377, while no indication of pulsation was found during the quiescent state. This result is in line with our interpretation of the changing system geometry of 4U 1700-377 caused by the precessing neutron star.

Due to the long periodicity we cannot derive a reliable ephemeris for the 'bright state' of 4U 1700-377 from the All-Sky monitors light curves. We speculate, however, that it is promising to use the RXTE ASM data as a trigger for pointed X-ray satellite observations of 4U 1700-377 in order to detect the X-ray pulsar during a 'bright state'.

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