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A search for X-ray periodicities from 4U 1700−37

M. Gottwald,★ N. E. White★ and L. Stella★† *EXOSAT Observatory, ESOC, Robert Bosch Strasse 5, D-6100 Darmstadt, West Germany*

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Summary. Using the *EXOSAT* observatory we have observed the massive X-ray binary system 4U 1700−37 for more than one complete orbital period. We report here on a search for X-ray pulsations. No coherent periodicity was detected with upper limits to the pulsed fraction over the frequency range 256 to 2×10^{-5} Hz (corresponding to rotational periods of 3.9 ms to 50 000 s) of ~0.5 to ~50 per cent.

1 Introduction

The 3.4 day eclipsing binary 4U 1700−37/HD 153919, is one of the few massive X-ray binary systems where coherent X-ray pulsations have not yet been detected. The X-ray luminosity of $\sim10^{36}$ erg s^{-1} is consistent with the X-ray source being powered solely by the gravitational capture of the stellar wind of the supergiant primary (Conti 1978). Inhomogeneities in the wind are believed to be the origin of the strong flaring activity 4U 1700−37 (White, Kallman & Swank 1983a). The variability caused by the flares can reach up to a factor of ~10 (e.g. Mason, Branduardi & Sanford 1976). Mass estimates for the companion suggest that the X-ray source is a neutron star (Hutchings 1974). The X-ray spectrum is well represented by a power law with a high-energy cut-off, similar to what is observed in most X-ray pulsars (White *et al.* 1983a).

Recently, the possibility that this system might be a pulsar was again raised by Murakami *et al.* (1984) who suggested a 67.4-s period with a ~4 per cent modulation of the X-ray flux during a single 20-min flare. Previously, evidence for a 24-min period was found in *Copernicus* data (Branduardi *et al.* 1979). A 97-min period reported by Matilsky, La Sala & Jessen (1978) was later shown to be caused by instrumental effects (Hammerschlag-Hensberge, Henrichs & Shaham 1979). White *et al.* (1983a) searched for pulsations between 160 ms and 6 min and found an upper limit for the amplitude of the modulation of ~2 per cent.

In this paper we report a temporal analysis of a 82 hr observation of 4U 1700−37 performed with *EXOSAT* in 1985 April.

2 Observation

EXOSAT observed 4U 1700−37 for more than one complete orbital cycle from 1985 April 4 04:30 UT to April 8 01:00 UT. A perigee passage of *EXOSAT* on April 4, during which data were

★Affiliated to Astrophysics Division, Space Science Department of ESA.
†On leave from I.C.R.A., Department of Physics 'G. Marconi', University of Rome.

not collected, caused a gap in the data between 09:00–20:00 UT (phase 0.57–0.71). The analysis described here is based on the data from the Argon detectors of the ME experiment (Turner, Smith & Zimmermann 1981). A number of different time resolutions were available. For most of the observation, energy-resolved data with an accumulation interval of 1 s were obtained. For ~28 hr (corresponding to 1/3 of the total exposure) during the time of the X-ray eclipse the resolution was degraded to 10 s. In addition the counts from the Argon detectors (1–15 keV) were sampled with a resolution of 1.95 ms for the last 15 hr of the observation and 31.25 ms for the rest of the time. The background was monitored with one half of the detector array coaligned and the other offset. The background was very stable over the entire observation period with a long-term variability of <10 per cent and a count rate of 17 counts s^{-1} (2–10 keV).

Fig. 1 shows the entire 2–10 keV light curve of the 4U 1700−37 observation. The X-ray eclipse occurred between phase 0.87 and 0.13. The source exhibited strong flaring behaviour throughout the observation, although there were notable intensity minima at phases 0.73, 0.23 and 0.52. At phase 0.73 the eclipse-like minimum resembled the dip event seen in GX 301−2 (Leahy *et al.* 1986). Flaring occurs on time-scales of minutes to hours with no underlying regularity. Previous observations (e.g. White *et al.* 1983a) have shown that the variability in the emission of 4U 1700−37 is almost entirely caused by the inhomogeneous stellar wind, which leads to a variable accretion rate, and not by photoelectric absorption events.

The length of the eclipse determined with the *EXOSAT* data is 20.2±0.2 hr corresponding to an eclipse semi-angle of 44.5°±0.5° for an orbital period of 3.4118 day (van Genderen 1977). This duration is comparable to the result of the *Copernicus* observation in 1974 but is significantly longer than that measured in 1975 and 1976 (Branduardi, Mason & Sanford 1978). Mid-eclipse

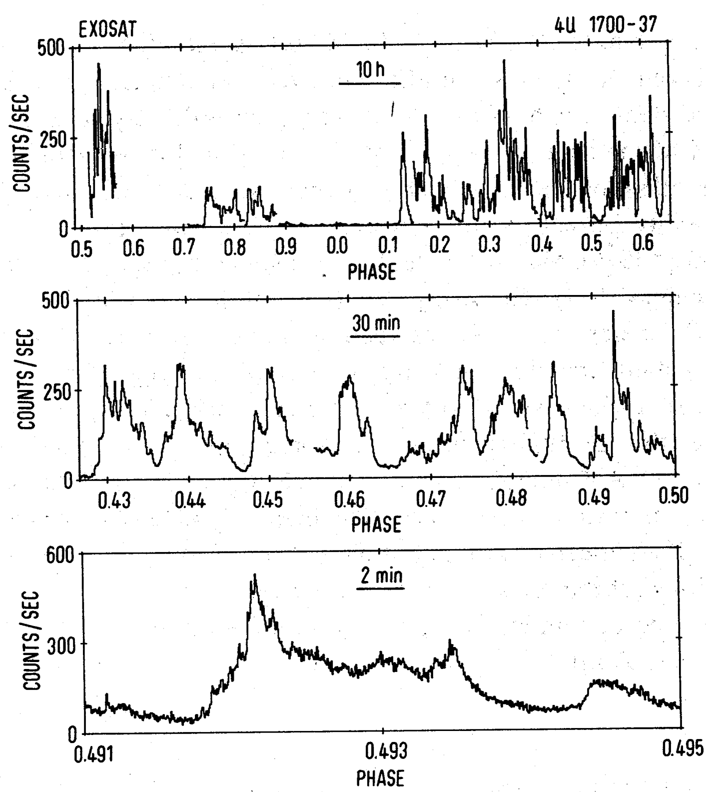

Figure 1. The 2–10 keV X-ray light curve of 4U 1700−37. The top panel shows more than one complete orbit with a time resolution of 8 min and corresponds to the entire *EXOSAT* observation. A perigee passage of *EXOSAT* caused a data gap in the first cycle between phases 0.57 and 0.71. Time variability on shorter time-scales can be seen in the two lower panels where the time resolution is 30 s (middle) and 2 s (bottom).

(phase=0) occurred at JD 2446161.340±0.003. The residual to the ephemeris given by Branduardi *et al.* (1978) is 0.084 day (for 1080 orbits).

3 A search for pulsations

We searched our energy-resolved (2–10 keV) and high time-resolution (all Argon channels) uneclipsed data of 4U 1700−37 for pulsations in the frequency range 256 Hz to 2×10^{-5} Hz (rotational period P_s=3.9 ms to 50 000 s). The method of analysis used was the fast Fourier transform (FFT). A continuous time interval, T, was divided into 2^m *bins, where* $9\leqslant m\leqslant 12$, and the FFT performed on to that time segment. For a given total observation interval T_{obs} the procedure was repeated M times ($T_{obs}=M\times T$) so that the final power spectrum was the average of M individual power spectra. Possible 'smearing out' effects resulting from the binary orbital motion were therefore avoided (these can become important for pulsations shorter than the light travel time across the system; <100 s for 4U 1700−37). We performed the FFT on time intervals T_{obs} ranging from ~30 min (short flares) to ~40 hr (post-eclipse phase). In no case did a power spectrum contain a significant detection of coherent pulsations. As an example Fig. 2 shows the power spectra of selected parts of the light curve (short flares, flat-topped flares, quiescent emission). The pronounced low-frequency noise (LFN) resulting from the flaring activity reduces strongly the sensitivity of the search towards lower frequencies. The distribution of the LFN indicates that variability in the X-ray flux is present on time-scales ≳1 s.

To set an upper limit on the strength of any coherent periodicity present we used the procedure described in Leahy *et al.* (1983). The pulsed fraction A is defined for a sinusoidal modulation $r(t)=r_0[1+A\times\sin(\omega t+\phi)]$ where r_0 is the unpulsed count rate. Because of the LFN, the noise component was defined by using the local power in the power spectrum. The standard deviation of the power in each of the LFN bins was evaluated by the scattering in the M individual power

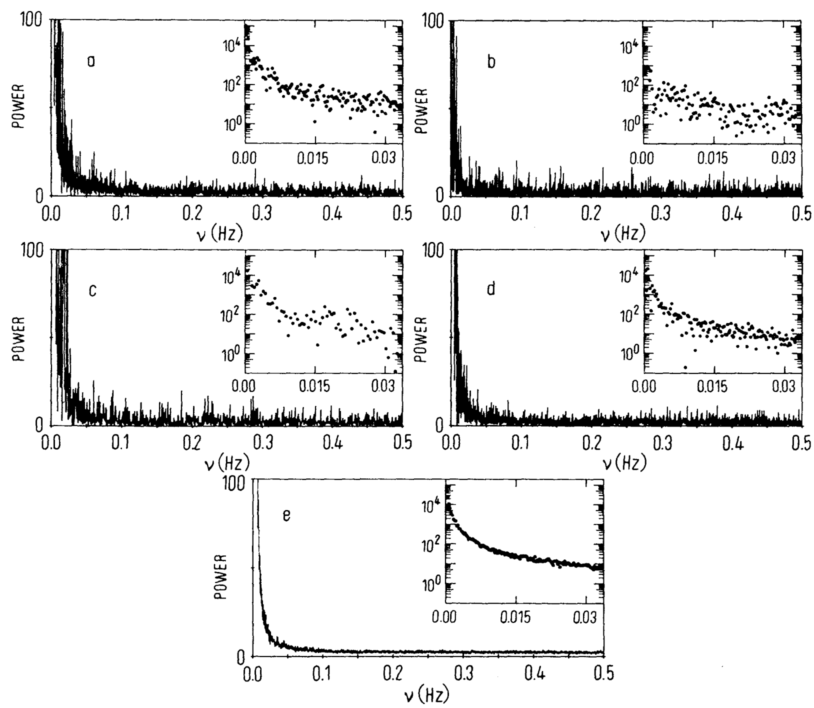

Figure 2. Five representative power spectra of selected parts of the 2–10 keV light curve of 4U 1700−37. The spectra are centred around phases 0.56 (a; strong variable flare), 0.76 (b; flat-top flare), 0.43 (c; short flare), 0.58 (d; long variable flare) and 0.15–0.65 (e; post-eclipse phase). The inset shows the low-frequency region of each power spectrum (ν<0.03 Hz) on an expanded logarithmic scale.

spectra ($M \leq 36$) around the average values. This way we determined the standard deviation in the power p_j of the jth frequency bin to be roughly equal to $p_j/\sqrt{M}$. We note that this result is not surprising since, for example, in autoregressive processes the standard deviation of the power is also equal to the power itself (Robinson & Nather 1979). Table 1 gives the upper limits to A (90 per cent confidence) for differing frequency ranges and orbital phases (see also the power spectra in Fig. 2). In addition, in the post-eclipse phase (0.45–0.65), when the 1.95-ms data were obtained, the upper limit to A for frequencies between 16 and 256 Hz was found to be 3 per cent.

For periods $2\,s < P_s < 100\,s$ the upper limits are less than 2 per cent. Only in the case of a short strong flare (phase 0.43) the upper limit in the period range 50–100 s significantly exceeds 2 per cent. For the 67.4-s period reported by Murakami *et al.* (1984) the upper limit that we obtain during this flare is ~3 per cent. It lies close to the pulsed fraction of 4 per cent given by Murakami *et al.* so that during this event the 67.4-s period could have escaped detection. However, during flares with similar strength (phases 0.56 and 0.58) but longer duration and therefore better statistics the upper limit for a 67.4-s period was constrained to be <2 per cent.

Fig. 3 shows the power spectrum for very low frequencies obtained from the 40-hr post-eclipse data. At $\nu_f = 0.32 \times 10^{-3}$ Hz a broad feature with a significance of $\sim 4.5\sigma$ is evident. The corresponding amplitude A (pulsed fraction) of an equivalent sinusoidal modulation would be ~32 per cent. We suggest that the feature indicates the preferred time-scale of the flaring events.

Table 1. Upper limits of the pulsed fraction (in per cent, 2–10 keV) as a function of the rotational period.

Period range	Upper limits of A at different phases[a]					
(s)	0.56[b]	0.76[b]	0.43	0.58	>0.15	Phase
	120	75	30	125	2.4×10^3	duration
	237.0	89.0	193.0	148.0	117.0	rate
0.06–1	–	3.8	2.3	2.4	1.1	
2–20	0.7	1.4	1.4	0.8	0.5	
50–100	1.7	1.5	4.7	1.6	1.3	
200–500	9.4	8.0	24.5	6.7	6.0	
1000–2000	–	–	–	–	13.8	
5000–10 000	–	–	–	–	26.6	
20 000–50 000	–	–	–	–	49.3	

[a] The phase intervals selected correspond to the power spectra shown in Fig. 2; the duration is given in min and rate is the average count rate (2–10 keV) in count s^{-1}.
[b] Pre-eclipse.

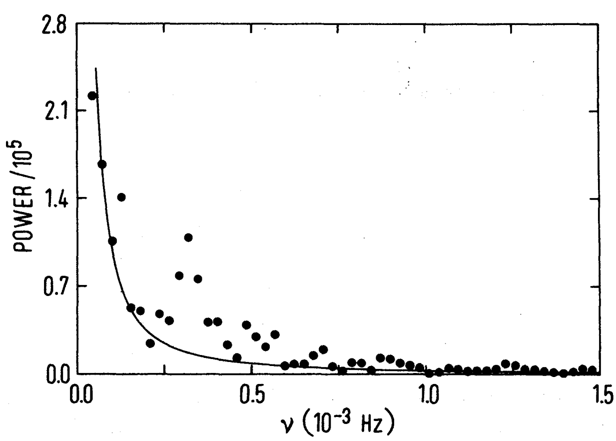

Figure 3. The post-eclipse power spectrum of 4U 1700–37 for very low frequencies. The solid line gives the best-fit power-law LFN.

A period of $1/\nu_f=52$ min is consistent with the average separation of individual flares as seen in Fig. 1 (top and middle panel).

4 Discussion

The pulsed fractions in supergiant massive X-ray binary systems range from ~35 per cent (SMC X-1) to ~60 per cent (Cen X-3) with periods lying between 0.71 s (SMC X-1) and 695 s (4U 1223−62) (White, Swank & Holt 1983b); (the values of the pulsed fraction are only estimates because none of the sources show a pure sinusoidal modulation in its light curve). It follows from Table 1 that the fraction of any pulsation in 4U 1700−37 must be much smaller than in the other supergiant systems (provided the period is comparable to the ones given above, $P_s<100$ s).

If we apply the empirical relationship between maximum X-ray luminosity and rotational period for the supergiant systems (Stella, White & Rosner 1986) a luminosity of 3×10^{36} erg s^{-1} predicts a period of ~1200 s for 4U 1700−37. This is close to the value of 24 min reported by Branduardi *et al.* (1979). Due to the presence of LFN activity such a period would be very difficult to detect during individual flares even if they last for a few hours. For longer time intervals like the post-eclipse phase in Table 1 the upper limit of ~14 per cent for $P_s=1000$–2000 s is obtained under the assumption that the pulsations are always present (although not detectable). If this is not the case the upper limit would increase correspondingly and the allowed pulsation amplitude will become closer to the one observed in the other supergiant binary system containing an X-ray pulsar (>30 per cent).

The lack of pulsations in 4U 1700−37 can thus be explained in two ways:

(i) The neutron star in 4U 1700−37 has a rotational period<1000 s and a pulsed fraction smaller than similar systems (due e.g. to the alignment of magnetic dipole and rotation axis or to differences in the accretion-flow pattern through the magnetosphere, see discussion in White *et al.* 1983a).

(ii) 4U 1700−37 contains a slowly rotating neutron star ($P_s>1000$ s) whose pulsating behaviour is hidden by the strong flaring activity of the source.

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