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A unique triple-peaked type-1 X-ray burst from 4U/MXB 1636−53

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Summary. We report the detection, with *EXOSAT*, of an X-ray burst from 4U/MXB 1636−53, whose intensity profile shows three distinct peaks. A time-resolved spectral analysis of this burst shows that this triple-peaked profile, which is clearly visible in the bolometric flux variations, is not the result of a major radius expansion of the neutron star photosphere. We suggest that recurrent energy release in quick succession is the most likely cause for this unusual burst profile.

1 Introduction

X-ray bursts with a double-peaked profile, particularly apparent at photon energies above 6 keV (Lewin *et al.* 1976; Hoffman, Cominsky & Lewin 1980; Grindlay *et al.* 1980; Matsuoka 1980; Basinska *et al.* 1984), are probably related to the fast transients with a 'precursor' (Hoffman *et al.* 1978; Tawara *et al.* 1984; Lewin, Vacca & Basinska 1984). These are believed to be the result of a major expansion (due to radiation pressure) and subsequent contraction of the neutron star photosphere, at an approximately constant (but very high) luminosity. As the photospheric radius increases (decreases) the effective temperature goes down (up), and the emission becomes softer (harder). This causes a dip in the X-ray flux (most prominent at higher energy X-rays; Tawara *et al.* 1984; Lewin *et al.* 1984). Recently, X-ray bursts were observed from 4U/MXB 1636−53, with a double peak in their *bolometric* flux profile, which are not due to such photospheric expansion (Sztajno *et al.* 1985). We report here the detection of a unique X-ray burst from the same source, with an even more complicated flux profile, showing *three distinct* *peaks*, which is also not accompanied by an expansion of the neutron star photosphere. This supports our previous suggestion (Sztajno *et al.* 1985) that in some X-ray bursts the energy is released in steps. Presently available models are inadequate to explain this result.

2 Observations and analysis

We observed 4U/MXB 1636−53 between 1985, August 6.81 and 10.79 UT, with the X-ray observatory *EXOSAT* (Taylor *et al.* 1981). The present analysis is based on data obtained with the medium-energy (ME) proportional counters (Turner, Smith & Zimmermann 1981), which were coaligned to optimize the observation for the study of X-ray bursts. Energy spectra were obtained every 0.31 s with the Argon detector (energy range 1–20 keV).

We detected 27 X-ray bursts, at intervals between 35 min and 12 hr. One burst, which occurred on August 9, UT $15^h 02^m$ has a very unusual profile, with three distinct maxima, separated by ~7 s (see Fig. 1). In the three peaks, the maximum fluxes (in the range 1–20 keV) are ~0.5, ~0.4, and ~0.5 Crab. In the two minima between the peaks the fluxes are ~0.15 and ~0.2 Crab. During the rise of the three peaks the rates of flux increase are the same (~0.1 Crab/s), to within their ~10 per cent accuracy. The time intervals between the first two peaks and the subsequent minima are ~4 s. The decay (e-folding) time after the third peak is ~7.5 s, similar to that after the first two peaks (5.5 and 7.0 s, respectively). The peak separations, and the rise and decay times are similar to those in the double-peaked bursts described by Sztajno *et al.* (1985). However, the relative peak fluxes in these double-peaked bursts differ substantially.

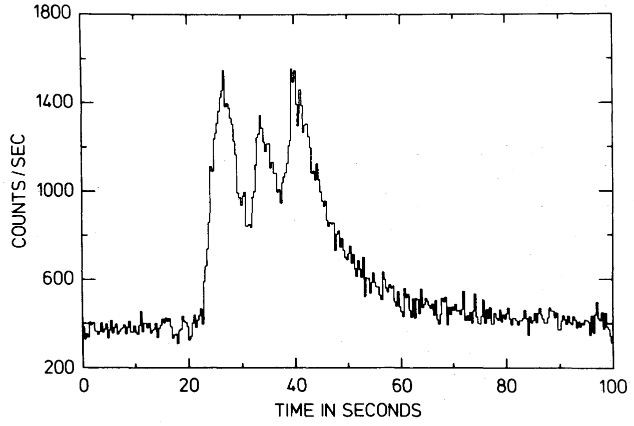

Figure 1. Raw counting-rate profile (1–20 keV) of the triple-peaked burst observed from 4U/MXB 1636−53 (no dead-time corrections have been made yet). Zero time is 1985 August 9, UT $15^h 01^m 50^s$.

We made a spectral analysis of the burst data in separate time intervals (with widths between ~1 and ~20 s, depending on the counting rates), after subtracting the persistent counting rate. Corrections for dead time were made. The data (in a range of energy varying between 1–10 and 1–6 keV, depending on the strength of the signal) were fitted with blackbody functions, which contain as parameters the blackbody (colour) temperature T_{bb}, a low-energy cutoff represented by an equivalent hydrogen column density N_H, and a normalization constant I_0. In most fits only upper limits to N_H were found, typically $(1–2)\times10^{22}\,cm^{-2}$. These are consistent with the value $(5.6\times10^{21}\,cm^{-2})$ inferred from the optical interstellar extinction (A_V=2.4±0.3 mag; Lawrence *et al.* 1982), using the relation between $E(B-V)$ and N_H of Gorenstein (1975). We therefore used blackbody fits with N_H kept fixed at this value. χ^2-values for the fits are between 0.6 and 1.5, except for one fit with $\chi^2=2.0$. The 1σ errors in the parameters were found from χ^2 contours (at a 68 per cent confidence level) in the (T_{bb}, I_0) plane (Lampton, Margon & Bowyer 1976; Avni 1976).

In each time interval the total X-ray flux was found by integrating over the energy interval used in the spectral fitting (in this integration we used a count rate to flux conversion based on an assumed incident blackbody spectrum at the fitted temperature). The bolometric flux F_{bol} was obtained by multiplying this flux by a bolometric correction factor, which because of the blackbody assumption, is a function of the observed colour temperature only. The apparent blackbody radius R_{bb} of the burst-emitting region is obtained from

$$R_{\mathrm{bb}}=d(F_{\mathrm{bol}}/\sigma T_{\mathrm{bb}}^4)^{1/2}=30.3\,d_{10}[F_8/(kT_{\mathrm{bb}})^4]^{1/2}\,\mathrm{km}. \tag{1}$$

Here d_{10} is the source distance in units of 10 kpc, F_8 is the bolometric flux in units of $10^{-8}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$, and kT_{bb} the fitted blackbody temperature in units of keV. In our estimates of the error in R_{bb} we took the correlation between the (asymmetric) error in T_{bb} and F_{bol} into account.

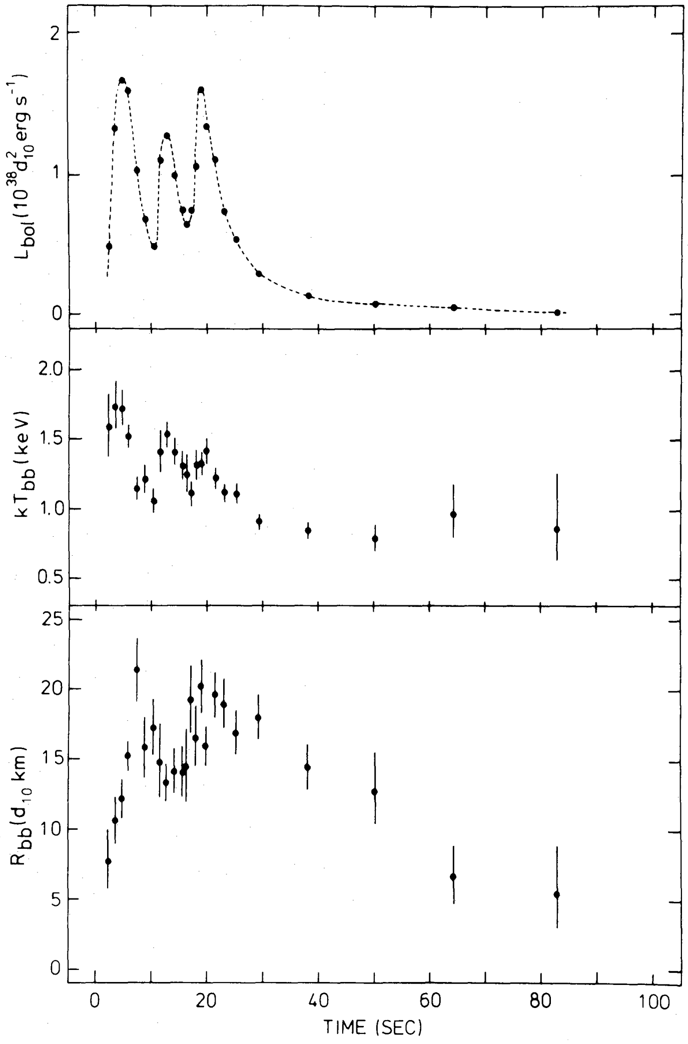

Figure 2. Variation of the *bolometric* luminosity (top), the blackbody (colour) temperature (middle), and the apparent blackbody radius (bottom) during the triple-peaked burst from 4U/MXB 1636–53.

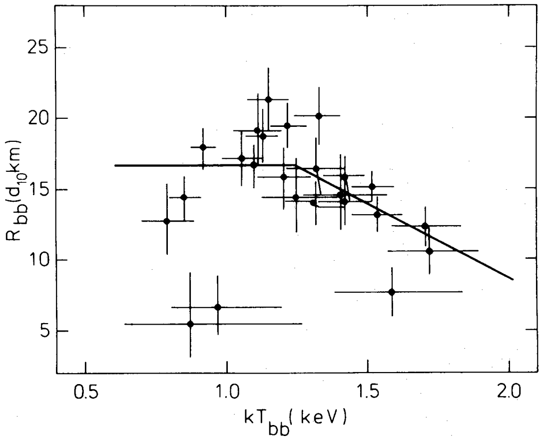

Figure 3. Relation between the apparent blackbody radius and blackbody (colour) temperature during the triple-peaked burst from 4U/MXB 1636–53. Also shown is the average relation as obtained from a previous observation of this source (Sztajno *et al.* 1985).

3 Results

The results of our spectral analysis are shown in Fig. 2, in which we display the temporal variation for F_{bol}, T_{bb}, and R_{bb}. The *triple-peaked structure* is clearly visible in the *bolometric* flux profile of the burst. The apparent blackbody radius shows variations, roughly anti-correlated with T_{bb} (see Fig. 3), except near the very end of the burst, where the apparent radii drop to very low values.

The apparent anti-correlation of R_{bb} and T_{bb} during the main part of the burst is probably due to the fact that X-ray burst spectra are not Planckian (Inoue *et al.* 1984; Sztajno *et al.* 1985; van Paradijs 1985), resulting in a systematic difference between the effective temperature T_{eff} [which should enter expression(1)] and the colour temperature T_{bb} (obtained from the spectral fits). From model-atmosphere calculations (van Paradijs 1982; Czerny & Sztajno 1984; London, Taam & Howard 1984; Ebisuzaki & Nomoto 1986) one expects that the ratio $T_{bb}/T_{eff}>1$, and increases with T_{eff} (for $kT_{eff}>1$ keV). Since the apparent radius is affected by a factor $(T_{eff}/T_{bb})^2$ it is expected that (for an assumed constant radius of the burst-emitting region) the apparent blackbody radius is anti-correlated with the colour temperature. The previously observed average relation (Sztajno *et al.* 1985) between R_{bb} and T_{bb} (also shown in Fig. 3) agrees reasonably well with that expected from model calculations of neutron star atmospheres (London *et al.* 1984). We have used this average relation to make an empirical correction to the observed blackbody radii, to take the deviations of the X-ray burst spectra from a blackbody into account. This empirical approach has the advantage that it is not affected by uncertainties in model atmospheres, e.g. input physics or atmospheric parameters. (Of course, it implies the assumption that in our previously published data this average relation reflects only the above ‘colour temperature effect’, at a constant photospheric radius.)

We find that these ‘corrected’ blackbody radii (see Fig. 4) do not show a significant correlation with the flux variations during the three peaks. The average ‘corrected’ blackbody radius equals 17.6 d_{10} km, with a standard deviation of the individual values of ±15 per cent. Clearly, there is no evidence for strong radius variations during this triple-peaked burst.

We therefore conclude that this triple-peaked burst is not due to radius expansion of the neutron star photosphere during the burst.

The low values of the apparent blackbody radius near the end of the burst may not reflect an actual decrease in the burst-emission area. It is possible that they are due to the presence in the persistent emission of a blackbody (or blackbody-like) component, which originates in the same

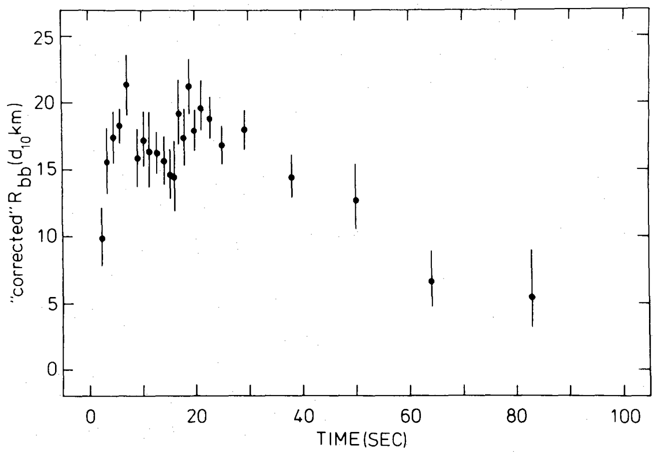

Figure 4. Variation of the blackbody radius, observed during the triple-peaked burst from 4U/MXB 1636−53, after an empirical correction was made for the (temperature-dependent) deviation of burst spectra from blackbodies, using the average radius–temperature relation observed previously (Sztajno *et al.* 1985, see fig. 3).

neutron star photosphere which transfers the burst energy. In such situations the apparent blackbody temperature of the burst flux (*i.e. the flux in excess of the persistent emission*) will remain constant, and consequently the apparent blackbody radii will decrease to zero as the burst flux goes to zero (van Paradijs & Lewin 1986). Analysis of the full sample of X-ray bursts from 4U/MXB 1636−53, using two-component spectral fits to the combined (burst plus persistent) emission, is presently in progress.

4 Discussion

Independent of the result of our spectral analysis, it is hard to see how radius expansion and subsequent contraction could produce three peaks, unless there are two consecutive bursts of which only one causes radius expansion. Furthermore, photospheric radius expansion in this burst is not expected, since the maximum luminosity in all three peaks is about a factor of 4 below that of the strongest bursts from this source, some of which have shown evidence for radius expansion (see e.g. Sztajno *et al.* 1985). One expects on theoretical grounds that strong radius expansion occurs when the burst luminosity is at the Eddington limit (see e.g. Kato 1983; Ebisuzaki, Hanawa & Sugimoto 1983; Paczynski 1983). If we assume that the Eddington luminosity is reached during the strongest bursts, earlier observed (Sztajno *et al.* 1985), the distance to 4U/MXB 1636−53 is ~6 kpc. There are many reports of super-Eddington luminosities at burst maximum, and the above assumption, that the Eddington limit was not exceeded, may be incorrect (see Lewin 1984, 1985, for a review of this controversial issue). However, it is worth noting that bursts with clear radius expansion from 4U/MXB 1820−30 do not necessarily exceed the Eddington limit (Vacca, Lewin & van Paradijs 1986).

Our result reinforces a previous suggestion (Sztajno *et al.* 1985) that in some X-ray bursts the energy is released in steps. It could be the result of spatial confinement of fuel: a thermonuclear flash would then start in a localized area on the neutron star surface, and subsequently ignite fuel at other places. Estimates of the time-scale for a burning front to propagate over a neutron star surface (~0.1 to ~10 s; Fryxell & Woosley 1982; Nozakura, Ikeuchi & Fujimoto 1984), are comparable to the ~7-s separation of the three peaks in the burst. Thus, successive ignition could conceivably explain our result. However, it is then unclear why such a sequence of localized thermonuclear flashes is so extremely rare (the triple-peak burst is unique among the $\sim 10^3$ type-1 X-ray bursts observed so far), and why the apparent blackbody radius would remain so constant.

If the thermonuclear flashes can be limited to a fraction of the neutron star surface, X-ray bursts would be ideally suited to search for possible coherent pulsations of the X-ray flux, due to the rotation of the neutron star [expected periods in the millisec range (Alpar *et al.* 1982)]. Such fast coherent pulsations have not been reported for any of the low-mass X-ray binaries.

'Localized' flashes could provide a natural explanation for the observed correlation between maximum burst flux and integrated burst flux observed in 4U/MXB 1636−53 (Ohashi 1981), and in other sources (Lewin & Joss 1983), since both quantities will then (to first approximation) be affected by the same geometric (surface area) factor. However, in that case the strongest burst should show a larger blackbody radius than the smaller bursts, and that is not observed (Ohashi 1981). It is rather uncertain whether spatially confined flashes can explain the triple-peaked burst profile we observed.

Perhaps the triple-peaked burst is the result of a variation in either the rate at which energy is released in the flash, or in the rate at which the energy is transported to the surface of the neutron star. Some model calculations of X-ray bursts have resulted in a step-wise release of energy in a thermonuclear flash, e.g. due to a delayed phase of rapid proton capture (Ayasli & Joss 1982), or due to post-burst mixing of mutually combustible layers (Woosley & Weaver 1984). However, the time-scales in these theoretical bursts do not fit the observed triple-peaked burst profile.

Presently available models are inadequate to explain our results, and our above suggestions are speculative. However, we can conclude with reasonable certainty that the very rare triple-peaked burst is unrelated to photospheric radius changes, and we believe that recurrent energy release in quick succession is the most likely cause for the unusual burst profile. We hope that these results will stimulate further theoretical work.

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