Discovery of type I X-ray bursts from the low-mass X-ray binary 4U 1708 – 40

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ABSTRACT
We report the discovery of type I X-ray bursts from the low-mass X-ray binary 4U 1708 – 40 during the 100-ks observation performed by BeppoSAX on 1999 August 15–16. Six X-ray bursts have been observed. The unabsorbed 2–10 keV fluxes of the bursts range from \( \sim 3 \) to \( 9 \times 10^{-10} \) erg cm\(^{-2}\) s\(^{-1}\). A correlation between peak flux and fluence of the bursts is found, in agreement with the behaviour observed in other similar sources. There is a trend of the burst flux to increase with the time interval from the previous burst. From the value of the persistent flux we infer a mass accretion rate \( \dot{M} \sim 7 \times 10^{-11} \) M\(_{\odot}\) yr\(^{-1}\), which may correspond to the mixed hydrogen/helium accretion regime triggered by thermally unstable hydrogen. We have also analysed a BeppoSAX observation performed on 2001 August 22 and previous RXTE observations of 4U 1708 – 40, where no bursts have been observed; we find persistent fluxes of more than a factor of 7 higher than the persistent flux observed during the BeppoSAX observation showing X-ray bursts.

Key words: accretion, accretion discs – stars: individual: 4U 1708 – 40 – stars: neutron – X-rays: bursts – X-rays: general.

1 INTRODUCTION
Many low-mass X-ray binaries (hereafter LMXBs) are known to show type I X-ray bursts which have proven to be important diagnostic tools for these systems [see Lewin, van Paradijs & Taam (1995) for a review]. X-ray bursts are thought to originate from thermonuclear flashes, caused by thermal instabilities, in the accreted matter on the surface of weakly magnetized neutron stars (NS). The time interval between the bursts ranges from tens of minutes to days. In a source the burst activity can stop for periods from days to months (but also years, as, for example, in the case of transient sources). In some cases, a relation has been observed between burst properties and persistent flux. As the persistent flux increases the recurrence time between bursts tends to increase (typically from a few hours to more than a day) and the bursts become less energetic (e.g. Hoffman, Lewin & Doty 1977). For instance, in the case of 4U 1705 – 44 the persistent flux increased by a factor of \( \sim 2 \) while the burst intervals increased by a factor of \( \sim 4 \) (Langmeier et al. 1987; Gottwald et al. 1989). When the persistent flux increases further the bursts disappear completely. This behaviour is observed in several sources such as, for example, MXB 1659 – 29 (Lewin, Hoffman & Doty 1976), GX 3+1 (Makishima et al. 1983) and EXO 0748 – 673 (Gottwald et al. 1986). However, in other sources (e.g. 4U 1820 – 30; Clark et al. 1977; 4U 1728 – 34: Basinska et al. 1984) the opposite behaviour is sometimes observed: the recurrence time between bursts decreases while the persistent flux increases. Nevertheless, at least in the case of 4U 1820 – 30 (Clark et al. 1977), the bursts (again) disappear for higher accretion rates, when the source is in its high state.

Current theories of type I X-ray bursts (Fujimoto, Hanawa & Miyaji 1981; Fushiki & Lamb 1987; see Bildsten 2000) predict three different regimes in mass accretion rate for unstable burning: (i) mixed H/He burning triggered by thermally unstable H ignition, at low accretion rates \( (M < 2 \times 10^{-10} \) M\(_{\odot}\) yr\(^{-1}\)) (ii) pure He shell ignition following steady H burning, at intermediate accretion rates \( 2 \times 10^{-10} < M < 4-11 \times 10^{-10} \) M\(_{\odot}\) yr\(^{-1}\)); and (iii) mixed H/He burning triggered by thermally unstable He ignition at high

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accretion rates \((4 \times 10^{-10} < M < 2 \times 10^{-8} \text{ M}_\odot \text{ yr}^{-1})\). At even higher \(M\), steady He burning occurs and the nuclear fuel for the burst is depleted, causing the bursts to disappear completely. On the basis of these theories, an anticorrelation between persistent flux and burst recurrence time is expected: since as \(M\) increases a smaller amount of time is needed to accumulate the critical amount of fuel necessary to begin the burst, the recurrence time between bursts is expected to decrease with increasing \(M\). This is contrary to what is observed (e.g. Hoffman et al. 1977; van Paradijs, Penninx & Lewin 1988). There are basically two interpretations for these observations. van Paradijs et al. (1988) found evidence of a continuous stable burning of accreted nuclear fuel in burst sources; the observed correlation between persistent emission and burst recurrence time can be explained as the rate of this stable burning increasing, removing nuclear fuel for a thermonuclear flash. Recently, Bildsten (2000) proposed that another solution of this mismatch between theory and observations can be obtained by relaxing the hypothesis of spherical accretion and assuming that the accretion of fresh material only occurs on a fraction (e.g. the equator) of the NS surface. The crucial parameter, in this case, is the accretion rate per unit area: if the covered area increases enough with increasing \(M\), the accretion rate per unit area indeed decreases. Indeed, the whole scenario is not yet completely clear, since recent results (e.g. Muno et al. 2000; Franco 2001; van Straaten et al. 2001) suggest that there is not a unique trend between \(M\) and burst properties for all the sources.

Type I X-ray burst profiles depend strongly on photon energy: decays are much shorter at high photon energies than at low photon energies (Lewin et al. 1995). This softening of the burst spectrum during the decay results from the cooling of the NS photosphere. If the luminosity during the burst reaches the Eddington limit \(L_\text{Edd}\), the NS photosphere expands. Since for a blackbody (see below) \(L_\text{eff} \propto R^2 \sigma T_\text{eff}^4\), when the radius of the photosphere \(R\) expands, the effective temperature \(T_\text{eff}\) decreases (Tawara et al. 1984; Lewin, Vacca & Basinska 1984; Vacca, Lewin & van Paradijs 1986). It is the luminosity during the burst that defines the burst temperature. The high luminosity during the burst results from the cooling of the NS photosphere. If the luminosity during the burst reaches the Eddington limit \(L_\text{Edd}\), the NS photosphere expands. Since for a blackbody (see below) \(L_\text{eff} \propto R^2 \sigma T_\text{eff}^4\), when the radius of the photosphere \(R\) expands, the effective temperature \(T_\text{eff}\) decreases (Tawara et al. 1984; Lewin, Vacca & Basinska 1984; Vacca, Lewin & van Paradijs 1986). In this paper we report on the discovery of type I X-ray bursts from the LMXB 4U 1708 – 40 (Forman et al. 1978) during a BeppoSAX observation. Not much is known about this system. A first analysis of the 2–12 keV X-ray spectrum of 4U 1708 – 40 was made by Warwick et al. (1988) using EXOSAT observations during which the 2–6 keV source flux was \(\sim 10^{-9}\) erg s\(^{-1}\) cm\(^{-2}\). The spectrum was well fitted by a power law with a spectral index \(\Gamma = 2.2 \pm 0.2\) and a column density \(N_H \sim 3 \times 10^{22}\) cm\(^{-2}\).

### 2 Observations and Data Analysis

We have analysed a BeppoSAX observation of 4U 1708 – 40, performed on 1999 August 15–16 for a total observation time of \(\sim 100\) ks. We report on results from the Low Energy Concentrator Spectrometer [LECS, a thin-window position-sensitive gas scintillator proportional counter with extended low-energy response, 0.1–10 keV, and a field of view (FOV) of 20 arcmin (Parmar et al. 1997)] and the Medium Energy Concentrator Spectrometers [MECS, position-sensitive gas scintillator proportional counters operating in the 1.3–10.5 keV band, with a FOV of 30 arcmin (Boella et al. 1997)]. The source was not detected in the Phoswich Detection System (PDS, energy range 13–200 keV; Frontera et al. 1997). For both imaging instruments we selected the data in circular regions of radius 8 arcmin centred on the source. We used the standard response matrices and background files (1997 version for MECS and 2000 for LECS) for the spectral analysis. To analyse the BeppoSAX spectra of the source we selected the energy range 0.12–4 keV for LECS and 1.8–10 keV for MECS. In the 1999 August 15–16 BeppoSAX observations six X-ray bursts are detected. We have used LECS and MECS combined to analyse the persistent emission and the second, third, fourth and fifth bursts, and only the MECS to analyse the first and the sixth bursts, since the LECS was off in these time intervals. The BeppoSAX observation is periodically interrupted because of Earth occultations and the passage through the South Atlantic Anomaly. These ‘gaps’ last on average \(\sim 2\) ks after \(\sim 4\) ks of on-source observation. The BeppoSAX instruments were off more often in the last part of the observation (namely between the fourth and the sixth bursts) so that the on-source exposure time is \(\sim 50\) ks.

We have also analysed a 150-ks BeppoSAX observation of 4U 1708 – 40 performed on 2001 August 22 (with an on-source exposure time of \(\sim 73\) ks) and 14 (non-contiguous) observations from the public RXTE data archive, five performed in 1997 and nine in 2000, with a total on-source exposure time of \(\sim 60\) ks. For the RXTE observations we have used data taken with the Proportional Counter Array [PCA], which consists of five co-aligned proportional counter units (PCUs), sensitive in the energy range 2–60 keV (Zhang et al. 1993)]. Starting from 2000 May 12, the propane layer on proportional counter unit 0 (PCU0), which functions as an anticoincidence shield for charged particles, was lost. Therefore we excluded the PCU0 data from the 2000 June spectrum that we have analysed. The PCA observations background, estimated using PCAICKEST v2.1e, was also subtracted.

We have produced light curves of the 2001 BeppoSAX observation and of all the RXTE observations; in all these data we did not find any burst. Although a small variation in average count rate (around 20 per cent) occurred in the RXTE data between the 1997 observations and the 2000 observations, the light curve of each observation shows steady persistent emission without any significant variation in count rate; we have analysed the spectrum of just one of the RXTE observations available, as a representative case. To analyse the PCA spectrum we have used Standard2 data in the energy range 2.5–25 keV and produced the detector response matrix with PCARDP v7.11. A systematic error of 1 per cent was added to account for residual uncertainties in the detector calibration. We have used XSPEC v11.1.0 to fit the spectra.

### 3 Results

In the 1-s time resolution LECS and MECS light curves of the 1999 observation we see persistent emission at a count rate of \(\sim 2–4\) count s\(^{-1}\) in the MECS light curve. The light curve also shows six X-ray bursts (the times at which each burst occurred are reported in Table 2, later). The bursts last \(\sim 40\) s. Excluding the bursts, the persistent emission does not show significant intensity variations during the whole observation. Five bursts out of six exhibit a rapid rise (\(\lesssim 5\) s) followed by a slower decay, whereas one of the bursts (the fourth) has a triangular shape with approximately equal rise and decay times of 20 s. In Fig. 1 we show the light curve in the MECS range (upper panel) and the corresponding hardness ratio (HR = 4–10 keV/2–4 keV, bottom panel) of the first burst, the one observed with the best statistics (the behaviour of the other bursts is comparable to this). The hardening during the rise and the softening during the decay, together with the shape of the bursts, identify 4U 1708 – 40 as a type I X-ray burster.

#### 3.1 Persistent emission

We produced LECS and MECS spectra of the persistent emission of the 1999 August 15–16 observation of 4U 1708 – 40, excluding intervals of 200 s around (starting about 7 s before) each of
X-ray bursts from the LMXB 4U 1708 – 40

Figure 1. Upper panel: light curve with 1-s time resolution of the first burst. Lower panel: hardness ratio (HR = 4–10 keV/2–4 keV) curve of the first burst with 2-s resolution. The shape of the burst, the hardening during the rise and the softening during the decay are typical of a type I X-ray burst.

the six detected bursts. The spectrum in the range 0.12–10 keV is shown in Fig. 2. We fitted the spectrum with a power law corrected for photoelectric absorption and a Gaussian emission line at 6.5 ± 0.1 keV which gives a reduced $\chi^2$ of 1.2 for 420 d.o.f. (the reduced $\chi^2$ without the Gaussian emission line is 1.3 for 423 d.o.f.). We find a high equivalent hydrogen column density, $N_H = (2.93 \pm 0.08) \times 10^{22}$ cm$^{-2}$, consistent with the position of the source in the direction of the Galactic Centre, and a power-law photon index $\Gamma = 2.42 \pm 0.02$. No significant thermal component (i.e. blackbody) is found (with an upper limit on the flux of $\sim 2 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$, fixing the blackbody temperature to 1.3 keV; see below). The 2–10 keV flux is $1.2 \times 10^{-10}$ erg cm$^{-2}$ s$^{-1}$, corresponding to a luminosity of $\sim 9 \times 10^{35}$ erg s$^{-1}$ at a distance of 8 kpc (see Section 4). We obtain a fit of similar quality (reduced $\chi^2 = 1.2$ with 421 d.o.f.) using the Comptonization model ComPTT (Titarchuk 1994), with a slightly lower column density, $N_H = (2.56 \pm 0.14) \times 10^{22}$ cm$^{-2}$, and a Gaussian emission line at 6.5 ± 0.1 keV. In Table 1 we show the fit parameters of the persistent emission corresponding to these two models.

For comparison we have also analysed the 4U 1708 – 40 spectrum during one of the RXTE observations (the 3-ks observation performed on 2000 June 18, ID 50060-04-01-00). A simple absorbed (the column density was fixed to $N_H = 2.9 \times 10^{22}$ cm$^{-2}$, in accordance with the BeppoSAX spectrum) power law is not able to fit the spectrum in the whole energy range. A blackbody component with a colour temperature of $\sim 1.3$ keV is needed to fit the data adequately (an $F$-test gives a probability of chance improvement of the fit for the addition of this component of $2 \times 10^{-7}$). A high-energy cut-off at relatively low energy ($E_{cut} \sim 5$ keV) is also necessary (reduced $\chi^2 = 0.9$ with 44 d.o.f.). We show this spectrum, together with residuals in units of $\sigma$ with respect to the best-fitting model, in Fig. 3 and the best-fitting parameters in Table 1. We measure a 2–10 keV unabsorbed flux of $\sim 7.4 \times 10^{-10}$ erg cm$^{-2}$ s$^{-1}$, a factor of $\sim 7$ times higher than the flux of the persistent emission that we measured during the BeppoSAX observation. In Fig. 3 we note residuals around 6–7 keV. For comparison with the spectrum during the 1999 August 15–16 BeppoSAX observation, we tried to add a Gaussian emission line in the range 6.4–6.9 keV. We find a Gaussian line at $\sim 6.75$ keV with an equivalent width of 87 eV. The parameters of the other components do not change significantly.

We have also analysed the MECS spectrum of the BeppoSAX observation performed on 2001 August 22. The best fit is obtained using a power law with a slope of $\Gamma = 2.68 \pm 0.28$, and a blackbody with a colour temperature of $kT = 3.4 \pm 0.03$ keV (reduced $\chi^2 = 1.07$ with 172 d.o.f.; Table 1). The spectrum is compatible with a Gaussian emission line between 6.4 and 6.7 keV, similar to the one used to fit the source spectrum during the previous BeppoSAX and RXTE observations, although this component is not required in this case. The unabsorbed 2–10 keV flux is $8.9 \times 10^{-10}$ erg cm$^{-2}$ s$^{-1}$. This model is consistent with the best-fitting model of the PCA 2–10 keV spectrum, which is well fitted with a power law with $\Gamma = 2.77$ and a blackbody with a colour temperature of $\sim 1.3$ keV.

3.2 X-ray bursts

We have analysed the six X-ray bursts of the 1999 BeppoSAX observation. We do not have enough statistics to select different intervals during the bursts and analyse the rise and decay spectra separately. Therefore we have analysed six spectra (one for each burst) each averaged over the whole $\sim 40$-s burst duration. From these spectra we have subtracted the spectrum of the persistent emission and fitted it with a blackbody component. In Table 2 we show the results of the fits for each of the six bursts. Note that, because the spectra of
the bursts soften significantly during the observation (see Fig. 1), the fit parameters, such as blackbody colour temperatures, have to be considered average estimates over the bursts.

4 DISCUSSION

We have analysed two BeppoSAX observations (taken in 1999 and 2001) and RXTE observations (taken in 1997 and 2000) of 4U 1708 − 40 and discovered this source to be an X-ray burster. This allows us to classify 4U 1708 − 40 as a NS system. In the 1999 BeppoSAX observation we found six bursts. Five bursts have a rapid rise (∼5 s) with a slow decay (∼35 s), and one has a triangular shape, although it shows spectral properties similar to those of the other bursts. The fluxes of the persistent emission in the RXTE observations and in the 2001 BeppoSAX observation are ∼7 and ∼8 times, respectively, higher than the flux of the persistent emission in the 1999 BeppoSAX observation. While we observe six bursts during the 1999 BeppoSAX observation, we do not observe any burst during the RXTE observations and during the 2001 BeppoSAX observation. This would be in agreement with the general behaviour of X-ray bursters: the bursts disappear above a certain threshold of the average spectral over 40 s of the six bursts with a blackbody component. In the first column in brackets is also indicated the time (with 1-s time resolution) from the beginning of the MECS observation (1999 August 15 at 05:01:10.5) at which the peak of each burst occurs.

Table 2. Blackbody colour temperature (kTbb in keV), normalization (Nbb, in units of L37/D10, where L37 is the source luminosity in units of 1037 erg s−1 and D10 is the distance to the source in units of 10 kpc) and Tbb is the temperature of the soft seed photons for the Comptonization, T is the electron temperature, τ is the optical depth of the spherical scattering cloud, N is the COMPT normalization (×10−2) in xspec v11.1.0 units (see Titarchuk 1994a,b), N is the normalization of the cut-off power law in units of 10−2 photon keV−1 cm−2 s−1 at 1 keV, Ecut is the cut-off energy, N is the normalization of the blackbody in units of L37/D10 (where L37 is the source luminosity in units of 1037 erg s−1 and D10 is the distance of the source in units of 10 kpc) and Tbb is the colour temperature of the blackbody. Eline is the centroid energy, σ is the width and eqw is the equivalent width of the Gaussian emission line. Ftot is the unabsorbed 2–10 keV flux in erg s−1 cm−2.
source. In Fig. 4 we plot the flux at the peak $F_p$ (calculated using the count rate at the peak of the burst in the 0.3 s resolution light curve) versus the fluence $E_b$ (the average bolometric flux times the duration of the burst) for each of the six bursts of 4U 1708 − 40. The plot shows an approximately linear correlation between $F_p$ and $E_b$. Although we do not see a saturation of $F_p$ in this correlation (and therefore we cannot derive the Eddington luminosity and the distance to the source), we can at least give an upper limit to the distance assuming the highest peak flux of the bursts to be less than $L_{\text{Edd}}$. Since $F_p \times 4\pi D^2 \lesssim L_{\text{Edd}} \sim 2.5 \times 10^{38} \text{ erg s}^{-1}$ (assuming $M = 1.4 \, M_\odot$ and correcting for gravitational redshift: van Paradijs & McClintock 1994), taking the bolometric flux at the peak of the first burst ($F_p = 8.6 \times 10^{38} \text{ erg cm}^{-2} \text{ s}^{-1}$), we obtain $D \lesssim 16 \text{ kpc}$, not a stringent constraint. Since the source is in the direction of the Galactic Centre we assume 8 kpc as the source distance. At 8 kpc, saturation would occur at 4 times this flux level.

Note that, as was pointed out by many authors, sometimes not all the accreted fuel is burned during the burst event, and the presence of a residual fuel can have significant implications for the lack of regularity of the burst behaviour (Ayasaki & Joss 1982; Hanawa & Fujimoto 1984; Woosley & Weaver 1985; Lewin et al. 1995). To investigate this point we have also calculated the values of $\alpha = (GM/R)/E_{\text{nuc}}$ (an observational quantity defined as the ratio of the average total energy in the persistent emission to that emitted in the burst) which is expected to be $\sim 40$ for a thermonuclear burst in the mixed hydrogen/helium burning regime (e.g. Lewin et al. 1995). We measure $\alpha \sim 40$ for all the bursts but one, starting from the first burst. Given that the accretion rate is constant with being constant, this implies a correlation between the time interval during which matter accretes on to the NS and the energy emitted in the following burst. The only exception is the last burst for which, assuming that the fifth and the sixth bursts are consecutive, we find a value for $\alpha$ that is much larger than 40 ($\alpha \sim 250$). In Fig. 5 we plot the fluence of the bursts as a function of the time interval between each burst and the previous one. There is a clear trend for the fluence to increase with time interval for all the bursts except the sixth. This trend is in agreement with the behaviour of other sources (see Lewin et al. 1995, for a review) and with the expectation that the longer the burst interval, the larger the amount of nuclear fuel available for the burst. The sixth burst seems not to follow this trend. Most probably we have missed some bursts in between the fifth and the sixth because of the presence of gaps (see Section 2). Indeed, we find a gap about 3000 s before the sixth burst, just where, following the correlation in Fig. 5, we would expect to find another burst.

Based on the observed persistent flux and the distance to the source, we can estimate the accretion rate and therefore the burning regime expected in this case. We find $M \sim 7 \times 10^{-11} \, M_\odot \, \text{yr}^{-1}$. This corresponds to the mixed hydrogen/helium burning regime triggered by thermally unstable hydrogen (Fujimoto et al. 1981; Fushiki & Lamb 1987; see also Bildsten 2000). This is consistent with the value of $\alpha \sim 40$ that we find for almost all the bursts.

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