Radius-expansion bursts from an enigmatic, episodic burster: 4U 1735−444

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1. Description of the proposed program

A) Scientific Rationale:

One of the highest priorities for observational studies of neutron stars (NS) is measurement of the mass and radius, sufficient to constrain the highly-uncertain equation of state (EOS; e.g. Lattimer & Prakash, 2007). A promising approach is to detect surface spectral features from accreting NS, which may preferentially show such features during thermonuclear (type-I) bursts, caused by unstable ignition of accreted H/He on the surface of the NS. Identifying such features allows measurement of the surface redshift, and hence the compactness (M/R ratio), which in turn allows constraints to be placed on the EOS. To date, only one claim for such features has been made (Cottam et al., 2002), although subsequent evidence for rapid rotation in the target source indicates the detected features could not arise from the neutron-star surface (Lin et al., 2010). The majority of observational efforts to date have focussed on sources which show frequent bursts, which tend to be faint, limiting the achievable signal-to-noise.

The brightest bursts are those exhibiting photospheric radius-expansion, as a consequence of reaching the Eddington limit, at which point the radiation pressure of the burst luminosity exceeds the local gravity. It is thought that such bursts may drive a wind containing heavy-element ashes from the burning, which would imprint absorption features on the X-ray spectrum at the peak of the burst (Weinberg et al., 2006). This prediction is supported by the residuals to blackbody fits seen in low-resolution spectra from so-called "super-expansion" bursts (in't Zand & Weinberg, 2010), but the only two studies with high-resolution spectroscopy of radius-expansion bursts have not resulted in detections. Both studies relied on small numbers (4 and 1, respectively) of these typically unpredictable events (Galloway et al., 2010b; in't Zand et al., 2013).

This proposal targets 4U 1735−444, which at times exhibits the most frequent Eddington-limited bursts of any known burst source.

4U 1735−444 (V926 Sco) is a bursting NS in a 4.654-hr binary orbit with a low-mass companion. The source exhibits absorption by dust and warm ISM gas along the line of sight, and thus is a target for measurements of the interstellar dust composition (Pinto et al., 2013). In observations by the *Rossi X-ray Timing Explorer* (*RXTE*) PCA and the *BeppoSAX* WFC[1] between 1996–2012, 4U 1735−444 displayed episodic bursting behaviour at low persistent flux levels, with short bursts (rise times $\lesssim 2$ s, and mean timescale of $\tau = 3.7 \pm 0.8$ s) characteristic of H-poor fuel. A significant fraction (73% of the bursts observed with *RXTE*; Galloway et al., 2008) of these bursts exhibited radius-expansion. In the last two decades, 4U 1735−444 has *only* exhibited bursts in the low phase of its long-term persistent flux variation (Fig. 1). With the persistent flux measured by *MAXI* now decreasing steadily from a maximum in 2012, the source appears to be returning to the persistent flux level at which it is expected to burst.

B) Immediate Objective:

We propose a 130 ks Target-of-Opportunity observation of 4U 1735−444 to be triggered on detection of bursts, to satisfy several goals: first, to accumulate a high signal-to-noise spectrum from the peak of radius-expansion bursts, to allow a deep search for discrete features; second, to characterise in detail the properties of the thermonuclear bursts, in particular their energetics, recurrence time, and low-energy spectrum; and third, to accumulate a high signal-to-noise low-flux persistent spectrum.

We will trigger this observation on detection of two or more thermonuclear bursts, most likely by the wide field instruments aboard *INTEGRAL* or *Swift*. Because it is a critical requirement of the science goals to obtain many bursts, we will only trigger if there is strong evidence for a burst recurrence time of 1.5 hr or less. Once in a bursting state, the source is likely to remain active for some time, so we expect that a response of a week should be sufficiently fast.

We request an uninterrupted observation, to avoid ambiguity for the burst recurrence time measurements (essential for our energetics study). We will identify all bursts in the observation, and extract lightcurves and time-resolved burst spectra. We will search for discrete spectral features in the accumulated spectrum from

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[1] now combined into the Multi INstrument Burst ARchive, or MINBAR; `http://burst.sci.monash.edu/minbar`

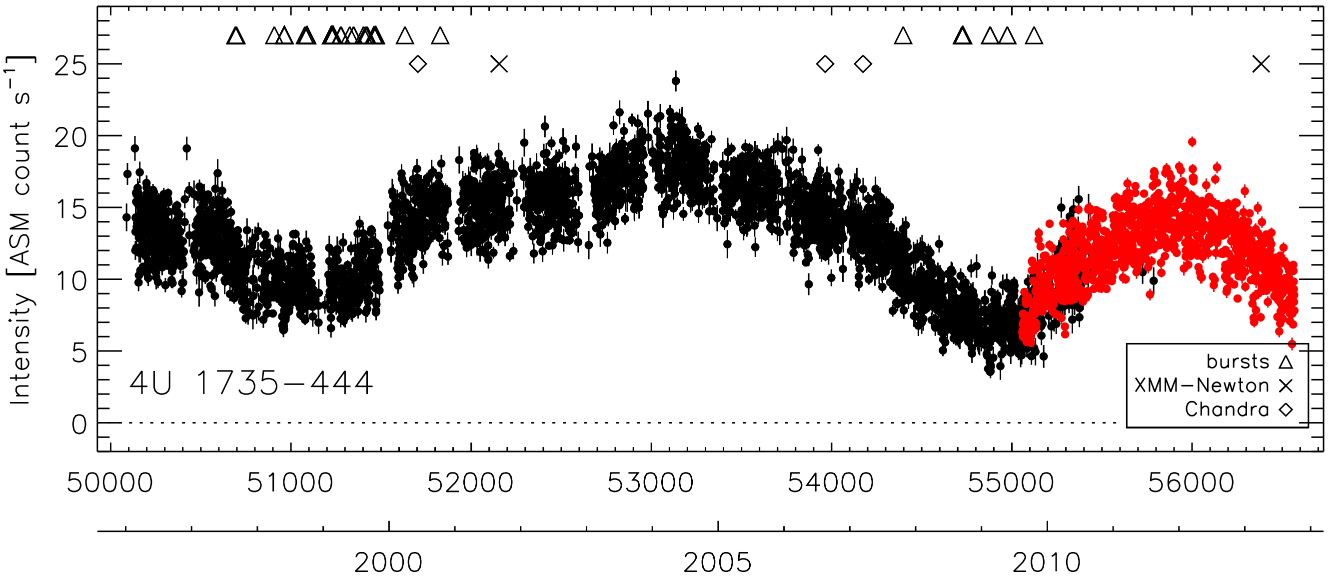

Figure 1: Long-term flux history and burst behaviour of 4U 1735−444. Plotted are 2–10 keV intensity measurements by *RXTE*/ASM (*black symbols*), along with the measurements in the same band made by *MAXI* (rescaled by a factor of 24.77 to match the ASM measurements where they overlap; *red symbols*). The times of thermonuclear bursts detected by *RXTE*/PCA and *BeppoSAX*/WFC (*open triangles*), as well as the epochs of observations by *XMM-Newton* and *Chandra* (*crosses* and *open diamonds*, respectively) are indicated. Note that the burst behaviour is restricted to the two epochs of low peak flux between 1997–2001, and 2007–10. The decrease in persistent intensity measured by *MAXI* from 2012 indicates that 4U 1735−444 will shortly return to a low-intensity, bursting state.

the peak of the radius-expansion bursts and attempt to identify them, potentially allowing measurement of the gravitational redshift at the NS surface. These spectra will also be fitted with standard models to measure the instantaneous burst temperature, flux, and the total burst fluence. Examination of the spectral evolution near the burst peak (using the time-resolved burst spectra, or hardness ratios) will allow us to test for radius-expansion in the bursts. The burst fluence and persistent flux can then be used to calculate the α-parameter, the ratio of persistent to burst energy, and thus constrain the burst fuel.

We will also search the persistent spectrum for discrete features, and measure the properties of neutral and ionised absorption edges. We will compare these measurements to corresponding ones from archival spectra obtained during the high state.

2. Justification of requested observing time, feasibility and visibility

Few sources show frequent, radius-expansion bursts; we have chosen 4U 1735−444 for this cycle because of the greater burst frequency (compared to 4U 1728−34, for example), as well as the rare opportunity of observing in its bursting state, for the first time in ≈ 5 years. Our observing strategy is chosen primarily to guarantee detecting as many bursts as possible. By triggering our observation strictly on detection of frequent bursting behaviour, we maximise the chance of achieving full science return. If the burst recurrence time is as short as was seen during the *RXTE* and *BeppoSAX* observations, i.e. one per ≈ 1.3 hr, we could accumulate as many as 30 bursts. Given that only ≈ 7 radius-expansion bursts have been observed from any source by *Chandra* or *XMM-Newton*, this will represent a significant addition to the available observational data on these events. The total exposure of 130 ks is the maximum possible for a single orbit when the source is visible (2014 September–October, and 2015 February–April, with minimum solar aspect angle 72°).

There is one other property of 4U 1735−444 that recommends it as a priority target for searches for discrete spectral features. While the optical spectrum bears a remarkable similarity to another well-known burst source, 4U 1636−536 (e.g. Augusteijn et al., 1998), the burst behaviour is markedly different. 4U 1636−536 shows at times long bursts, characteristic of H-rich fuel, which are not seen in 4U 1735−444, despite the evidence for H in the mass donor via optical spectral lines. This dissimilarity could be attributed to a lower spin rate for the NS. Piro & Bildsten (2007) studied the effect of mixing between the fuel and ash layers in He-accretors, and found that these layers will become mixed preferentially at high accretion rates and low spin frequencies. Low neutron-star spin frequency results in a larger shear between the innermost Keplerian-orbiting material in the disk and the neutron-star surface, enhancing mixing. The ashes are rich in CNO nuclei, which if mixed into the fuel layer may allow more rapid exhaustion of the accreted hydrogen through steady burning, perhaps explaining the short time-scales of bursts from 4U 1735−444. While the spin rate in 4U 1636−536 has been measured at 581 Hz via burst oscillations (e.g. Strohmayer & Markwardt, 2002), no such oscillations or pulsations have been detected in 4U 1735−444. We note that the burst properties of the 11 Hz pulsar in Terzan 5 have demonstrated a link between frequent (thermounuclear) bursts and slow spin (e.g. Linares et al., 2012), and the Rapid Burster is another system in which the frequent bursts have been suggested to arise (indirectly) via a slow spin rate (Bagnoli et al., 2013). If the burst properties of 4U 1735−444 arise because the source is a slow rotator, then the chance of detecting surface features is increased over other, more rapidly spinning NS, because the slow rotation causes less Doppler broadening.

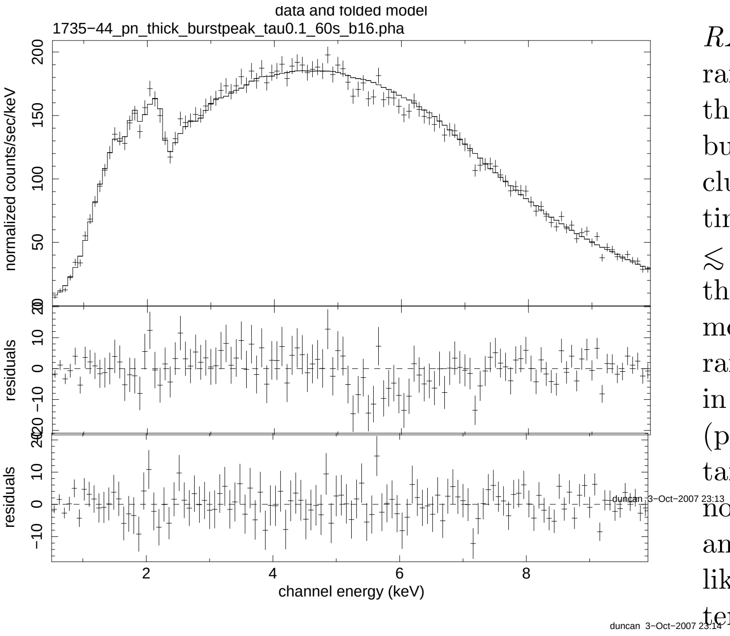

Figure 2: Simulated pn spectra from the peak of 30 radius-expansion thermonuclear bursts (*top panel*). The spectrum includes a photoionisation edge at 5.25 keV, arising from a Fe Kα edge red-shifted by $z = 0.35$, i.e. emitted from the surface of a $1.4 M_{\odot}$, 10-km radius NS. We can likely detect a photoionisation edge with depth 300 eV (equivalent to $\tau = 0.1$, *upper panel residuals*) and also measure the edge position to an accuracy of a few %, and the depth to 15%. The fit including the edge component accounts well for the residuals (*lower panel*).

The persistent flux of 4U 1735−444 measured by *RXTE* during the burst-active intervals was in the range 2.3–$4.5 \times 10^{-9}\ \mathrm{erg\,cm^{-2}\,s^{-1}}$ (2–10 keV), while the maximum peak flux of the radius-expansion bursts was $4.3 \times 10^{-8}\ \mathrm{erg\,cm^{-2}\,s^{-1}}$ (bolometric; including the latest PCA response matrices and dead-time corretion). The bursts typically rise within $\lesssim 1$ s to a peak lasting ≈ 2 s, followed by a decay for the next ≈ 8 s or so. PIMMS estimates of timing mode countrates for the persistent flux are in the range 480–1100 $\mathrm{count\,s^{-1}}$ in pn, 210–520 $\mathrm{count\,s^{-1}}$ in MOS1/2, and 30–60 $\mathrm{count\,s^{-1}}$ in RGS first order (persistent). These estimates are somewhat uncertain as they are based on PCA spectra, which do not extend below 2.5 keV. The bursts add at most another 800 (425) $\mathrm{count\,s^{-1}}$ for pn (MOS), giving a likely peak count rate (including burst and persistent emission) of 1900 (950) $\mathrm{count\,s^{-1}}$.

Sustained count rates this high will exceed the telemetry capacity of the EPIC cameras in all modes except pn burst mode, which offers an unacceptably low duty cycle (3%). We adopt the pn camera as the primary instrument, due to its greater sensitivity. In AO-5 we investigated the feasibility of observing radius-expansion bursts in 4U 1728−34, which has fainter persistent emission but brighter bursts. That proposal was approved (priority C) following discussions with the *XMM-Newton* GOF, who advised that the observation was feasible so long as most of the satellite's telemetry was allocated to the pn camera. Thus, for the proposed observation of 4U 1735−444, we also choose timing mode, and we adopt similar telemetry mitigation strategies as for the earlier proposal. No data from the optical monitor (OM) are required, and the count rate from the two MOS cameras are comparable to that returned by the single pn camera. Prior to the observation, we will plan to deactivate (in order of priority) the OM and one or both of the MOS cameras in order to ensure full telemetry return from the pn camera and the RGS. With these precautions, the pn PI team has earlier confirmed that the telemetry will not saturate immediately for a combined burst & persistent intensity reaching $2 \times 10^{3}\ \mathrm{count\,s^{-1}}$.

Assuming we detect 30 radius-expansion bursts (possible given the burst rate observed previously), we will accumulate up to 6×10^{4} counts in pn, and up to 700 counts in RGS 1&2 first order around the 2-s peak of the bursts. Simulations indicate we will have sensitivity to photoionisation edges down to a few hundred eV depth (Fig. 2), well within the predicted range (Weinberg et al., 2006). We will have greater sensitivity to narrow line features, possible if the spin rate of 4U 1735−444 is indeed slow. These data may also be combined with future observations in order to increase the sensitivity for narrow features.

This observation will also result in exquisite signal-to-noise persistent spectra from 4U 1735−444. We will accumulate at least 2×10^{6} counts with the pn camera within each inter-burst interval, as well as more than 2×10^5 counts combined in RGS 1&2 first order. Integrating over longer intervals is usually not feasible because of intensity and spectral changes over these time-scales. The low column density toward 4U 1735−444 ($N_{\rm H} \approx 3 \times 10^{21}\,{\rm cm}^{-2}$) and the high count rate will also guarantee excellent quality RGS spectrum. We will perform a detailed study of the absorption features (e.g by N, O and Fe) produced in both the accretion disk atmosphere (e.g. Cottam et al. 2007) and in the ISM (e.g. Costantini et al. 2005, Juett et al. 2006). The contribution to the absorption by compounds in molecular form (i.e. from dust particles) in the ISM is a debated issue. With this observation we will characterize in unprecedented detail the chemistry of the dust grains for this source through the modeling of the O and Fe edges, located in the soft-Xray band (e.g. Costantini et al., 2012). Thanks to the technique developed by Xiang et al (2005), we will be able to recover the scattered light fraction, the other essential part of extinction by dust.

Report on previous proposals and observations

This proposal is a resubmission from AO7, and was rejected in that round primarily on the basis of doubts about guaranteeing the burst rate. For this reason, we have revised our triggering criterion to strictly require frequent bursts, with recurrence time of 1.5 hr or less.

This proposal is part of a campaign that has observed several sources exhibiting radius-expansion bursts, including 4U 1728−34, 3A 1820−30, and SAX J1808.4−3658. 4U 1735−444 has not been a target for the last few years as it was in a high (non-bursting) state. Earlier *XMM-Newton* or *Chandra* observations detected no bursts, likely because they took place during the high state. One episode of increased flux during the most recent *XMM-Newton* observation (#069349021, 2013 April) may be due to a single burst (C. Pinto, pers. comm). Thus, the exisiting observations cannot satisfy our science goals.

3. Report on the last use of XMM-Newton data[2]

The symbiotic neutron-star binary 4U 1700+24 was observed via a TOO (#0155960601; GO: Jansen), following the outburst in 2002, and an AO-2 GO observation (#0151240201/301/401, PI: Galloway) in 2003 March–August. In collaboration with A. Tiengo (University of Amsterdam), we reported the discovery of a presumed O VIII emission line in this source in A&A (see below)

A 10 ks observation of 4U 1728−34 (#0701190101), coordinated with a longer *INTEGRAL* observation took place in 2013 October, and data analysis is underway.

4. Most relevant applicant's publications

in 't Zand, J. J. M., Galloway, D. K., Marshall, H. M., Ballantyne, D. R., Jonker, P. G., Paerels, F. B. S., Palmer, D. M., Patruno, A., Weinberg, N. N. (2013) A bright thermonuclear X-ray burst simultaneously observed with *Chandra* and *RXTE*. A&A 553, #A83

Galloway D.K., Yao Y., Marshall H., Misanovic Z., Weinberg N. (2010). Radius-expansion burst spectra from 4U 1728-34: an ultracompact binary? ApJ, 724, 417

Tiengo A., Galloway D.K., di Salvo T., Méndez M., Miller J.M., Sokoloski J., van der Klis M., 2005, A&A, 441, 283: Discovery of a redshifted X-ray emission line in the symbiotic neutron star binary 4U 1700+24.

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Costantini, E., et al. 2012, A&A, 539, A32

Cottam, J., Paerels, F., & Mendez, M. 2002, Nature, 420, 51

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Lattimer, J. M. & Prakash, M. 2007, Phys. Rep., 442, 109

Lin, J., Özel, F., Chakrabarty, D., & Psaltis, D. 2010, ApJ, 723, 1053

Linares, M., Altamirano, D., Chakrabarty, D., Cumming, A., & Keek, L. 2012, ApJ, 748, 82

Pinto, C., Kaastra, J. S., Costantini, E., & de Vries, C. 2013, A&A, 551, A25

Piro, A. L. & Bildsten, L. 2007, ApJ, 663, 1252

Strohmayer, T. E. & Markwardt, C. B. 2002, ApJ, 577, 337

Weinberg, N. N., Bildsten, L., & Schatz, H. 2006, ApJ, 639, 1018

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[2] An approved AO-5 proposal (#040690, PI: Galloway, priority: C) also targeting radius-expansion bursts was not observed.