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A NON-PRE DOUBLE-PEAKED BURST FROM 4U 1636–536: EVIDENCE FOR BURNING FRONT PROPAGATION

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ABSTRACT

We analyse Rossi X-ray Timing Explorer (RXTE) Proportional Counter Array (PCA) data of a double-peaked burst from the low mass X-ray binary (LMXB) 4U 1636–536 that shows no evidence for photospheric radius expansion (PRE). We find that the X-ray emitting area on the star increases with time as the burst progresses, even though the photosphere does not expand. We argue that this is a strong indication of thermonuclear flame spreading on the stellar surface during such bursts. We propose a model for such double-peaked bursts, based on thermonuclear flame spreading, that can qualitatively explain their essential features, as well as the rarity of these bursts.

Subject headings: accretion, accretion disks — relativity — stars: neutron — X-rays: binaries — X-rays: bursts — X-rays: individual (4U 1636–536)

1. INTRODUCTION

X-ray bursts are produced by thermonuclear burning of matter accumulated on the surfaces of accreting neutron stars (Grindlay et al. 1976; Belian, Conner, & Evans 1976; Woosley, & Taam 1976, Joss 1977; Lamb, & Lamb 1978). For most of the bursts, profiles are single peaked, with rise times of the order of a fraction of a second to a few seconds, and decay times of the order of ten or a few tens of seconds. However, for some bursts, double-peaked structure is observed. These peaks (with time separation of a few seconds) in a single luminous burst can normally be explained in terms of photospheric radius expansion (PRE; due to radiation pressure) and contraction (Paczynski 1983; Ebisuzaki, Hanawa, & Sugimoto 1984). As the photosphere expands, the effective temperature decreases, and the emitted photons shift towards lower energies. A subsequent contraction of the photosphere has the opposite effect. This can cause a dip (and hence the double-peaked structure) in the high-energy burst profile (Lewin et al. 1976; Hoffman, Cominsky, & Lewin 1980), although such a structure is not frequently seen in bolometric or low-energy profiles (see Smale 2001).

Double-peaked structure in weak X-ray bursts was discovered by Sztajno et al. (1985) using EXOSAT observations of the low mass X-ray binary (LMXB) system 4U 1636–536. For these bursts, two peaks are seen in the bolometric profile, and even in low-energy profiles. For this reason, and as these bursts are not strong enough to cause photospheric expansion, some other physical effects are needed to explain them. Several models have been put forward to explain these non-PRE double peaked bursts: (1) two-step energy generation due to shear instabilities in the fuel on the stellar surface (Fujimoto et al. 1988), (2) a nuclear waiting point impedance in the thermonuclear reaction flow (Fisker, Thielemann, & Wiescher 2004), (3) heat transport impedance in a two-zone model (Regev, & Livio 1984), and (4) interactions with the accretion disk (Melia, & Zylstra 1992). As we will elaborate in § 4, none of these models can explain various aspects of these bursts satisfactorily.

Here, we propose a model for these bursts based on thermonuclear flame spreading on neutron stars. In our model, we consider that the fuel (accreted matter) is distributed over the entire stellar surface (Inogamov & Sunyaev 1999; Spitkovsky, Levin, & Ushomirsky 2002), the burst is ignited at a certain point (which is natural, because simultaneous ignition over the whole surface requires very fine tuning), and then propagates on the surface to ignite all the fuel gradually. Double-peaked structure can appear, if the propagation speed decreases considerably for a few seconds, and then increases again. This allows the temperature to decay considerably, but the emission area remains almost the same in those few seconds, hence producing a dip in the emitted flux. We justify the validity of this phenomenon in § 3. Our model reproduces the observed burst profile (in different energy bands), time evolutions of hardness, stellar surface blackbody temperature, and emission area, at least qualitatively, and also gives an explanation of the rarity of the double-peaked bursts.

In this Letter, we analyse the RXTE data of a double-peaked burst from 4U 1636–536, and in conjunction with model calculations, and spectral fitting of the models, we show that thermonuclear flame spreading on the neutron star surface can explain the double-peaked structure in weak X-ray bursts.

2. DATA ANALYSIS AND RESULTS

We analyse the RXTE PCA archival data of a double peaked burst (Date of observation: Jan 8, 2002; ObsId: 60032-01-19-000) from 4U 1636–536. The heights of the two peaks are almost identical ($\sim 6600-6700$ counts/s for 3 PCUs on), with a dip depth more than half the peak height (panel *a* of Fig. 1). This is a weak burst compared to PRE bursts from this source, which can have ~ 35000 counts/s for 5 PCUs on (see Strohmayer et al. 1998). The burst profiles at different energy bands are very similar

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(panel *a* of Fig. 1), showing that this is not a PRE burst. However, the hardness in panel *b* of Fig. 1 shows two striking features: (1) the first peak of the hardness occurs $2-3$ seconds before that of the burst profile; (2) the second hardness peak is much lower than the first one, while the burst profile peaks are of similar height. As the emitted flux primarily depends on source hardness (which is a measure of temperature) and source emission area, feature (1) indicates that the emission area increases with time. Feature (2) is possible if the emission area at the time of the second peak is much higher than that at the time of the first peak. For a non-PRE burst, the emission area can increase only if the burning region spreads on the stellar surface from an initially small size. Therefore, the panels *a* & *b* of Fig. 1 are consistent with thermonuclear flame spreading.

As a next step, we break the burst profile into smaller time bins, and for each bin perform spectral fitting. This gives the time evolution of the spectral parameters. We fit the data with a single temperature blackbody model (bbodyrad in XSPEC), as generally burst spectra are well fit by a blackbody (Strohmayer & Bildsten 2003). In doing this, we fix the hydrogen column density $N_{\rm H}$ at a value 0.56×10^{22} cm^{-2}. This value (which is consistent with the values obtained without fixing $N_{\rm H}$) was inferred from the optical interstellar extinction (Lawrence et al. 1982), using the relation between $E(B-V)$ and $N_{\rm H}$ of Gorenstein (1975). The results of these fits are shown in panels *c* & *d* of Fig. 1. The radius is calculated from the "normalization" and provides a measure of the source emitting area. The panels show that the evolution of the temperature is similar to that of the hardness (as expected), and the size of the emission area increases with time (indicating flame spreading), first quickly, and then slowly. The temporal behavior of the radius also shows that this is not a PRE burst, otherwise the radius would decrease from the time when the burst profile attains its minimum between the two peaks. However, the reduced χ^2 values are high for these fits (>1.5 for most of the time bins, and >3 for two out of 29 time bins). Considering the arguments of the previous paragraph, this may be because of the following reason: the emission is locally blackbody, but temperatures at different locations on the stellar surface are significantly different (as a result of slow flame spreading in comparison to the timescale of temperature decay at a given location), and hence a single temperature blackbody model can not fit the observed spectra well. However, the similar evolution of temperature to that of the hardness indicates that from single temperature blackbody fits we get an average blackbody temperature on the stellar surface. This may explain the reason for the smaller height of the second temperature peak (panel *c* of Fig. 1), even if each stellar surface location has the same peak temperature. This is because, with the slow flame spreading, temperature decays considerably on most part of the star before the flame engulfs the whole star, making the average temperature smaller during the second peak.

The error bars in panels *c* & *d* of Fig. 1 give 1σ errors. As the reduced χ^2 values are high, increasing χ^2 by 1 from the best fit value (to get the errors in parameters) would tend to underestimate the errors. Therefore, we increase χ^2 by the amount of the reduced χ^2 of the fit to calculate the 1σ errors.

From the above analysis we infer that double peaked bursts may be caused by thermonuclear flame spreading on the stellar surface. In the next section, we show by simple modeling, that certain types of flame spreading can qualitatively account for these bursts.

3. MODEL CALCULATIONS

In our model we assume that for the particular double peaked burst analysed here the burning region forms a ϕ-symmetric belt very quickly after ignition, and then the burning front propagates latitudinally. This is necessary because this burst does not show any millisecond period brightness oscillation, and this is possible if the burst is ignited near the equator (Spitkovsky et al. 2002) or a pole. However, we find that equatorial ignition can not naturally produce a double-peaked structure.

We will argue that in order to produce a double-peaked structure, burning must ignite at or near the north pole (while the observer's inclination angle, measured from this pole, is $\leq 90^{\rm o}$), and the initially fast moving front must "stall" for a time as it approaches the equator, before speeding up again into the opposite hemisphere. Is such a decrease in the flame speed plausible? We argue that accretion may provide a natural mechanism to slow the front. As 4U 1636-53 is not a millisecond X-ray pulsar, the magnetic field of the neutron star is probably comparatively low, and accretion will proceed via a disk around the equatorial plane. Therefore, the gravitational force on particles falling onto the star is closely balanced by the centrifugal force (assuming that the disk almost touches the star), and hence accretion may be interrupted by a modest increase in the radiation pressure force (Inogamov & Sunyaev 1999). As a result, even weak bursts can probably inhibit accretion to some extent, if thermonuclear flux is radiated near the equator. However, during accretion the accreted matter spreads from the equator towards the poles, first rapidly, then more slowly (Inogamov & Sunyaev 1999). A burning front spreading equator-ward from a pole may be impeded by this pole-ward flow of accreted matter in the mid-latitudes. This could cause the front to stall for two reasons: (1) as the accreted matter has a small effective gravity (due to the large centrifugal force), the friction and mixing (between hot and cold fuel) may be less efficient, reducing the front speed; (2) as the accreted matter is moving pole-wards, the equator-ward speed of the burning front with respect to the stellar surface will naturally be reduced (by mixing). Therefore, the burning front will take more time to reach the equator from the mid-latitudes, and during that time hot portions of the star will have had time to cool, causing a decrease of the emitted flux. Approaching the equator, the flux from the burning front will be able to inhibit accretion sufficiently to allow the front propagation speed to increase again, causing an increase of the emitted flux and the observed double-peaked structure.

To qualitatively test this hypothesis we calculate model burst profiles and spectra, implementing the ideas of the previous paragraph in a simple way. We assume the emitting region is a ϕ-symmetric belt extending from the north pole to a polar angle θ, determined by the time elapsed since burst onset and the burning front speed as a function of θ. We compute lightcurves and spectra from such a system, considering the Doppler, special relativistic, and general relativistic (gravitational redshift and light-bending in Schwarzschild spacetime) effects, and qualitatively compare them with the data (after convolving the models with the relevant PCA response matrix). We use the following stellar and binary parameters for our calculations: (1) neutron star mass M, (2) dimensionless neutron star radius to mass ratio R/M, (3) neutron star spin frequency ν_*, and (4) observer's inclination angle (measured from the north pole) i. We fix the value of ν_* to 582 Hz (known from millisecond oscillations during many other bursts; Giles et al. 2002; Strohmayer & Markwardt 2002). With a fast spin rate, the effect of the Coriolis force on the flame speed should be important, and therefore, following Spitkovsky et al. (2002), we assume the flame speed is $\dot{\theta}(\theta) = 1/(t_{\rm total} \times \cos\theta)$ at locations where the effect of accretion is negligible. Here, $t_{\rm total}$ is the time needed by the front to propagate from a pole to the equator in the absence of accretion, and if $\theta > 90°$, $\cos\theta$ should be replaced by $\cos(180° - \theta)$. However, due to the rapid pole-ward motion of accreted matter, $\dot{\theta}(\theta)$ decreases linearly from θ_1 to θ_m, reaching a value $s/t_{\rm total}$, and then, as the accretion ceases, increases linearly to θ_2 reaching a value $1/(t_{\rm total} \times \cos\theta_2)$. At each point, after ignition, the temperature is assumed to increase from $T_{\rm low}$ to $0.99 \times T_{\rm high}$, and then decays exponentially with an e-folding time $t_{\rm decay}$. During the increase, the temperature follows: $T(t) = T_{\rm low} + (T_{\rm high} - T_{\rm low}) \times (1 - \exp(-t/t_{\rm rise}))$.

We compute model lightcurves and spectra for a range of parameter values, and show an example in Fig. 2 which qualitatively reproduces the observed features of the double-peaked burst. In this example, the stellar and binary parameter values are realistic: (1) the moderately high value of R/M is consistent with the rapid stellar spin, and the possible near contact of the star and the accretion disk, (2) the mass is consistent with the chosen R/M and ν_* values for realistic EOS models, and (3) the value of i is consistent with the small amplitude of the optical lightcurve of this non-dipping source (Melia & Zylstra 1992). We have chosen plausible values for the other parameters as well.

For all the panels of Fig. 2 the model burst is normalised so that its first intensity peak has the same count rate as that of the first peak of the observed burst. In panel *a* of Fig. 2, the burst profiles (bolometric and channel-dependent) qualitatively match (including the depth of the dip) the data (see panel *a* of Fig. 1), except the initial rise. For the model, the initial rise time is longer than that for the data. An effect which may account for this discrepancy is the radiative diffusion time, ie. the delay been ignition at depth and emergence of the radiation. Note also that we calculate the model flux only up to the time when the burning front reaches the south pole, while in Fig. 1, the real data probably extend beyond the time at which all the fuel has ignited. In panels *b* and *c* of Fig. 2, we plot the model hardness and average temperature on the stellar surface, respectively. We also fit our normalised model spectra with the XSPEC model bbodyrad, in the same manner as for the data. The resulting blackbody temperature and radius are shown in panels *d* and *e* of Fig. 2. Panels *b*, *c* and *d* show a similar temporal behavior: both hardness and temperature increase at the beginning rapidly, then decrease up to the point when the burst profile reaches a minimum, increase slightly up to the point when the burst profile reaches the second peak, and then decrease again. This behavior is strikingly similar to that seen in the burst data (panels *b* and *c* of Fig. 1). We note that the temporal behavior of the model average temperature (panel *c* of Fig. 2) suggests that spectral fitting with a single temperature blackbody model actually does give the average temperature on the stellar surface. In panel *e* of Fig. 2, the evolution of the radius shows an initial rapid increase, and then a slower increase, which is also quite similar to the data (panel *d* of Fig. 1). Therefore, even using relatively simple assumptions, modeling of thermonuclear flame spreading from pole to pole with accretion-induced stalling of the front can reproduce the essential features of this double-peaked burst.

4. DISCUSSIONS AND CONCLUSIONS

In this Letter we have presented a new model for double-peaked bursts, that we believe has several advantages over existing models. First, it includes the natural expectation of thermonuclear flame spreading, which other models do not. For example, our model naturally explains the observed increase in emission area suggested by panels *a* and *b* of Fig. 1. Moreover, it appears unlikely that model 1 (see § 1) can reproduce both the burst profile and the temporal evolution of hardness (or, temperature) simultaneously, as it does not consider the emission area increase. There is also no real calculation of double-peaked profiles from this model. In addition, if thermonuclear flames spread in the way Spitkovsky et al. (2002) argue, it is very difficult to see how sufficient unburnt fuel (as required by this model) can be maintained on top of the burnt fuel, as the full scale height of the hot fuel is likely overturned and mixed with the cold fuel. We suggest that models 2 & 3 (see § 1) are probably unable to reproduce the large dip (judging from the figures of Regev, & Livio 1984; Fisker, Thielemann, & Wiescher 2004), seen in the observed burst. It is also unclear whether these models, as well as model 4 (see § 1), can reproduce the observed hardness and/or temperature evolution, or if they can explain the rarity of the double-peaked bursts.

Our model can qualitatively reproduce the essential features of the double-peaked bursts (see § 3), including the burst profile (with a large dip) and the hardness evolution. Double-peaked structure appears only to be associated with weak bursts, perhaps because strong bursts would tend to disrupt accretion sufficiently to preclude the kind of front stalling that is required for the occurence of two peaks according to our model. The double-peaked feature is somewhat rare even among the weak bursts. This may be because in order to have the double-peaked structure, the burst needs to be ignited at or near a pole (so that the accretion can continue for a few seconds), which is less probable than equatorial ignition (Spitkovsky et al. 2002). The fact that double-peaked bursts are seen from only a few sources (mostly from 4U 1636–536) can be understood in our model as follows. These bursts require a low stellar magnetic field (for a given accretion rate), so that accretion happens mostly through a disk in the equatorial plane, and the disk must closely approach the star (so that the gravitational force is closely balanced by the centrifugal force near the surface). This is possible, if the equatorial R/M is large, and ν_* is high (making the radius of the innermost stable circular orbit small; see Fig. 1 of Bhattacharyya et al. 2000). This relatively fine tuning among magnetic field, accretion rate, equatorial R/M and ν_* may exist for a relatively small fraction of LMXBs. Therefore, our model may not only qualitatively explain the enigmatic rarity of the non-PRE double-peaked bursts, but may also, in principle, enable constraints on stellar magnetic fields and equatorial R/M to be obtained.

Our work suggests that non-PRE double-peaked bursts can be important in understanding thermonuclear flame spreading on neutron stars, which may also provide important insights about the millisecond period brightness oscillations during X-ray bursts. These oscillations can be used to constrain equation of state models of the cold dense matter in the cores neutron stars (Bhattacharyya et al. 2005). However, the rarity of such bursts has been an obstacle to understanding them, and thus new attempts to expand the sample of these bursts seems well warranted.

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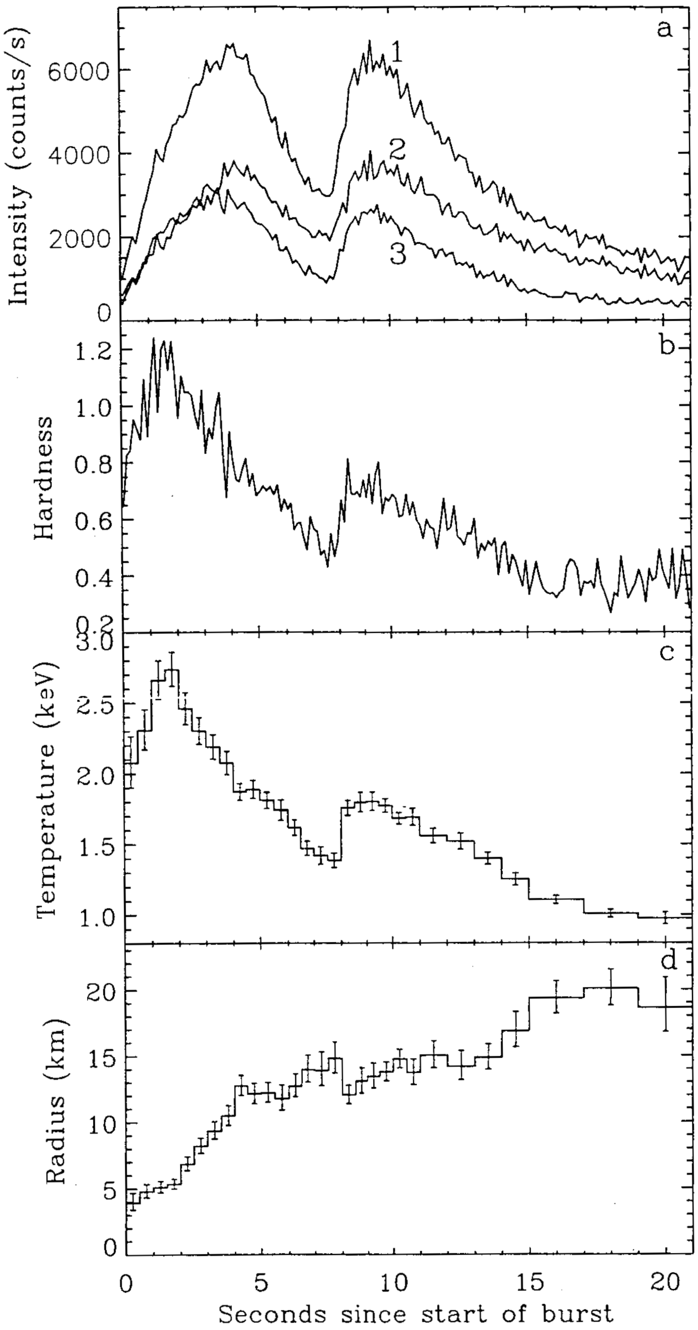

FIG. 1.— A double-peaked burst from 4U 1636–536: panel *a* gives the burst profiles: curve 1 is for the channel range 0 – 63 (nearly bolometric), curve 2 is for the channel range 0 – 10 (energy < 6.52 keV), and curve 3 is for channel range 11 – 63 (energy > 6.52 keV). Panel *b* shows the time evolution of hardness (ratio of counts in 11 – 63 channel range to that in 0 – 10 channel range). For both these panels, the size of the time bin is 0.125 s. Panels *c* & *d* show the time evolution of the blackbody temperature and the apparent radius (assuming 10 kpc source distance) of the emission area respectively, obtained by fitting the burst spectrum (persistent emission subtracted) with a single temperature blackbody model. The horizontal bars give the size of the time bins.

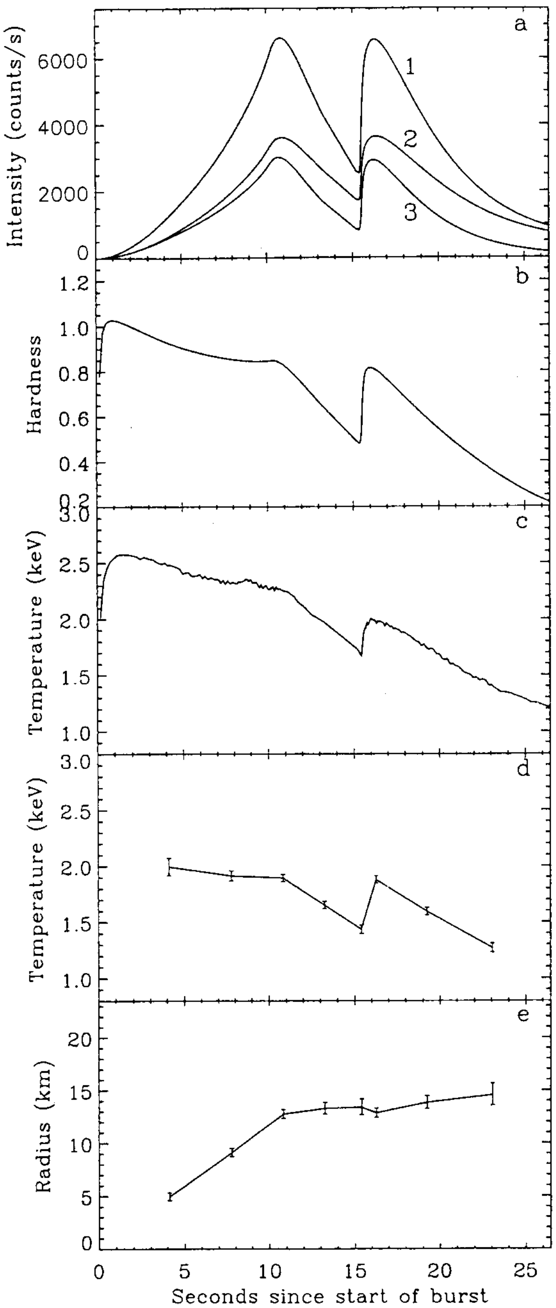

FIG. 2.— Model (convolved with a PCA response matrix) of double-peaked bursts: for all the panels, the burst is normalised so that its first intensity peak has the same count rate as that of the first peak of the observed burst. Panels *a* & *b* are similar to those of Fig. 1. Panel *c* gives the time evolution of average blackbody temperature on the stellar surface. Panels *d* & *e* are similar to panels *c* & *d* of Fig. 1 respectively. For these two panels, spectra are calculated for 0.5 s time bins for each point. Model parameter values are the following: stellar mass $M = 1.5 M_{\odot}$, dimensionless stellar radius to mass ratio $R/M = 5.5$, stellar spin frequency $\nu_* = 582$ Hz, observer's inclination angle (measured from north pole) $i = 50^{\circ}$, $\theta_1 = 67^{\circ}$, $\theta_m = 83^{\circ}$, $\theta_2 = 87^{\circ}$, $s = 0.04$, $t_{\rm total} = 11$ s, $t_{\rm rise} = 0.05$ s, $t_{\rm decay} = 6$ s, $T_{\rm low} = 1$ keV, and $T_{\rm high} = 2.8$ keV (see text for the definitions of the other parameters).