ON THE NATURE OF THE FLUX VARIABILITY DURING AN EXPANSION STAGE OF A TYPE I X-RAY BURST: CONSTRAINTS ON NEUTRON STAR PARAMETERS FOR 4U 1820–30

NICKOLAI SHAPOSHNIKOV1 AND LEV TITARCHUK2

Received 2003 December 17; accepted 2004 March 15; published 2004 April 7

ABSTRACT

We investigate closely the flux profile during the burst expansion stage observed from 4U 1820–30 with the Rossi X-Ray Timing Explorer on 1997 May 2. We are able to uncover the behavior of a photospheric radius and to simulate the evolution of the neutron star (NS) accretion disk system. We argue that although the bolometric luminosity is always the Eddington value $L_{\text{Edd}}$, the photon flux at the bottom of the expanded envelope can decrease during the expansion stage. In fact, at the initial moment of explosion when the bottom burning temperature is $\sim 2 \times 10^9$ K, the bottom flux $L_{\text{bot}}$ is a few times the Eddington limit, because the electron cross section is a few times less than the Thomson cross section at such high temperatures. The surplus of energy flux with respect to the Eddington, $L_{\text{bot}} - L_{\text{Edd}}$, goes into the potential energy of the expanded envelope. As cooling of the burning zone starts the surplus decreases, and thus the envelope shrinks while the emergent photon flux stays the same, $L = L_{\text{Edd}}$. At a certain moment the NS low hemisphere, previously screened by the disk, becomes visible to the observer. Consequently, the flux detected by the observer increases. We estimate the anisotropy due to geometry and find that the system should have a high inclination angle. Finally, we apply an analytical model of X-ray spectral formation in the NS atmosphere during the burst decay stage to infer the NS mass-radius relation.

Subject headings: accretion, accretion disks — stars: fundamental parameters — stars: individual (4U 1820–30) — X-rays: bursts

1 INTRODUCTION

4U 1820–30 is one of the brightest low-mass X-ray binaries. It resides in the globular cluster NGC 6624. An extremely short 685 s orbital period discovered by Stella et al. (1987) from EXOSAT observations implied that the system is ultra-compact and the secondary is a low-mass helium-rich degenerate star. Using the analysis of UV diagrams of NGC 6624, Vacca, Lewin, & van Paradijs (1986, hereafter VLP86) evaluate the distance to be 4U 1820–30 by $6.4 \pm 0.6$ kpc, while the optical observations give a distance estimate of 7.6 kpc (Rich, Minniti, & Liebert 1993, hereafter RML93). Kuulkers et al. (2003) used this distance to evaluate the neutron star (NS) mass in this source considering X-ray bursts with a radial expansion as a standard candle.

Type I X-ray bursts from 4U 1820–30 were discovered by Grindlay et al. (1976). It is now well established that these short ($\sim 10–15$ s) outbursts of energy are due to the unstable thermonuclear burning of a hydrogen/helium mixture at the bottom of the NS atmosphere accumulated by the accretion process.

All bursts observed from 4U 1820–30 show the radial expansion with an apparent photospheric radius increase by a factor of $\sim 20$. Such an expansion is accompanied by spectral softening, which moves the spectrum completely out of the X-ray bandwidth and results in a so-called precursor effect (see Strohmayer & Bildsten 2004, hereafter SB04, and references therein).

The X-ray spectral formation along with hydrodynamics during expansion and decay stages of type I bursts were studied by Ebisuzaki, Hanawa, & Sugimoto (1983, hereafter EHS83), Titarchuk (1994, hereafter T94), and Shaposhnikov & Titarchuk (2002, hereafter ST02). In these papers the important effect of the radiative expansion was pointed out. Specifically, while the emergent photon luminosity is always the Eddington, $L_{\text{bot}} - L_{\text{Edd}}$ the photon flux at the bottom of the expanded envelope can reach a value of a few times greater than the Eddington limit. Indeed, at the initial moment of explosion when the bottom burning temperature is $\sim 2 \times 10^9$ K, the bottom flux $L_{\text{bot}}$ is a few times more than Eddington luminosity, because the electron cross section is a few times less than the Thomson cross section for such high temperatures (see eq. [1] below). The surplus of energy flux with respect to the Eddington limit, $L_{\text{bot}} - L_{\text{Edd}}$, goes into the potential energy of the expanded envelope. As cooling of the burning zone starts, the surplus decreases, and thus the envelope shrinks (contraction stage of the radial expansion phase) while the emergent photon flux stays the same, $L = L_{\text{Edd}}$. Shaposhnikov, Titarchuk, & Haberl (2003, hereafter STH03) draw attention to the fact that at a certain moment of the contraction stage, the NS low hemisphere becomes visible to the observer, having previously been screened by the disk. In this Letter we provide more details into the physical insight of this phenomenon and its relation to the data.

The spectral formation model, employed in the present work, accounts for the effects of Comptonization, free-free absorption, and emission, and we apply this methodology in analyzing the burst from 4U 1820–30 observed by the Rossi X-Ray Timing Explorer (RXTE) on 1997 May 2. The high spectral and statistical quality of the data allows us to infer tight constraints on the NS parameters (cf. Haberl & Titarchuk 1995). We find a strong evidence of accretion disk-star geometry evolution, which closely resembles the behavior of 4U 1728–34. We compare our results for 4U 1820–30 with equations of state (EOSs) of NS matter.

A brief description of the data used in the analysis is given in § 2. We consider the general burst phenomenology. We specifically address its behavior during the expansion stage in...
§ 2.1 and calculate photospheric radius and bottom temperature profiles. We discuss in detail different processes that may affect the behavior of the source flux during the burst expansion. We present the model and the results of its application to the burst data of 4U 1820−30 in § 2.2. Specifically, we obtain the dependence of the NS mass on the radius as error contours, calculated for a set of distances to the system taken from the interval obtained by VLP86. We summarize our results in § 3.

2. OBSERVATIONS, DATA ANALYSIS, AND RESULTS

4U 1820−30 was observed by the Proportional Counter Array (PCA; Jahoda et al. 1996) on 1997 May 2 under observation ID 20075-01-05-00. All five detectors were operative during the observation. In addition to the permanent Standard1 (one energy channel, 1 s time resolution) and Standard2 (129 energy channels, 16 s time resolution) mode data, data in event mode with 125 μs time resolution and 64 energy channels were recorded. Although the high-resolution event mode overloaded the satellite telemetry system during the peak of X-ray bursts, this effect resulted in data loss only for three short intervals during the expansion stage, and thus did not prevent us from being able to perform detailed spectral analysis of the event. The burst started at 17:33:50 Terrestrial Time. Prior to the burst the source was in its low-intensity state with 3.3 × 10^{-9} ergs cm^{-2} s^{-1} flux in the 2–10 keV energy range.

The light curve of the burst is presented in Strohmayer & Brown (2002). The initial rise of the photosphere is followed by the contraction stage when the spectrum hardens and becomes detectable by the RXTE/PCA detector array. We start our spectral analysis of burst radiation beginning 2 s after the start of the burst when the spectrum shifts back to the PCA detection bandwidth.

We first extracted the spectrum of the persistent emission for 100 s immediately prior to the burst. We used the extracted persistent spectrum as a background for the burst spectra. During the burst we extract spectral slices for consecutive time intervals of 1/2 s. We used the high-resolution event mode for extraction of both persistent and burst spectra, and we utilized Standard1 mode for calculating all appropriate count rates for dead-time corrections for the extracted spectra. Counts from all three detector layers were added during data reduction. We fitted burst spectra by the absorbed blackbody shape. Quality of the models is good for the entire decay stage and for most of the expansion episode with χ^2_{red} ~ 1.0.

Temporal profiles of unabsorbed 0.001–100.0 keV model flux and temperature are given in Figure 1. The initial rise of the photosphere occurs in less than a second, and the enormous expansion of NS atmosphere is achieved within the first second of the burst. Subsequent contraction is accompanied by spectral hardening and bolometric flux growth. Temperature and flux reach their maxima of 3.1 ± 0.1 keV and 7.0 ± 0.3 × 10^{-8} ergs cm^{-2} s^{-1} simultaneously at the moment of photospheric “touchdown.” After that both profiles decay exponentially.

2.1. The Expansion Stage

Through the part of the expansion episode during which the burst spectrum is observable by the PCA, the photosphere temperature rises from 1 up to 3 keV. As it is shown in Figure 1, observed flux gradually grows as the photosphere contracts and color temperature increases.

![Fig. 1.—Bolometric flux (red) and color temperature (blue) of the burst spectrum vs. time. Inferred photospheric radii are shown in green. The peaks of the temperature and the radius curves correspond to the touchdown of the photosphere.](image-url)
details on nuclear burning on the NS surface). The Eddington limit is exceeded, and atmospheric expansion occurs. The structure of the expanded atmosphere during the burst is regulated by the bottom conditions (EHS83; T94; ST02). In fact, the observed radial expansion episode lasts about 3–5 s. The photospheric contraction is not governed by free fall, but rather it is quasi-steady, since cooling off the burning zone is a relatively slow process, of the order of seconds (see Spitkovsky et al. 2002). For the strong and extensive burst such as in 4U 1820–30, the bottom temperature $kT_b$ is $\sim 2 \times 10^9$ K, and thus the flux at the bottom is a few times larger than the Eddington limit because of the attenuation of the cross section due to the relativistic corrections (see eq. [1]). This fact allows the super-Eddington energy rate to be effectively transferred into potential energy of the outer layers of the atmosphere. Numerical results of ST02 show that overall energy outflow from the expanded envelope stays within 1%–2% of the Eddington radiation flux only. In other words, the atmosphere acts as a reservoir for the surplus energy. It releases the stored energy at the Eddington rate until the photosphere reaches the NS surface. According to the model atmosphere, the potential energy of the burst atmosphere during strong expansion can reach up to $\sim 10^{40}$ ergs. This energy supply explains the overall energetics of the event. Throughout this particular contraction stage of the radial expansion episode, the bottom cools off while the photospheric temperature grows. This whole picture is counterintuitive to the observer, who detects only the flux at approximately the Eddington level and sees spectra that harden during this stage.

Applying the semianalytical theory developed by ST02, we obtain the various parameters of the expanded envelope as functions of the observed temperature of the photosphere, its chemical composition, and the NS mass and radius. Using pure helium atmosphere and NS parameters inferred in § 2.2 for the source distance of 5.8 km ($m = 1.29$, $R_{NS} = 11.2$ km), we establish the dependence of $R_{ph}$ on $kT_b$ and correspondingly on $l$. The dependence of $T_b$ on $R_{ph}$ is presented in Figure 2. It is important to note that these calculations are geometry independent because the color temperature $kT_b$ is a geometry independent quantity.

The hydrodynamic profiles, given by the model, allow us to evaluate the total mass $M_{env}$ of the expanded envelope. For the maximum temperature of $2 \times 10^9$ K and given NS parameters $M_{env} = 5.8 \times 10^{-5}$ g. The corresponding mass column of $M_{env}/4\pi R_{NS}^2 = 3.6 \times 10^4$ g cm$^{-2}$ is an agreement with the column required for ignition (e.g., Bildsten 1998).

The apparent flux increase during contraction of the photosphere is consistent with the photospheric radius profile given by the theoretical model. A geometric anisotropy factor (which takes into account the observed flux increase due to geometry evolution, decrease due to gravitational redshift, and slight increase due to relativistic correction to opacity) is

$$\xi_a \approx 1.35(z + 1)/1.06 = 1.26(z + 1).$$  (2)

### 2.2. The Burst Decay Stage: NS Mass and Radius

Here we present the final formula for the color temperature $kT_b$ as a function of input parameters of the problem (see T94 and Titarchuk & Shaposhnikov 2002 for details):

$$kT_b = 2.17T_e \left( \frac{lm}{(2 - Y_{He}(z + 1) \gamma^2)} \right)^{1/4} \text{keV},$$  (3)

where $m$ is the NS mass in units of solar mass, $r_e$ is the NS radius in units of 10 km, and $l = L/L_{Edd}$ is the dimensionless luminosity in units of the Eddington luminosity. Here $T_e$ is the color (hardening) factor, which depends on $l$ and $Y_{He}$. Parameters of the model are $m$, $r_e$, and $Y_{He}$, and $d_{10}$ is the distance to the object in units of 10 kpc. The luminosity is expressed by

$$l = 0.476\xi_a d_{10}^2 F_8 (2 - Y_{He}(z + 1)/lm),$$  (4)

where $\xi_a$ is anisotropy factor and $F_8 = F/10^{-8}$ erg cm$^{-2}$ s$^{-1}$. There are strong indications that 4U 1820–30 is the pure helium accretor and bursts originate in a helium-dominated environment (e.g., SB04), so we put $Y_{He} = 1.0$ for the entire model fitting procedure. The model gives the functional dependence of $kT_b$ on $F_8$, which are two observables obtained from spectral fits. We fit our model to the data in the range $0.5 < F_8 < 6.5$, which approximately corresponds to $0.1 < l < 0.9$.

First we assume that the anisotropy of the system does not change throughout burst decay. In this case $\xi_a$ cannot be evaluated independently from distance because they come into the model only as a product $\xi_a d_{10}^2$. We put $\xi_a = 1.0$ and perform the model fits by minimizing $\chi^2$. We use three fixed values for the distance 5, 8, 6, 4, and 7.0 according to the error interval given by VLP86 and obtain fits with $\chi^2_{red} \geq 2.0$. None of these fits is statistically acceptable, if we require $\chi^2_{red} \sim 1.0$.

The fit behavior for $\xi_a$ = const indicates the disk occultation hypothesis mentioned in the previous section. According to this hypothesis, the entire NS is exposed to the observer until some moment, when the accretion disk returns to the NS surface. We identify the time when the disk comes back with the moment of the flux drop. This occurs around the seventh second of the burst when the flux falls down to $\approx 2.5 \times 10^{-8}$ ergs cm$^{-2}$ s$^{-1}$. Just before this moment, the NS is openly viewed, and thus the system has the geometry corresponding to $\xi_a = 1.0$, i.e., the disk subtends the lower NS hemisphere and the system makes a transition to the geometry state with $\xi_a$. We modify our model to include the effect of the disk occultation introducing two additional parameters: anisotropy during occulta-
tion $\xi^*$ and dimensionless flux $F^*$ at the moment when occultation occurs. In this analysis we consider only the dependence of $\xi^*$ on the inclination angle, i.e., $1.0 \leq \xi^* \leq 2.0$ (see STH03 for details). We use equation (2) for a self-consistent calculation of $\xi^*$ during the model fitting. When the occultation effect is consistently incorporated into the model, we obtain good quality fits with $\chi^2_{\text{red}} < 1.0$. The results are summarized in Table 1.

In Figure 3 we show the best-fit parameters and $M_{\text{NS}}$-R$_{\text{NS}}$ error contours for 68%, 90%, and 99% confidence levels. Curves GM and FPS present $M$-$R$ relationships for nuclear matter EOSs calculated by Glendenning & Moszkovski (1991) and Friedman & Pandharipande (1981), respectively.

The fact that during the expansion stage the Eddington limit is achieved puts an additional constraint on the NS fundamental characteristics. One should observe gravitationally redshifted flux $F_{\text{Edd}}^*$ from the unocculted NS at the moment of the burst atmosphere touchdown, when both flux and temperature peak (i.e., on the fifth second in Fig. 1). With this assumption the dimensionless luminosity can be calculated as $l = \xi^* F^*/F_{\text{Edd}}^*$.

Moreover, in this case the distance is not a parameter, and we can calculate alternative domain in the $M$-$R$ plane dictated by the observed Eddington flux. The $M$-$R$ values for 90% confidence level, obtained with this method, are located between two dashed curves. The $M$-$R$ domain is most consistent with a distance of 5.8 kpc, while the 90% contours obtained with two methods for 7 kpc and higher do not overlap (cf. RML93's distance estimate).

3. SUMMARY

We investigate in detail the physics governing the burst properties during the expansion stage. The super-Eddington energy excess is deployed into the gravitational potential energy of the expanded atmosphere, which is a result of the dependence of the electron opacity on temperature. The emergent luminosity (cooling rate of the expanded atmosphere) is at the Eddington limit. When the bottom temperature drops and photospheric contraction occurs, one can intuitively expect the overall flux decrease. However, the exact contrary situation is observed. The photospheric temperature increases and the bolometric flux grows, presumably because of a geometrical NS recovery from behind the accretion disk inner edge. Simple arguments lead to the value of geometrically induced anisotropy of $\xi \approx 1.55$–1.71, which corresponds to the local system inclination angle $i \approx 73^\circ$–$80^\circ$ (see Table 1).

We infer the mass-radius relationship and error contours for a given distance by modeling the spectral temperature dependence on the bolometric flux. Both the statistical behavior of the model and the Eddington flux limit strongly suggest that the distance to 4U 1820–30 is close to 5.8 kpc, for which we obtain $M_{\text{NS}} = 1.29^{+0.19}_{-0.07} M_\odot$ and $R_{\text{NS}} = 11.2^{+0.4}_{-0.3}$ km.

REFERENCES

Bildsten, L. 1998, in The Many Faces of Neutron Stars, ed. R. Buccheri, J. van Paradijs, & M. A. Alpar (Dordrecht: Kluwer), 419
Ebisuzaki, T., Hanawa, T., & Sugimoto, D. 1983, PASJ, 35, 17 (EHS83)
Friedman, B., & Pandharipande, V. R. 1981, Nucl. Phys. A, 361, 502
Glendenning, N. K., & Moszkovski, S. A. 1991, Phys. Rev. Lett., 67, 2414
Grindlay, J. E., Gursky, H., & Schnopper, H. 1976, ApJ, 205, L127
Haberl, F., & Titarchuk, L. 1995, A&A, 299, 414
Jahoda, K., et al. 1996, Proc. SPIE, 2808, 59
Kuulkers, E., et al. 2003, A&A, 399, 663
Paczyński, B. 1983, ApJ, 267, 315
Rich, R. M., Minniti, D., & Liebert, J. 1993, ApJ, 406, 489 (RML93)
Shaposhnikov, N., & Titarchuk, L. 2002, ApJ, 567, 1077 (ST02)
Shaposhnikov, N., Titarchuk, L., & Haberl, F. 2003, ApJ, 593, L35 (STH03)
Spitkovsky, A., Levin, Y., & Ushomirsky, G. 2002, ApJ, 566, 1018
Stella, L., Friedman, W., & White, N. E. 1987, ApJ, 312, L17
Strohmayer, T. E., & Bildsten, L. 2004, in Compact Stellar X-Ray Sources, ed. W. H. G. Lewin & M. van der Klis (Cambridge: Cambridge Univ. Press), in press (astro-ph/0109124) (SB04)
Strohmayer, T. E., & Brown, F. B. 2002, ApJ, 566, 1045
Titarchuk, L. 1994, ApJ, 429, 340 (T94)
Titarchuk, L., & Shaposhnikov, N. 2002, ApJ, 570, L25
Vacca, W. D., Lewin, W. H. G., & van Paradijs, J. 1986, MNRAS, 220, 339 (VLP86)