Restrictions on the parameters of boundary layer and accretion disk of X-ray bursters in the low state

Revnivtsev M.¹,², Gilfanov M.²,¹, Churazov E.²,¹, Sunyaev R²,¹.

Space Research Institute, Moscow, Russia
Max-Planck Institut für Astrophysik, Garching, Germany

ABSTRACT Using ASCA observations of several X–ray bursters in the low spectral state \( (L_x \sim 1-5 \times 10^{36} \text{ erg/s}) \) restrictions on the parameters of the accretion disk and the boundary layer were obtained. The low state spectra of X–ray bursters observed with ASCA often can be well described by a power law with photon index of 1.7–2.2 and are not consistent with significant contribution of the soft spectral component to the total luminosity. For a blackbody spectrum with temperature of 0.2–2 keV the upper limits correspond to < 10–20% of the total 0.5–10 keV luminosity. On the other hand, theoretical calculations predict that in the case of a Keplerian accretion disk around a slowly rotating neutron star (with radius of \( 3R_g \)) \( \sim 2/3 \) of the total gravitational energy released in the system can be released in the boundary layer between the inner part of the accretion disk and the neutron star surface.

More accurate analysis of the ASCA spectra shows that: (1) The inner radius of the standard geometrically thin optically thick part of the accretion disk exceeds \( R_{in} > 10^{-25} R_g \). (2) The characteristic temperature in the inner part of the accretion flow including the boundary layer exceeds \( \sim 2 \text{ keV} \) independently upon the assumption about the density in the accretion flow. The electron scattering gives the dominant contribution to the opacity in this region.

KEYWORDS: Stars:Binaries:General, X-rays:Stars, Stars:Neutron, Radiative Transfer, Scattering

1. INTRODUCTION

Observations of the X-ray bursters show that in the high luminosity state \( (L_x > \text{few} \times 10^{37} \text{ erg/s}) \) they have sufficiently soft spectra, which can be often described as a superposition of a blackbody emission and an emission of an optically thick accretion disk (e.g. White et al. 1988). It is often assumed, that the blackbody component originates in the optically thick boundary layer (BL) between the inner edge of a Keplerian accretion disk and the surface of a slowly rotating neutron star (Mitsuda et al. 1984, White et al. 1988). The importance of the BL contribution was emphasized by many authors (e.g. Kluzniak&Wagoner 1985, Shakura&Sunyaev 1986, White et al. 1988). In particular, it has been shown, that even in Newtonian approximation the luminosity of the BL equals to the luminosity of the extended accretion disk. In Schwarzschild geometry the luminosity of the BL can by a factor of 2 or more exceed that of accretion disk (Shakura&Sunyaev 1986). As was shown
TABLE 1. The list of ASCA observations of several X-ray bursters and best fit parameters of the power law approximation for GIS2 and GIS3 data.

| X-ray burster   | Date obs. | Exposure | \(\alpha\) | \(N_H\) cm\(^{-2}\) | \(L_x\) \(\times 10^{36}\) erg/s |
|----------------|-----------|----------|-------------|----------------|-------------------------------|
| 4U0614+091     | 18/04/93  | 3548     | 2.24 ± 0.01 | 0.33 ± 0.01    | 1.78 ± 0.01                  |
| 4U1724-30      | 24/09/95  | 8853     | 1.77 ± 0.02 | 1.60 ± 0.03    | 3.60 ± 0.04                  |
| SLX 1735-269   | 15/03/95  | 18378    | 2.13 ± 0.01 | 1.45 ± 0.02    | 1.75 ± 0.02                  |
| 4U1850-56      | 06/10/95  | 20444    | 2.15 ± 0.01 | 0.19 ± 0.01    | 1.39 ± 0.01                  |

\(\alpha\) Luminosity not corrected for interstellar absorption, assuming 2.5 kpc distance for 4U0614+091, 7.5 kpc for 4U1724-30, 8.5 kpc for SLX 1735-269 and 6.8 kpc for 4U1850-56.

by Sibgatullin & Sunyaev (1998) the account for the realistic time-space geometry around a rotating neutron star reduces this value for a prograde accretion disk, but for any reasonable parameters of the rotating neutron star the BL luminosity exceeds that of the accretion disk. As was noted by White et al. (1988), the simplest approximation of the spectra of X-ray bursters in the high state by the superposition of a black body emission and an emission of an optically thick accretion disk results in the blackbody luminosity less than predicted for the BL.

In the low spectral state the spectra of X-ray bursters usually can be adequately approximated by a single power law with low energy absorption and are not consistent with significant contribution of the soft spectral component to the total luminosity. Therefore assumption of an optically thick BL emitting a nearly blackbody spectrum encounters even greater difficulties.

In this work we derive some simple constraints on the parameters of BL and accretion disk basing on the fact that the spectra of X-ray bursters in the low spectral state do not have strong soft components.

2. CONSTRAINS ON THE PARAMETERS OF THE BOUNDARY LAYER AND ACCRETION DISK

For our analysis we used data of ASCA (Tanaka, Inoue & Holt 1994) observations of four X-ray bursters in the low spectral state in 1993–1995. A brief summary of the observations and the best fit parameters of the power law with low energy absorption approximation are presented in Table 1.

A black body spectrum is a usual choice of a spectral model for a soft component, in particular in the context of the BL emission (e.g. White et al. 1988). It is well known however, that a black body emission spectrum can be formed only if the free-free opacity dominates (see e.g. Zeldovich & Shakura 1969, Felten & Rees 1972, Shakura 1972, Shakura & Sunyaev 1973). In the opposite case (scattering opacity dominates) scattering can significantly distort the emergent spectrum. We shall assume for simplicity that the region of the main energy release in the BL is isothermal and consider two kinds of the density distribution – exponential and homogeneous (more realistic density profiles were considered in Illarionov & Sunyaev, 1972). The isothermal exponential atmosphere can be formed near the surface of the
NS if the local energy flux in the BL is sufficiently smaller than the local Eddington flux. If the BL luminosity is $\sim 10^{36}$ erg/s and the emitting area of the BL is a small fraction of the neutron star surface area ($< 0.01$) then the local energy flux will be comparable with the Eddington value and the radiation pressure will significantly modify the density profile in the BL. In this case the spectrum of an isothermal homogeneous atmosphere might be a better approximation to the BL spectrum.

For the spectral approximation of the ASCA data we used three different two-component models: 1) power law + black body spectrum, 2) power law + spectrum of isothermal exponential atmosphere and 3) power law + spectrum of isothermal homogeneous atmosphere. The scale height of isothermal exponential atmosphere was calculated for any given temperature of the atmosphere assuming a neutron star with mass $1.4 M_\odot$ and radius 10 km. The density and the height of isothermal homogeneous atmosphere were fixed at $N = 10^{22}$ cm$^{-3}$ and $h = 2000$ cm. The choice of density corresponds to the minimal value required to produce luminosity $\sim 10^{36}$ erg/s assuming that the emitting area equals to the neutron star surface area and the temperature is $\sim 1$ keV. The height of the atmosphere $h$ was chosen so that the “true opacity” $\tau \sim \sqrt{\tau_{ff}(\tau_T + \tau_{ff})} > 1$ for $kT = 1$ keV at $E = 1$ keV ($\tau_{ff}$ – free-free, $\tau_T$ – electron scattering optical depth). In this case the spectrum is almost independent on $h$ and depends only on the ratio $\tau_T/\tau_{ff}$ and as $\tau_T/\tau_{ff} \rightarrow 0$ ($\rho$ increases) the spectrum $\rightarrow$ blackbody spectrum. Fixing the temperature of the soft component in the 0.2-2.0 keV interval and varying its normalization we obtained the upper limits on the soft component luminosity as a function of temperature. In Fig.1 (left panel) we present the 2$\sigma$ upper limits on the luminosity of the soft components for three spectral model mentioned above as a function of $T$, in the units of total 0.5–10 keV luminosity of the source. One can see that the contribution of the soft component does not exceed $\sim 10$–$20\%$ of the 0.5–10 keV luminosity. Thus, the contribution of the soft component is considerably lower than that expected for the BL emission.

Therefore none of the considered simple models of the BL emission, with the temperature in the range 0.2-2.0 keV, is consistent with the ASCA data. Moreover, as we considered low density (homogeneous atmosphere with $N = 10^{22}$ cm$^{-3}$) and high density (black body) limits of the BL, we can tentatively conclude that independently on the BL density the BL temperature should exceed $\sim 2$ keV. For such temperature the emergent spectrum of BL should be significantly modified by the electron scattering both in case of isothermal exponential and homogeneous atmosphere.

The upper limits on the soft spectral component constrain also the parameters of the optically thick part of the accretion disk. Assuming that the emission of the optically thick part of the accretion disk can be described by the simple multicolor black body disk model (Shakura&Sunyaev, 1973, Mitsuda et al., 1984) we can use the observational data to obtain the upper limits on the inner radius of the accretion disk.

\footnote{Note, that for a typical low state spectrum the bolometric luminosity can exceed the 0.5–10 keV luminosity by a factor of 2 or more.}
FIGURE 1. Upper limits on the luminosity of the various soft components in the units of total 0.5-10 keV flux (left panel). Solid line – black body model, dotted line – model of isothermal exponential, dashed line – model of homogeneous atmosphere. In the right panel the upper limits on the inner radius of the standard optically thick part of the accretion disk as a function of its temperature are presented. Solid line shows the theoretical dependence for parameter $\dot{m} = 0.1$.

ation disc as a function of the disk temperature (Fig.1, right panel). Furthermore, assuming that the 0.5–10 keV luminosity can be used to estimate the mass accretion rate in the disk we can obtain the theoretical dependence of the temperature of the inner edge of the optically thick part of the accretion disk on its radius. The overlap of these two regions would define the allowed range of $T_{in}$ and $R_{in}$. From the Fig.1 (right panel) one can see that the typical lower limit on the inner radius of the optically thick part of the accretion disk is about 40–100 km. For a neutron star with $M = 1.4M_\odot$ it corresponds to $\sim 10–25R_\odot$. The regions closer to the compact object should have spectra significantly modified by the electron scattering, so they will have higher temperatures.

ACKNOWLEDGMENTS M.R. thanks the RBRF grant N980227566. Research has made use of data obtained through the High Energy Astrophysics Science Archive Research Center Online Service, provided by the NASA/Goddard Space Flight Center.

REFERENCES
Czerny, Czerny&Grindlay 1986
Kluzniak&Wagoner 1985
Felten&Rees 1972, A&A, 17, 226
Illarionov&Sunyaev 1972, Astroph.&Space Sci., 19, 61
Mitsuda et al. 1984, PASJ, 36, 741
Shakura 1972, Sv.A., v.16., No.3, p.532
Shakura&Sunyaev 1986, PAZH, v.12, N.4, p. 286
Sibgatullin&Sunyaev 1998, in press, see also astro-ph/9811028
Tanaka, Inoue&Holt, 1994, PASJ, 46, L37
White et al. 1988, ApJ, 324, 363
Zel’dovich&Shakura 1969, Astron. Zh., 46, 225