Effect of the neutron star size on the total spectrum from LMXB

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We show how shape of the spectrum of a non-spherical system as low mass X-ray binary (LMXB) depends on the size of the neutron star. We computed the continuum emission from system of axial symmetry as a neutron star with an accretion disk, which is a typical configuration for LMXB. Adopting the standard disk model, we expect that such disk is hot with the inner disk temperature of the order of 10^7 K. In addition, the neutron star usually may be hot up to few$\times10^7$ K. Therefore, the whole system is visible in UV/X-ray energy domain and the overall spectral shape may display double bump which is frequently observed in accreting sources. We show that systems with neutron stars of larger radii are brighter. An overall shape of emitting continuum depends on viewing angle in the whole energy range.

1 Introduction

It is commonly known that multiwavelength observations of accreting objects, from optical through UV up to X-rays, cannot be fitted by a single spectral component. Usually, the multi-color black body disk component is necessary to explain the high energy bump, which in case of galactic sources is typically observed in the X-ray domains. The problem appeares for different type of sources as: low mas X-ray binaries (LMXB) (Kolehmainen et al., 2011), black hole accretion disks with hot coronae (Janiuk et al., 2001; Petrucci et al., 2013; Fabian et al., 2015) and ultraluminous X-ray sources (ULXs) (Walton et al., 2013, 2018). For such sources additional spectral component is needed to fully explain the observed spectral shape.

Recently, it was shown by Różańska et al. (2017, 2018) that instead of adding additional component during spectral analysis of those sources, we should take into account that all of those objects are not spherically symmetric. In case of non-spherical systems we do not observe locally emitted flux, which is in case of spherically symmetric stars given by standard formula, derived by Mihalas (1978) (Eq. 1-27). When the source is not spherically symmetric we observe specific intensity of radiation integrated over a small solid angle as seen by the distant observer. The observed quantity has the same units as the flux, but it is not proportional to the locally emitted flux (specific intensity integrated over full solid angle). The most common example is the emission from an accretion disk (Shakura & Sunyaev, 1973), which is axially symmetric. Observed quantity is the monochromatic intensity, I_ν emitted in the specific direction, which then is integrated over the whole disk surface from the inner to outer disk radii.

In the paper by Różańska et al. (2017) authors studied the appearance of the neutron star – accretion disk system as seen by a distant observer in the UV/X-ray domain. Observed intensity spectra were computed by integration of the specific

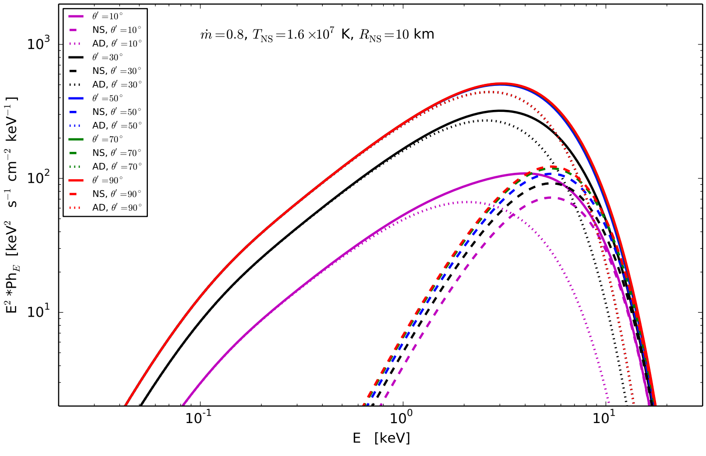

Fig. 1: The emitting continuum from LMXB depending on the viewing angle for $R_{\rm NS}$ = 10 km. Total model is presented by solid line. For clarity, the only disk component and the emission from NS are shown by dotted and dashed lines, respectively

intensity over emitting areas taking into account mutual attenuation. For such a non-spherical system, only part of energy from NS reaches an observer. Furthermore, the specific intensity was integrated over much larger area than the neutron star surface, i.e. the surface of an accretion disk, both regions with different temperatures. Therefore, the total spectral shape is broadened by contribution from different emission regions, which is clearly visible at the high energy end of each model depending on initial parameters. The observed spectrum depended on viewing angle in the whole energy range.

In this paper we show how the spectral shape from the whole system: a neutron star with the accretion disk depends on the neutron star radius. Our model reproduces emission from both neutron star and the multi-color disk. Neutron star radius and the inner temperature are free parameters of the model. Here, we consider the case, where the neutron star temperature is comparable with the inner disk temperature, Then, the effect of spectral broadening is clearly visible and strongly depends on the viewing angle. We show that, when neutron star radius increases up to 14 km, the resulted spectral broadening is larger at the high energy end of the observed spectrum.

2 Spectral shape of total emission

LMXBs are binary systems, where the primary star is a compact object, either the black hole or the neutron star. The secondary is a late type main sequence star, classified as K or M of low mass slightly less than the solar mass. In many of those sources accretion of matter onto the compact object occurs if the system is tight enough. Accretion can proceed under different scenarios. In principle, when falling matter has non-zero initial angular momentum, then the accretion disk may form down to the innermost stable circular orbit (ISCO).

We consider LMXB as a non-spherical system containing neutron star with the accretion disk around it. For such object geometry, the infinitesimal energy $d\mathcal{F}_\nu$

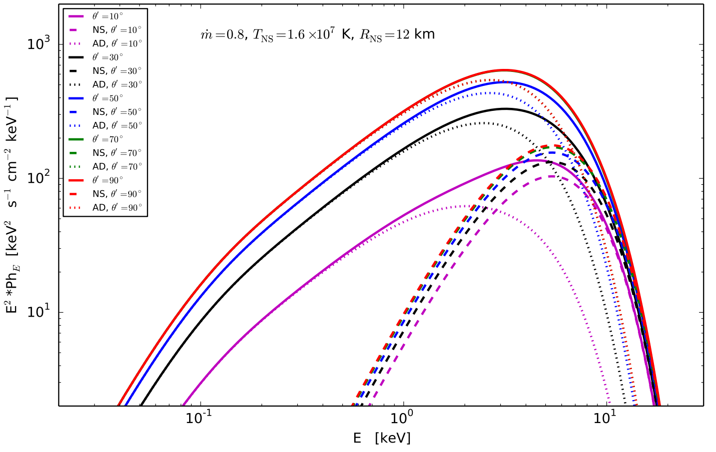

Fig. 2: The same as in Fig. 1 but for $R_{\rm NS} = 12$ km.

measured by a distant observer is defined as:

$$d\mathcal{F}_\nu = I_\nu d\omega, \tag{1}$$

where $d\omega$ is a solid angle in steradian [sr] (Mihalas, 1978). This formula is applicable for the flat space, as we assumed in this paper. In case when the emitter is located close to black hole, both general and special relativistic corrections should be taken into account as in Fabian et al. (1989, Eq. A4). Nevertheless, in this paper we show purely geometrical effect obtained by proper integration of above equation over the emitting surface. Integrating Eq. 1 over the solid angle subtended by the source, we obtained energy dependent intensity: $\mathcal{F}_\nu$ as seen by the observer. This quantity diminishes with the increasing distance and it is not an intrinsic property of the source.

In the case of emission from the whole system i.e. neutron star with the accretion disk around it, we have the contribution from different emitting parts (for details see: Różańska et al., 2017) and the final observed energy dependent intensity directed to the observer is computed analytically as:

$$\begin{aligned}
\mathcal{F}_\nu \quad = \quad & \pi \left(\frac{R_{\rm NS}}{D}\right)^2 \left[\int_0^1 I_\nu \mu d\mu + \int_{\cos\theta'}^1 I_\nu \mu d\mu\right] \\
+ \quad & \frac{2}{D^2}\left[\int_0^{R_{\rm NS}} I_\nu \sin\theta' \sqrt{R_{\rm NS}^2 - x^2}\, dx\right. \\
- \quad & \left.\int_0^{R_{\rm NS}\sin\theta'} I_\nu \sqrt{R_{\rm NS}^2 \sin^2\theta' - x^2}\, dx\right] \\
+ \quad & \pi \frac{\sin\theta'}{D^2}\left(\int_{R_{\rm in}}^{R_{\rm out}} I_\nu R dR + \int_{R_{\rm boost}}^{R_{\rm out}} I_\nu R dR\right),
\end{aligned} \tag{2}$$

where $R_{\rm NS}$ is the neutron star radius, D – the distance to the system, and I_ν – the specific intensity emitted from the source surface towards the observer. Several

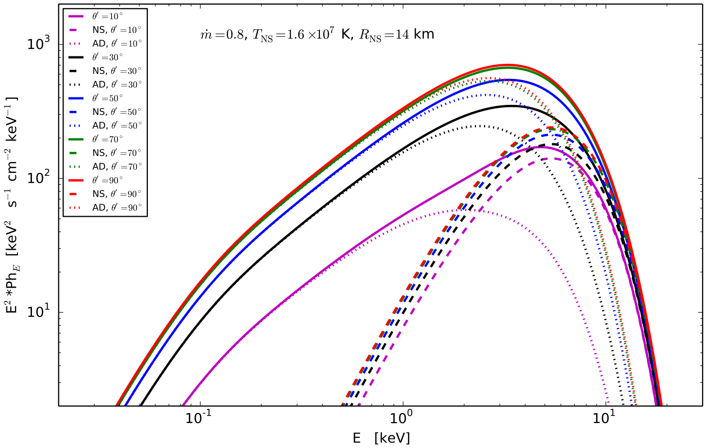

Fig. 3: The same as in Fig. 1 but for $R_{\rm NS} = 14$ km.

other variables denote respectively: $\mu = \cos\theta$, where θ is the angle between direction of the light beam and the normal to the neutron star surface, θ' is viewing angle related to the disk inclination angle as $i = 90^\circ - \theta'$ (see Fig. 3 in Różańska et al. (2017) for illustration), and x is the variable of integration over the source surface projected on the sky.

First two parts of above equation correspond to the emission from the neutron star surface taking into account the attenuation by the disk, while second two parts describe the multi-color black body disk emission with eventual attenuation by the neutron star. Due to mutual attenuation one part of the disk is integrated over radius from the innermost stable orbit $R_{\rm in}$ all the way up to the outer radius $R_{\rm out}$, while the second part of the disk – from $R_{\rm boost} = R_{\rm NS}/\sin\theta'$ up to the outer radius $R_{\rm out}$, where $R_{\rm boost}$ is the radius up to which the neutron star attenuates the inner part of an accretion disk.

We assumed, that the neutron star radiation is isotropic and equals black body intensity at the given effective temperature $I_\nu = B_\nu(T_{\rm eff,NS})$. Furthermore, we assumed that the emission at different disk radii equals to the local Planck function $I_\nu = B_\nu(T_{\rm eff}(R))$, with effective temperature given by the standard Shakura & Sunyaev (1973) formula: $\sigma T^4_{\rm eff}(R) = 3GM\dot{M}/8\pi R^3(1-(R_{\rm in}/R)^{1/2})$, where σ is the Stefan-Boltzman constant, G is the gravitational constant, M – mass of the central object and $\dot{M}$ – disk accretion rate. We note here, that our model also is useful for systems where the angle dependent specific intensity is given as the results of the radiative transfer calculations (Madej, 1991; Hubeny et al., 2001; Davis et al., 2005; Różańska et al., 2011). We plan to implement atmospheric models in the future work.

3 Results and discussion

Non-rotating neutron star in our model has the canonical mass 1.4 $M_\odot$. For the purpose of this paper we consider only one neutron star effective temperature: $T_{\rm NS} = 1.6 \times 10^7$ K, and three different radii: $R_{\rm NS} = 10, 12, 14$ km. The disk local emission

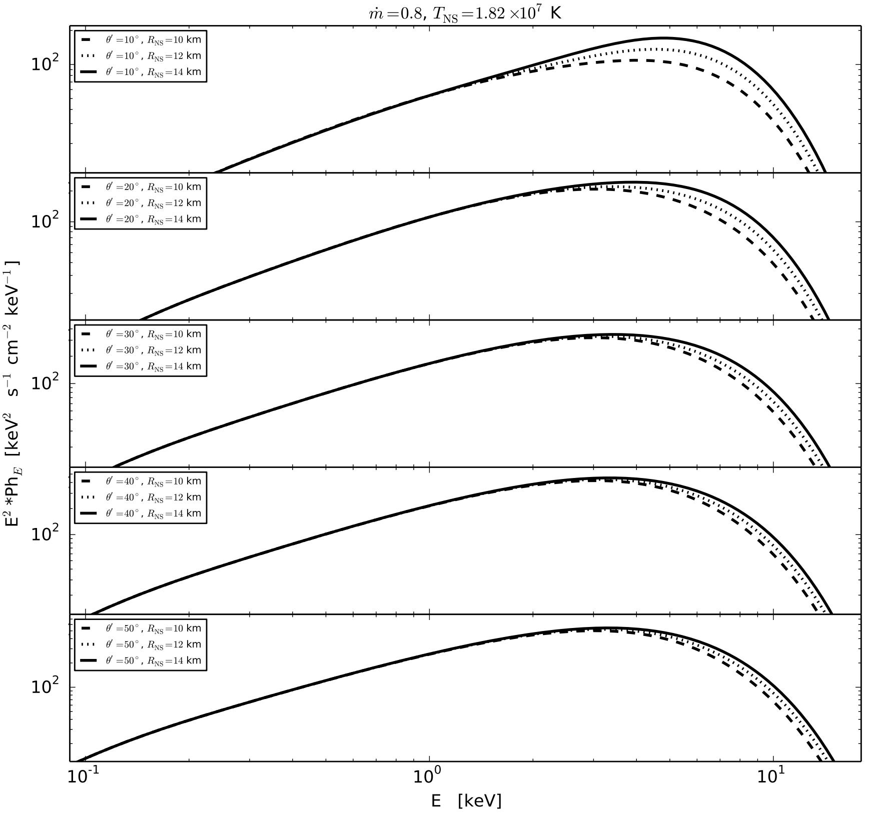

Fig. 4: The comparison of spectra from LMXB for different $R_{\rm NS}$ and viewing angles.

was computed for one accretion rate: $\dot{m} = 8 \times 10^{-1}$ in the unit of the Eddington accretion rate, with accretion efficiency equal 0.08 (Schwarzschild metric).

For the disk model, we calculated multi-black body spectrum from $R_{\rm in}$ to $R_{\rm out}$ in the range 3-1000 $R_{\rm Schw}$, where the $R_{\rm Schw} = 2GM_{\rm NS}/c^2$. The inner disk radius can change due to the: large value of magnetic field, strong boundary layer, and when the relativistic corrections are taken into account. We plan to include them in the future paper together with full ray tracing procedure. The outer disk radius depends on the secondary object, and resulting size of the Roche lobe. We have checked that for the typical mass of the secondary less than the solar mass, there is enough space for the disk of the radius up to 1000 $R_{\rm Schw}$ (Paczyński, 1971). Since the outer disk regions emit in optical band, its value does not influence our results, and we keep it constant within this paper.

The grid of θ' angles spans from 10° up to 90°. The lowest value of this angle corresponds to the almost *edge on* disk, whereas the highest value to *face on* disk. We used the lowest value of $\theta' = 10°$, since for smaller viewing angles the disk geometrical thickness is large enough to obscure neutron star completely. Furthermore, in the disk model (Shakura & Sunyaev, 1973), the disk height increases with radius, and for the disk seen *edge on* we observe only the disk rim.

Figs. 1, 2 and 3 present spectral shapes from LMXB for three different neutron star radii equal to 10, 12, 14 km, respectively. Effective temperature of the neutron star and the disk accretion rate are fixed here. When the neutron star radius increases, then emission area of the neutron star black body radiation becomes larger and the spectral broadening of the total continuum at the high energy end is larger than in case of the lowest radius. This is clearly seen from those figures while the only neutron star emission is marked by dashed line. At each figure the emission from an accretion disk only marked by dotted line has the same level for a given θ'.

Final overall continuum and its relative normalization dramatically depends on the viewing angle. For the disk seen edge on, i.e. for $\theta' = 10°$, the intensity coming from neutron star is the largest in comparison with accretion disk intensity. Note, that the value of energy for which the total emission is maximal decreases with increasing value of θ'. For the same system seen face on, spectral broadening is minimal but still is clearly seen even for the lowest neutron star radius.

Finally Fig. 4 compares the high energy spectral end from the whole system for three different neutron star radii seen at different viewing angles: from 10° up to 50°. The differences between different neutron star emitting regions are clearly seen. Our results clearly show that in case of accreting objects, before adding separate component to explain X-ray data, we should take into account the total emission from non-spherical system by integrating specific intensity over proper emitting surface. Recently, our model was succesfully fitted to X-ray data of three ULX sources (Różańska et al., 2018).

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