We present an extended set of model atmospheres and emergent spectra of X-ray bursting neutron stars in low-mass X-ray binaries. Compton scattering is taken into account. The models were computed in LTE approximation for six different chemical compositions: pure hydrogen, pure helium, and solar mix of hydrogen and helium and various heavy elements abundances: $Z = 1, 0.3, 0.1, \text{and } 0.01 Z_\odot$. For each chemical composition the models are computed for three values of gravity, $\log g = 14.0, 14.3, \text{and } 14.6$, and for 20 values of relative luminosity $l = L/L_{\text{Edd}}$ in the range 0.001–0.98. The emergent spectra of all models are fitted by the diluted blackbody in the redshifted RXTE/PCA band 3–20 keV and the corresponding values of color correction factors $f_c$ as function of $l$ are presented. We also show how to use these dependencies to estimate the basic parameters of neutron stars.
1. Method

Neutron stars (NSs) showing photospheric radius expansion X-ray bursts can be used to determine NS parameters, such as their radius $R$ and mass $M$ if the distance to the source is known (if, for example, a source is situated in the globular cluster, [1,2]). The relation between the observed normalization of the blackbody $K$ as fitted to the spectra and the ratio of $R$ to the distance during late burst phases is:

$$K^{1/2} = \frac{R_{BB}\text{(km)}}{D_{10}} = \frac{R(\text{km})}{f_c D_{10}^2} (1 + z),$$

(1.1)

where $D_{10}$ is the distance in units 10 kpc, and $f_c = T_c / T_{\text{eff}}$ is the color correction factor. Therefore, during the cooling phases of X-ray bursts the dependence $K(t)$ reflects the variations of the $f_c(t)$ only. We suggest to fit the observed $K^{-1/4} - F$ relation by the theoretical $f_c - l$ relation, where $F$ is the bolometric observed flux. From this fit we can obtain two independent values:

$$A = \left( \frac{R(\text{km}) \times (1 + z)}{D_{10}} \right) - \frac{1}{2}$$

and $F_{\text{Edd}} \propto L_{\text{Edd}} / ((1 + z) D_{10}^2)$. Combining these values we can obtain a relation between $M$ and $R$, which is independent on the distance and corresponds physically to the maximum possible observed effective temperature on a NS surface (the Eddington temperature)

$$T_{\text{eff}} \propto \left( \frac{GMc(1 + z)}{\sigma R^2 k_e} \right)^{1/4} \frac{1}{1 + z} = 6.4 \times 10^9 F_{\text{Edd}}^{1/4} A^{-1} \text{ K}.$$  

(1.2)

Here $k_e = 0.2(1 + X) \text{ cm}^2 \text{ g}^{-1}$ is the electron scattering opacity and $X$ is the hydrogen mass fraction. In order to use this method we need an extended set of theoretical $f_c(l)$ curves. The existing models [3] do not provide enough accuracy. In this paper, we present a new set of models as well as the application of the method to one of the X-ray bursters.

2. Results of atmosphere modeling

We computed model atmospheres of X-ray bursting NSs subject to the constraints of hydrostatic and radiative equilibrium assuming planar geometry in LTE approximation with Compton scattering taken into account (see details of the code in [4,5]).

We calculated an extended set of NS model atmospheres with 6 chemical compositions (pure H, pure He, and solar H/He mixture with $Z = 1, 0.3, 0.1$ and 0.01 $Z_\odot$ or [Fe/H] = 0, −0.5, −1 and −2), three surface gravities $\log g = 14.0, 14.3$ and 14.6, and twenty luminosities $L/L_{\text{Edd}}$: 0.001, 0.003, 0.01, 0.03, 0.05, 0.07, 0.1, 0.15, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.75, 0.8, 0.85, 0.9, 0.95, and 0.98. Corresponding $T_{\text{eff}}$ were calculated from $L$ using $\log g$ and the chemical composition. The model emergent spectra were fitted by diluted blackbody spectra $F_{\text{E}} = wB_{\text{E}}(f_c T_{\text{Edd}})$ using four slightly different procedures in the redshifted RXTE/PCA energy band $(3 - 20)(1 + z)$ keV. Here $w \approx f_c^{-4}$ is the dilution factor. The redshifts were calculated from $\log g$ assuming $M = 1.4 M_\odot$. Results are presented in Figs. 1 and 2. See details in [6].
Figure 1: Left panels: Emergent (unredshifted) spectra (top panel) and temperature structures (bottom panel) of the model atmospheres with four relative luminosities ($l = 0.5, 0.1, 0.01$ and $0.001$) and fixed surface gravity ($\log g = 14.0$) for solar hydrogen-helium mixture and various abundances of heavy elements: $Z/Z_\odot = 1$ (solid curves), $0.3$ (dash-dotted curves), $0.1$ (dotted curves), $0.01$ (dashed curves). In the top panel the blackbody spectra with effective temperatures are also shown by short-dashed curves. Right panels: Dependence of the color correction factors on the relative luminosity for various NS atmosphere models. Top panel: Dependences for hydrogen and solar H/He mixture with $Z = 0.3 Z_\odot$ models and different surface gravities $\log g = 14.0$ (solid curves), $14.3$ (dotted curves) and $14.6$ (dashed curves). For clarity the dependences for hydrogen models are shifted by +0.2. Bottom panel: Dependences for low gravity ($\log g = 14.0$) models with various chemical compositions: pure hydrogen (upper curve), pure helium (lowest curve), and solar H/He mixture with $Z/Z_\odot = 1$ (dashed curve), $0.3$ (dash-dotted curve), $0.1$ (dotted curve), and $0.01$ (solid curve).
Figure 2: Examples of NS atmosphere spectra computed for solar H/He mixture with $Z = 0.3 Z_\odot$ for high ($l=0.95$) and low ($l=0.001$) luminosity and low gravity ($\log g = 14.0$). The computed spectra are shown by the solid curves, the fits with the blackbody with arbitrary dilution factor $w$ are shown by the dashed curves, and the fits with $w = f^{-4}_c$ are shown by the dotted curves. The fits were performed in the 3–20 keV band.

Figure 3: Comparison of the X-ray burst data for 4U 1724–307 to the theoretical NS atmosphere models. The crosses represent the observed dependence of $K^{-1/4}$ vs. $F$ for the long burst, while diamonds represent two short bursts. The solid curves correspond to the three best-fit theoretical models for various chemical compositions.
3. Application to 4U 1724-307 and conclusion

We fitted the $K^{-1/4} - F$ relation as observed by RXTE [7] from the long burst of 4U 1724–307 on 1996 November 8 by the theoretical $f_c$--$l$ relations (see Fig. 3). We obtained limits on $R$ and $M$ for various chemical compositions and the adopted distance between 5.3 and 7.7 kpc with Gaussian tails of $1\sigma=0.6$ kpc [8] (see Fig. 4 and [9] for more details). For H-rich compositions, the obtained $M$ and $R$ correspond to a stiff equation of state in the inner NS core. The atmospheres consisting of pure He are not acceptable.

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