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X-ray bursting neutron star atmosphere models

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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, and 0.01 $Z_{\odot}$. For each chemical composition the models are computed for three values of gravity, $\log g$ =14.0, 14.3, and 14.6, and for 20 values of relative luminosity $l = L/L_{\rm Edd}$ 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 $f_{\rm c}$ as function of l are presented. We also show how to use these dependencies to estimate the basic parameters of neutron stars.

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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:

$$K^{1/2} = \frac{R_{\rm BB}(\rm km)}{D_{10}} = \frac{R(\rm km)}{f_{\rm c}^2\, D_{10}}(1+z), \tag{1.1}$$

where D_{10} is the distance in units 10 kpc, and $f_{\rm c} = T_{\rm c}/T_{\rm eff}$ is the color correction factor. Therefore, during the cooling phases of X-ray bursts the dependence $K(t)$ reflects the variations of the $f_{\rm c}(t)$ only. We suggest to fit the observed $K^{-1/4}$–F relation by the theoretical $f_{\rm c}$–l relation, where F is the bolometric observed flux. From this fit we can obtain two independent values: $A = (R(\rm km) \times (1+z)/D_{10})^{-1/2}$ and $F_{\rm Edd} \propto L_{\rm Edd}/((1+z)D_{10}^2)$. 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)

$$T_{\rm eff,\infty} = \left(\frac{GMc(1+z)}{\sigma R^2 k_{\rm e}}\right)^{1/4} \frac{1}{1+z} = 6.4 \times 10^9\, F_{\rm Edd}^{1/4}\, A^{-1}\ {\rm K}. \tag{1.2}$$

Here $k_{\rm e} = 0.2(1+X)$ cm^2 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 $f_{\rm c}(l)$ 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 $L/L_{\rm Edd}$: 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 $T_{\rm eff}$ were calculated from L using $\log g$ and the chemical composition. The model emergent spectra were fitted by diluted blackbody spectra $F_{\rm E} = wB_{\rm E}(f_{\rm c}T_{\rm Edd})$ using four slightly different procedures in the redshifted *RXTE*/PCA energy band $(3-20)(1+z)$ keV. Here $w \approx f_{\rm c}^{-4}$ 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].

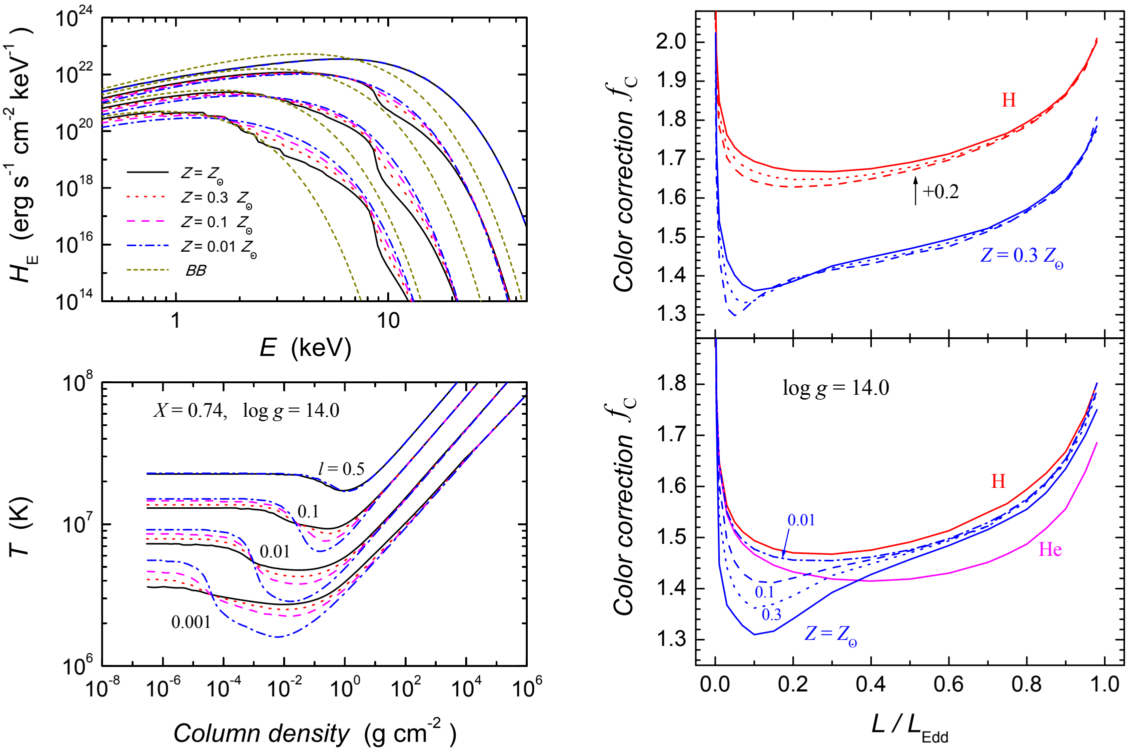

Figure 1: Left panels: Emergent (unredshifted) spectra (*top panel*) and temperature structures (*bottom panel*) of the model atmospheres with four relative luminosities (l = 0.5, 0.1, 0.01 and 0.001) and fixed surface gravity ($\log g$ = 14.0) for solar hydrogen-helium mixture and various abundances 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).

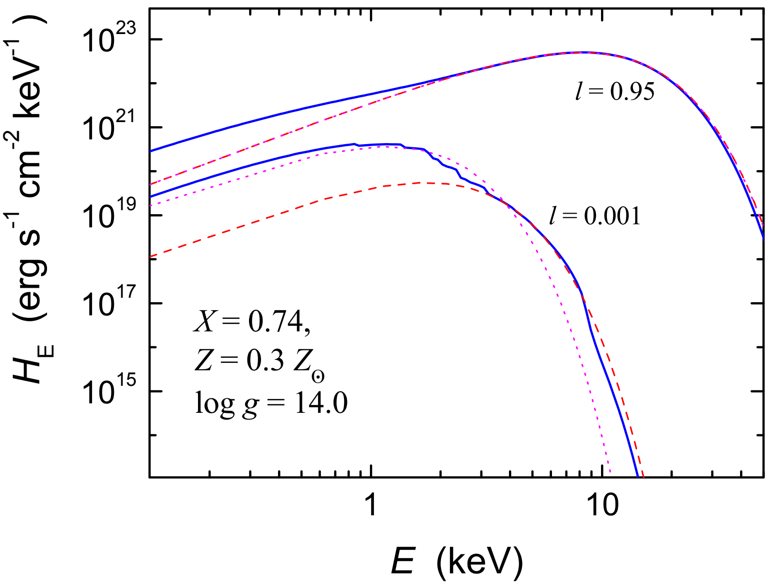

Figure 2: Examples of NS atmosphere spectra computed for solar H/He mixture with $Z = 0.3\ Z_\odot$ for high (l=0.95) and low (l=0.001) luminosity and low gravity ($\log g$ = 14.0). The computed spectra are shown by the solid curves, the fits with the blackbody with arbitrary dilution factor w are shown by the dashed curves, and the fits with $w = f_c^{-4}$ are shown by the dotted curves. The fits were performed in the 3–20 keV band.

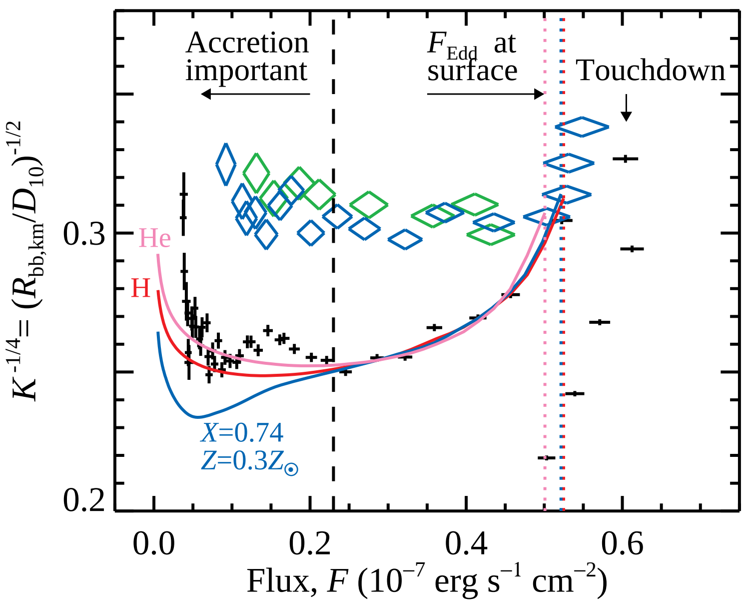

Figure 3: Comparison of the X-ray burst data for 4U 1724–307 to the theoretical NS atmosphere models. The crosses represent the observed dependence of $K^{-1/4}$ vs. F for the long burst, while diamonds represent two short bursts. The solid curves correspond to the three best-fit theoretical models for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

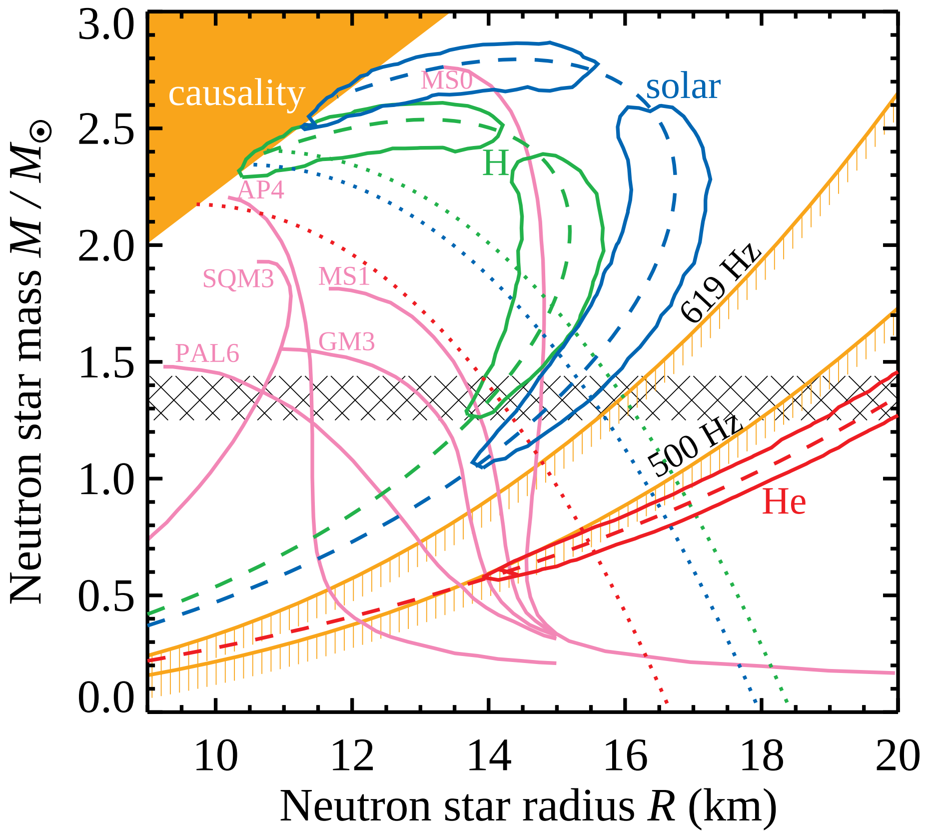

Figure 4: Constraints on mass and radius of the NS in 4U 1724–307 from the long burst spectra (fitted with the blackbody model and constant absorption). For a flat distribution of the distance between 5.3 and 7.7 kpc with Gaussian tails of 1σ=0.6 kpc, the constraints are shown by contours (90% confidence level). The countours are elongated along the fixed Eddington temperature $T_{\rm Edd,\infty}$, which is shown by the dashed curves. The countours plotted correspond to the three chemical compositions: green for pure hydrogen, blue for the solar ratio of H/He and subsolar metal abundance $Z = 0.3Z_\odot$ appropriate for Terzan 2 [8], and red for pure helium. The mass-radius relations for several equations of state of neutron and strange stars matter are shown by solid pink curves. The brown solid curves in the lower-right region correspond to the mass-shedding limit for various possible rotational frequencies.

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 1σ=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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