Model atmospheres of hot neutron star

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We present model atmospheres for very hot neutron stars (X-ray burst sources). The model equations assume both hydrostatic and radiative equilibrium, and the equation of state of an ideal gas in local thermodynamic equilibrium (LTE). The equation of radiative transfer includes terms describing Compton scattering of photons on free electrons in fully relativistic thermal motion, for photon energies approaching $m_e c^2$. Model equations take into account many bound-free and free-free energy-dependent opacities of hydrogen, helium, and the iron ions, and also a dozen bound-bound opacities for the highest ions of iron. We calculated large grid of our models, which were used to fitting the observed spectra.

1 Model atmospheres ATM24

Model atmospheres and theoretical X-ray spectra of hot neutron stars, used in this paper, were computed with the ATM 24 code (Madej, 1991; Majczyna et al., 2005). The accuracy of the code was recently proven in recent paper (Madej et al., 2017; Vincent et al., 2018). The ATM 24 code calculates the radiative transfer equation in plane-parallel geometry. It takes into account the effect of Compton scattering on free, relativistic electrons, where initial photon energies can approach the electron rest mass. We assumed the equation of state of ideal gas being in the local thermodynamical equilibrium (LTE). Nevertheless, the Compton scattering redistribution functions of X-ray photons $\Phi(\nu, \nu')$ are fully non-LTE terms of radiative transfer equation. We neglected the effects of electron degeneracy, which is unimportant in the hot atmospheres relevant our study.

The equation of transfer was adopted from Pomraning (1973) (see also, Sampson, 1959). The working equation of transfer and the temperature correction procedure were presented in Madej (1989) and Madej (1991):

$$
\begin{aligned}
\mu \frac{dI_\nu}{d\tau_\nu} = & \, I_\nu - \frac{k_\nu}{k_\nu + \sigma_\nu} B_\nu - \left(1 - \frac{k_\nu}{k_\nu + \sigma_\nu}\right) J_\nu + \\
+ & \left(1 - \frac{k_\nu}{k_\nu + \sigma_\nu}\right) J_\nu \int_0^\infty \Phi(\nu, \nu') \left(1 + \frac{c^2}{2h\nu'^3} J_{\nu'}\right) d\nu' + \\
- & \frac{k_\nu}{k_\nu + \sigma_\nu} \left(1 + \frac{c^2}{2h\nu^3} J_\nu\right) \times \\
\times & \int_0^\infty \Phi(\nu, \nu') J_{\nu'} \left(\frac{\nu}{\nu'}\right)^3 \exp\left[-\frac{h(\nu - \nu')}{\mathrm{k}T}\right] d\nu' . \qquad (1)
\end{aligned}
$$

The equation of transfer was written on the monochromatic optical depth scale $d\tau_\nu = -(k_\nu + \sigma_\nu)\,\rho\,dz$, where k_ν and σ_ν denote coefficients of absorption and electron scattering, respectively. Other variables are as usual: I_ν is the energy-dependent specific intensity, J_ν is the mean intensity of radiation, and z – geometrical depth in the considered atmosphere.

We used angle-averaged redistribution function $\Phi(\nu, \nu')$ and Compton scattering cross-section $\sigma(\nu \to \nu', \vec{n} \cdot \vec{n'})$, following the method by Guilbert (1981), which is corrected here for the computational error in the latter paper. Both variables and the method of computing were recently described in detail and proven by Madej et al. (2017). The Compton redistribution function is related to cross section as defined in the latter paper by:

$$\Phi(\nu, \nu') = \frac{1}{\sigma_\nu} \oint_{\omega'} \frac{d\omega'}{4\pi}\, \sigma(\nu \to \nu', \vec{n} \cdot \vec{n'}). \qquad (2)$$

We solved the model atmosphere assuming hydrostatic and radiative equilibrium. The influence of magnetic field and accretion on neutron star was neglected. Our code takes into account energy-dependent opacities from hydrogen, helium and heavy element ions. The ionization equilibrium is fully solved, allowing for appearance of iron lines for specific initial parameters (Majczyna et al., 2005).

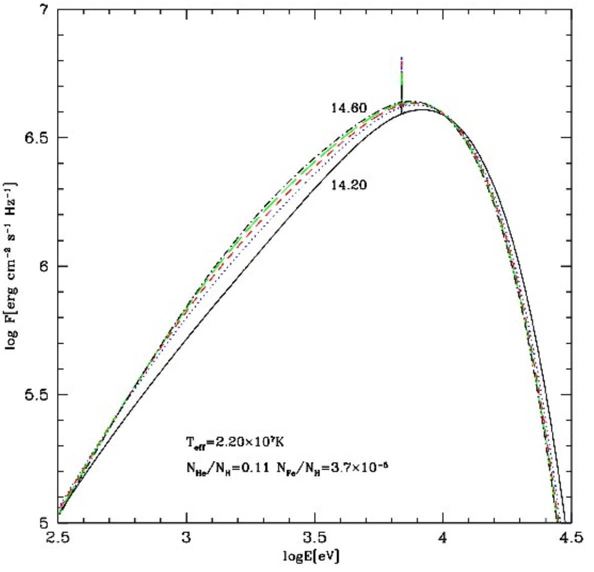

Fig. 1: Theoretical spectra of hot neutron star atmospheres with parameters: $T_{\rm eff} = 2.20 \times 10^7$ K and different surface gravities.

Fig. 1 shows example of few theoretical spectra for $T_{\rm eff} = 2.20 \times 10^7$ K, for assumed chemical composition and different surface gravities. For higher gravities spectrum become softer than these for lower gravities. Such effect is related to the fact, that in denser atmosphere true absorption is more important source of opacities than it takes place in the atmosphere of neutron star with lower surface gravity. Near the maximum, a few emission iron lines are clearly seen.

2 Our method of neutron star mass and radius determination

Our theoretical spectra of hot neutron stars could be used for the fitting of X-ray spectra observed by different instruments. The full procedure of fitting our theoretical spectra were described in Majczyna & Madej (2005) (see also, Kuśmierek et al., 2011). In these papers authors fitted theoretical spectra to those observed by PCA/RXTE instrument.

Here we present our preliminary results of our method used for the fake spectrum of WFI/ATHENA future X-ray mission. In this manner we checked capabilities of the planned satellite and also accuracy of our method. Using public calibration files given by ATHENA's team we simulated fake spectrum of hot neutron star. We assumed the following parameters: the effective temperature $T_{\rm eff} = 2.2 \times 10^7\,{\rm K}$, logarithm of surface gravity $\log(g) = 14.30$, gravitational redshift $z = 0.30$, normalization $N_{\rm ATM} = 2.5 \times 10^{-22}$ (which gives the flux $F_{2-10{\rm keV}} \sim 3.5 \times 10^{-8}\,{\rm erg\,cm^{-2}\,s^{-1}}$ at 1 keV) and chemical composition of mixture hydrogen, helium and iron. Assumed values of $\log(g)$ and z correspond to the mass $M = 1.64\,{\rm M}_\odot$ and radius $R = 11.95\,{\rm km}$. Such parameters are not related to the any existing neutron star but star with these mass and radius could be realized in nature.

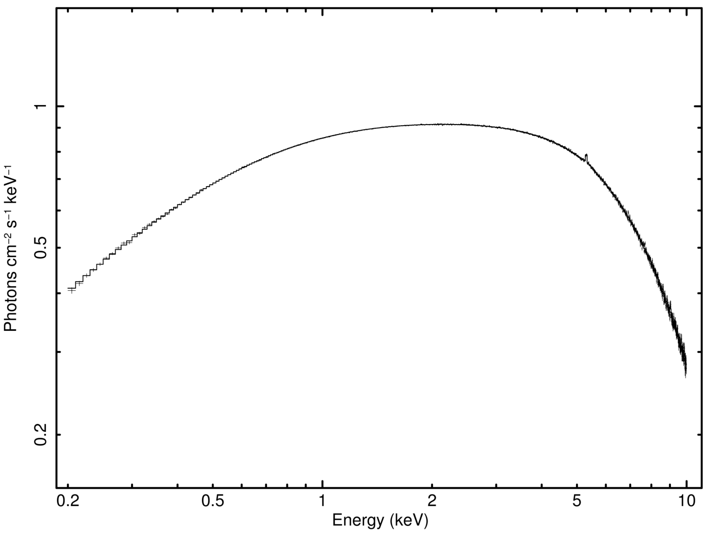

Fig. 2: Fake spectrum calculated for $T_{\rm eff} = 2.20 \times 10^7\,{\rm K}$, $\log(g) = 14.30$, $N_{\rm ATM} = 2.5 \times 10^{-22}$ and assumed chemical composition (see text for details).

By using ATM 24 code we calculated large grid of models with different effective temperatures ($T_{\rm eff} = 1.5 - 2.7 \times 10^7\,{\rm K}$ and $\Delta T_{\rm eff} = 0.02 \times 10^7\,{\rm K}$) and surface gravities (from critical up to $\log(g) = 15.0$ with $\Delta \log(g) = 0.02$) for assumed chemical composition (the same as for calculation of the fake spectrum). These theoretical spectra were fitted to the fake spectrum by using XSPEC 12.8.2 package (Arnaud, 1996). We assumed that gravitational redshift changes in the range from 0.10 up to 0.60 with the step of $\Delta z = 0.02$. For given $T_{\rm eff}$, $\log(g)$ and z we determined the normalization factor $N_{\rm ATM}$ corresponding to the minimum of χ^2. In this manner we obtained large 4-dimensional table, from which we chose the set of parameters ($T_{\rm eff}$,

$\log(g)$, z and χ^2), which correspond to the lowest value of χ^2. This best fit values we recognized as determined parameters of our hypothetical neutron star.

During our procedure we intended to reproduce assumed values during fake spectrum calculation, and indeed we obtained the best fit values of $\log(g) = 14.30$ and $z = 0.30$. We determined also 1, 2 and 3σ confidence ranges for one free parameter. In our case, all these ranges contain only one point. So, we defined errors of parameter determination as $\Delta\log(g)/2 = 0.01$ and $\Delta z/2 = 0.01$. Surface gravity and gravitational redshift with their errors allow us to calculate mass and radius. Therefore, we obtained $M = 1.64^{+0.13}_{-0.12}\,\mathrm{M}_\odot$ and $R = 11.95^{+0.64}_{-0.62}\,\mathrm{km}$.

In this paper we presented model atmospheres of hot neutron stars and our method of mass and radius determination. We calculated fake spectrum as seen by WFI/ATHENA instrument for assumed parameters of the neutron star. This fake spectrum was fitted by our large grid of theoretical spectra calculated by ATM 24 code. During this fitting procedure, we reproduced assumed parameters and estimated determination uncertainties. We determined also 1, 2 and 3σ confidence ranges. Note, that even 3σ confidence range contains only one point. It means that our grid of models should be calculated with lower values of ΔT_{eff} and $\Delta\log(g)$. The next step is to calculate a denser grid of theoretical spectra and repeat the same fitting procedure.

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