Accuracy of mass and radius determination of neutron star in X-ray bursters from simulated LOFT spectrum

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Large Area Detector (LAD) on the board of LOFT satellite, due to the large surface area, will allow us to obtain spectra of hot neutron star with very good energy resolution at 1 second integration time. Such spectra could be fitted by model spectra to obtain mass and radius determination. We present simulated spectra of type I X-ray bursters. Since these objects have very high temperatures, we could observe them in the LOFT energy band. To simulate our synthetic spectra we used the response matrix prepared by the LAD detector team. Then simulated spectrum was analysed to estimate accuracy of the determination of the neutron star parameters, mass and radius. Accurate values of both parameters allow us to constrain the equation of state of neutron star matter. Errors of mass end radius determination, which were defined here as the half of 3σ confidence contours, equal $\delta\mathrm{M} = 0.12\ \mathrm{M}_\odot$ (7%) and $\delta\mathrm{R} = 1.68$ km (14%).

1 Introduction

The existence of neutron stars was predicted by Landau (1932) and Baade & Zwicky (1934), soon after a discovery of the neutron (Chadwick, 1932). For thirty years, real neutron stars were not identified, but it was changed when Joselyn Bell (Hewish et al., 1968) discovered radio pulsars. From that time neutron stars became specific astrophysical objects. Even now, internal structure and the equation of state (EOS) of matter building up neutron star are open questions. Many theoretical models of EOS of super dense matter consisting of various types of particles were proposed – see the extensive review by Haensel et al. (2007). To verify assumptions made during EOS calculations we may use only astronomical observations. Astronomers seek for more and more massive neutron stars (Demorest et al. (2010), Antoniadis et al. (2013)), because it could eliminate those EOS which predict too low maximum mass. If we can simultaneously determine mass and radius for a given neutron star, then we could constrain or even find specific equation of state. One of the method is the continuum fitting method i.e. mass and radius determination by fitting observed spectra of hot neutron stars with theoretical models. The main and critical problem with this method is an accuracy of parameters determination. To reduce uncertainties of parameters still better observed X-ray spectra are needed, those of lower errors and better energy resolution. Detectors on board of planned LOFT satellite give us such an opportunity. Large Area Detector (LAD) should be very useful, because of its energy range (2–80 keV), energy resolution (< 260 eV at 6 keV) and time resolution of $\sim 7\mu$s.

2 Results

We simulated LOFT spectrum of a hot neutron star for some arbitrarily chosen values of the effective temperature $T_{\rm eff} = 2.2\times10^7$ K, surface gravity $\log g = 14.3$ and the surface gravitational redshift $z = 0.3$. Solar chemical composition was assumed here. These parameters (corresponding to $M = 1.64\,{\rm M}_\odot$ and $R = 11.95$ km) are not related with any existing neutron star, but such compact object could be realised in the nature. To simulate LOFT spectrum we have used publicly available response matrix (http://www.isdc.unige.ch/loft/), and we generated signal detected by LAD instrument using FAKEIT standard HEASOFT tool[1].

Next, such prepared spectrum was fitted by our grid of model atmospheres of hot neutron stars calculated with ATM radiative transfer code (Madej (1991), Majczyna et al. (2005)). We intended to determine accuracy of our determination method of neutron star parameters. We calculated 227 models for the chemical composition of assumed mass abundances X = 0.6950, Y = 0.3036 and Z = 1.425×10^{-3} (only Fe). Our grid of models was moderately dense because $\Delta\log(g) = 0.1$ and $\Delta {\rm T_{eff}} = 10^6$ K. For each combination of $\rm T_{eff}$, log(g) and z we determined only a normalization factor $\rm N_{\it ATM}$, corresponding to the minimum value of χ^2. Then, we ignored $\rm N_{\it ATM}$ and took into account only χ^2_{min} as the function of $\rm T_{eff}$, log(g) and z. Finally, we found the minimum χ^2 in 3-dimensional space of parameters. We concluded that the effective temperature, corresponding to the minimum χ^2 is not essential in further considerations. Logarithm of surface gravity and z, corresponding to the minimum χ^2, determines the best values of mass M and radius R of a neutron star.

During our fitting procedure we were able to reproduce initial values of log(g) and z. Assuming that the errors of log(g) and z are defined by the width of 3σ confidence level contour, we obtained δlog(g) ≈ 0.1 (cgs units) and δz ≈ 0.03. Furthermore, mass and radius errors are defined as:

$$\delta_R^2 = \left(\frac{\partial R}{\partial g}\right)^2 \delta_g^2 + \left(\frac{\partial R}{\partial z}\right)^2 \delta_z^2 + 2\frac{\partial R}{\partial g}\frac{\partial R}{\partial z}\delta_{gz} \tag{1}$$

$$\delta_M^2 = \left(\frac{\partial M}{\partial g}\right)^2 \delta_g^2 + \left(\frac{\partial M}{\partial z}\right)^2 \delta_z^2 + 2\frac{\partial M}{\partial g}\frac{\partial M}{\partial z}\delta_{gz} \tag{2}$$

where: σ_g and σ_z are standard deviations of g and z, respectively, and σ_{gz} is the covariance for g and z parameters.

From the above formulae we calculated mass and radius errors, obtaining

$$\delta M = 0.12\ M_\odot \quad \text{and} \quad \delta R = 1.68\ \text{km}. \tag{3}$$

3 Summary and conclusions

We fitted extensive grid (227 models) of theoretical models of hot neutron star atmospheres to the single synthetic LAD spectrum. Low theoretical observational errors of

[1] http://heasarc.gsfc.nasa.gov/ftools/

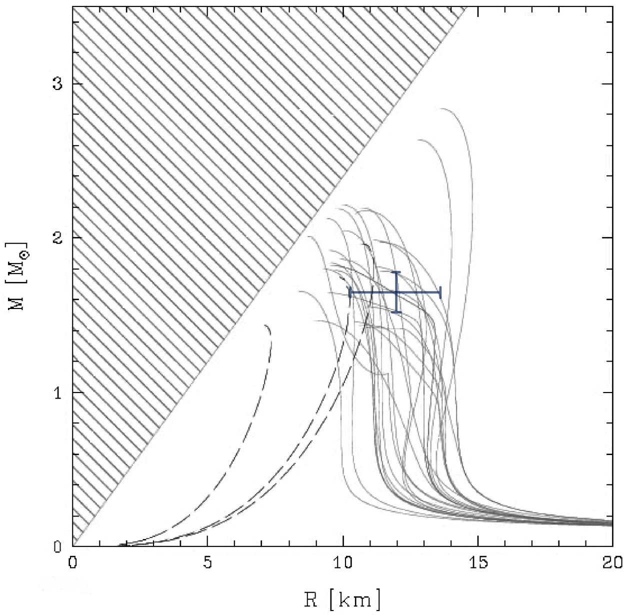

Fig. 1: Our mass and radius determination (cross) for neutron star. Solid and dashed lines are EOSs, shaded area is forbidden because of General Relativity and causality conditions (figure adopted from Bejger & Haensel 2002).

the fitting spectrum allowed us to retrieve very accurately previosly assumed values of mass and radius of the neutron star.

Errors of log(g) and z, estimated from 3σ contours are equal to $\delta\log(g) = 0.1$ and $\delta z = 0.03$. Mass and radius errors were calculated from $\delta\log(g)$ and δz: $\delta M = 0.12\ M_\odot$ and $\delta R = 1.68$ km. We expect that the above errors could be smaller, when we fit new, more numerous grid, with $\Delta\log(g) = 0.02$, $\Delta T_{\rm eff} = 2\times 10^6$ K of our numerical models. Calculations are in progress.

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