Model Atmospheres of Hot Neutron Stars

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We demonstrated here that X-ray spectral observations of the WFI detector of the *Athena* mission can constrain the equation of state of superdense matter of a neutron star. The *Athena* mission is planned to be launched in 2031. We applied here our continuum fitting method and determined mass and radius of the spherical, non-rotating neutron star. Model spectra of a hot neutron star were calculated using the atmosphere code ATM24. Next, those models were fitted to the simulated spectrum of the neutron star calculated for *Athena's* WFI detector, using the satellite calibration files. Our analysis shows the high precision of our method and demonstrates the need for a fast detector onboard of *Athena*. We calculated a large grid of theoretical spectra with various parameters, effective temperature and surface gravity and a hydrogen-helium-iron composition of solar proportion. Model spectra were fitted to the simulated spectrum of a neutron star. We obtained very precise mass and radius values with errors equal to 9% for mass and 8% for radius within the 2σ confidence error.

1 Simulated spectrum

The model atmospheres and theoretical X-ray spectra of hot neutron stars used in this paper were computed with the ATM24 code, which is the next version of ATM21 code (Madej, 1991; Majczyna et al., 2005) upgraded for its numerical precision. The working equation of transfer and the temperature correction procedure were presented originally by Madej (1989, 1991) and used correctly by Madej et al. (2017); Vincent et al. (2018).

We simulated a sample spectrum which will be detected by the WFI/*Athena* instrument. We used publicly available calibration files[1] provided by the *Athena* mission team. The effective area at 1 keV equals 1.4 m^2. We used "fake" command in XSPEC 12.6.0 fitting package (Arnaud, 1996) to simulate the observed spectrum with WFI detector. The above command uses a theoretical model and simulates data taking into account WFI/*Athena* responses and background files for the newest design of mirror with 15 rows[1]. The obtained data file is accompanied by the relevant new simulated background file. In the case of simulated spectrum and background all errors are Poissonian.

To produce simulated data, we have chosen sample model with following parameters of the neutron star atmosphere: the effective temperature $T_{\rm eff} = 2.20 \times 10^7$ K, surface gravity $\log g = 14.30$, gravitational redshift $z = 0.30$ and the normalization factor $N_{\rm ATM} = 2.50 \times 10^{-24}$. Value of $\log g$ and z correspond to particular mass $M = 1.653\ {\rm M}_\odot$ and radius $R = 11.954$ km of a neutron star.

These parameters are not related to any particular existing neutron star, but compact objects with those parameters could be realized in nature. We assumed a

[1] `http://www.mpe.mpg.de/ATHENA-WFI/response_matrices.html`

mixture of hydrogen $N_{\mathrm{He}}/N_{\mathrm{H}} = 0.11$ and iron $N_{\mathrm{Fe}}/N_{\mathrm{H}} = 3.7 \times 10^{-5}$ (number abundances). Finally, all our models were multiplied by the interstellar absorption model (TBABS in `xspec`) with assumed hydrogen column density $N_{\mathrm{H}} = 0.01 \times 10^{22}\,\mathrm{cm}^{-2}$. We set the exposure time t_{exp} equal to 1 second. Such a value of t_{exp} can be used for objects like isolated neutron stars or X-ray transients during the time when the neutron star does not accrete matter.

2 Fitting procedure

We calculated an extensive grid of theoretical spectra (almost 5000 models) with the chemical composition which was given above. In our initial grid of models, the effective temperature ranges from 10^7 K to $2.70 \times 10^7\,\mathrm{K}$ with step $\Delta T_{\mathrm{eff}} = 0.02 \times 10^7\,\mathrm{K}$, surface gravity $\log g$ from the critical gravity up to 15.0 (cgs) with $\Delta \log g = 0.02$. However, we found that the error of $\log g$ is lower than 0.02, so it was obvious that we needed a denser grid of models. Next, we have chosen smaller steps of parameters around our reference values for T_{eff} and $\log(g)$. For the effective temperatures in the range from $T_{\mathrm{eff}} = 2.18 \times 10^7\,\mathrm{K}$ to $2.22 \times 10^7\,\mathrm{K}$ steps were $\Delta T_{\mathrm{eff}} = 0.01 \times 10^7\,\mathrm{K}$, and for surface gravity ranging from $\log g = 13.9$ to 14.60 we have selected $\Delta \log g = 0.01$. All our models were converted to FITS format (Wells et al., 1981), suitable to XSPEC 12.6.0 package (Arnaud, 1996). The latter software was also used to fit our models to simulated WFI/ATHENA spectrum.

For each given combination of T_{eff} and $\log(g)$, the surface redshift z changed from 0.1 to 0.6 with steps of 0.005. Value of the model normalization factor value N_{ATM} corresponding to the best fit was determined. During the fitting procedure we assumed a fixed value of $N_{\mathrm{H}} = 0.01 \times 10^{22}\,\mathrm{cm}^{-2}$ in model of Galactic absorption (TBABS model in `xspec`). We obtained set of four parameters (T_{eff}, $\log(g)$, z and N_{ATM}) which correspond to the fit with the lowest value of χ^2. We found also 1, 2 and 3σ confidence levels in $\log(g) - z$ parameters space, requiring that $\chi^2_{\mathrm{min}} < \chi^2 < \chi^2_{\mathrm{min}} + \Delta\chi^2$, and additionally that $0.1 < M < 3\,\mathrm{M}_\odot$. The value of $\Delta\chi^2$ corresponds to the 1, 2 and 3σ confidence levels for two free parameters (Press et al., 1992).

3 Results and summary

Determination of basic parameters of neutron stars is very important for the determination of the equation of state of superdense matter. We presented a method of mass and radius determination for neutron stars. Our method is based on the fitting of theoretical spectra to the observed one. We note that our method is independent of the distance, which is proportional to the normalization of our model. The normalization factor N_{ATM} is the result of our fitting procedure. Therefore, the knowledge of the distance to the source is not necessary if we determined neutron star parameters with our method.

We fitted fake spectrum by a large grid of our theoretical spectra and we obtained best fit (2σ) parameters: $M = 1.73^{+0.14}_{-0.16}\,\mathrm{M}_\odot$ and $R = 12.52^{+0.56}_{-1.03}\,\mathrm{km}$, and corresponding 3σ confidence ranges $M = 1.53 - 1.96\,\mathrm{M}_\odot$ and $R = 11.25 - 13.38\,\mathrm{km}$.

We obtained very good precision of mass and radius measurement with an error of 9% for mass and 8% for radius within the one confidence error. All errors (2σ) are small and 3σ confidence ranges are narrow for the WFI/ATHENA detector. We showed that our method allows one to constrain the equation of state of the neutron

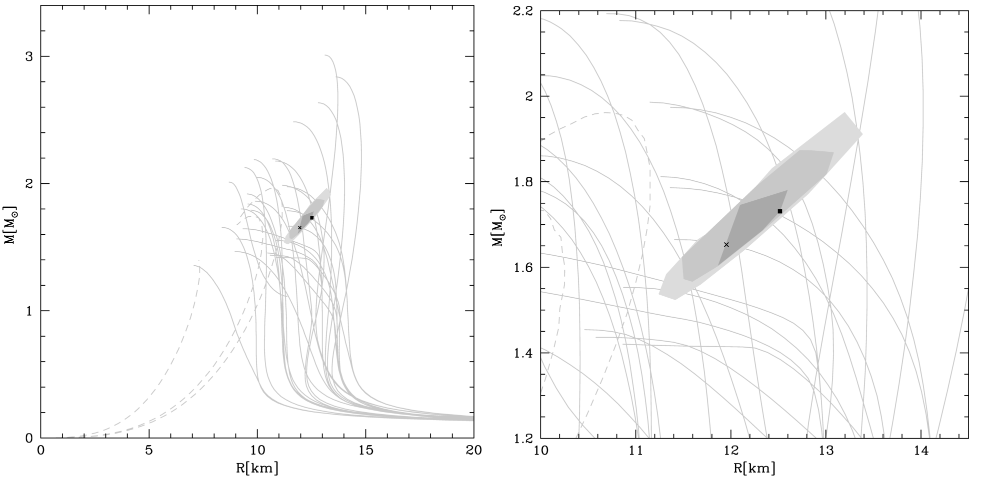

Fig. 1: 1, 2 and 3σ confidence contours for two free parameters. The right panel is the enlarged version of the left panel. Black point denotes our best-fit mass and radius values $M = 1.731\,\mathrm{M}_\odot$ and $R = 12.518\,\mathrm{km}$, whereas black cross denotes our reference values. Thin grey lines represent possible equations of state solutions (Haensel et al., 2007).

star matter with future observations using the *Athena* mission.

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