Accuracy of surface gravity and gravitational redshift determination for neutron stars in X-ray bursters from simulated LOFT spectra

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We present sample simulated spectrum of a hot neutron star, as seen by the LAD detector on board the LOFT satellite. The spectrum was computed for the effective temperature $T_{eff} = 2.2\times10^7$ K, the surface gravity log(g) = 14.3 (cgs) and the surface gravitational redshift z = 0.3. We assumed hydrogen, helium and iron composition of solar proportion. These parameters correspond to the compact star in a Type I X-ray burster. Fitting of the simulated spectrum by our extensive grid of 4200 model spectra with XSPEC 12.0.8 software we retrieved previously assumed values of all three parameters ($T_{eff} = 2.2\times10^7$ K, log(g) = 14.3 and z = 0.3) with 3σ confidence ranges of z = 0.25 - 0.36 and log(g) = 14.20 - 14.64.

Super dense matter

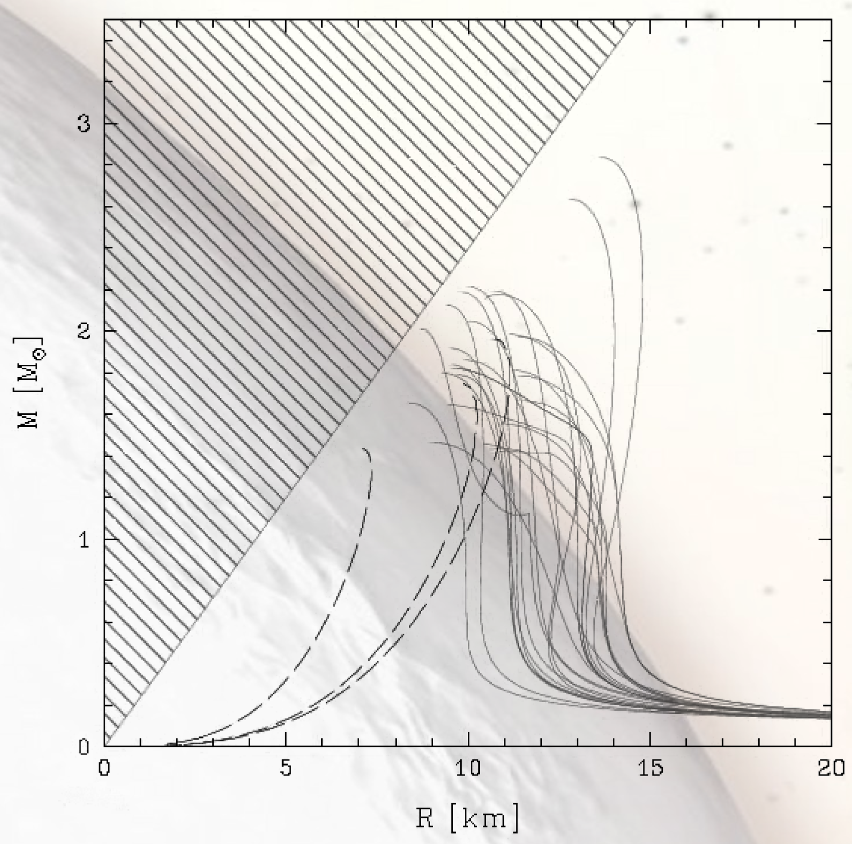


Fig. 1 Example of several equations of state taken from Bejger & Haensel (2003). Dashed lines denote EOS with quark matter in the core, whereas solid lines normal matter or normal matter plus strange matter. Shaded area is excluded by General Relativity and causality condition.

Many theoretical models of equation of state (EOS) of super dense matter were proposed, see the extensive review by Haensel et al. (2007). These models assumed both normal matter and matter in exotic states, like condensate of pion or kaon, superfluid or superconductive matter or even free quarks (dashed lines on Fig. 1 correspond to the quark matter). The only way to verify EOS's are astronomical observations of neutron stars, because in Earth laboratories we are unable to reproduce conditions similar to the neutron star interiors. Very important property of theoretical models is the existence of maximum mass of the neutron star and unique mass vs. radius relation for each assumed EOS.

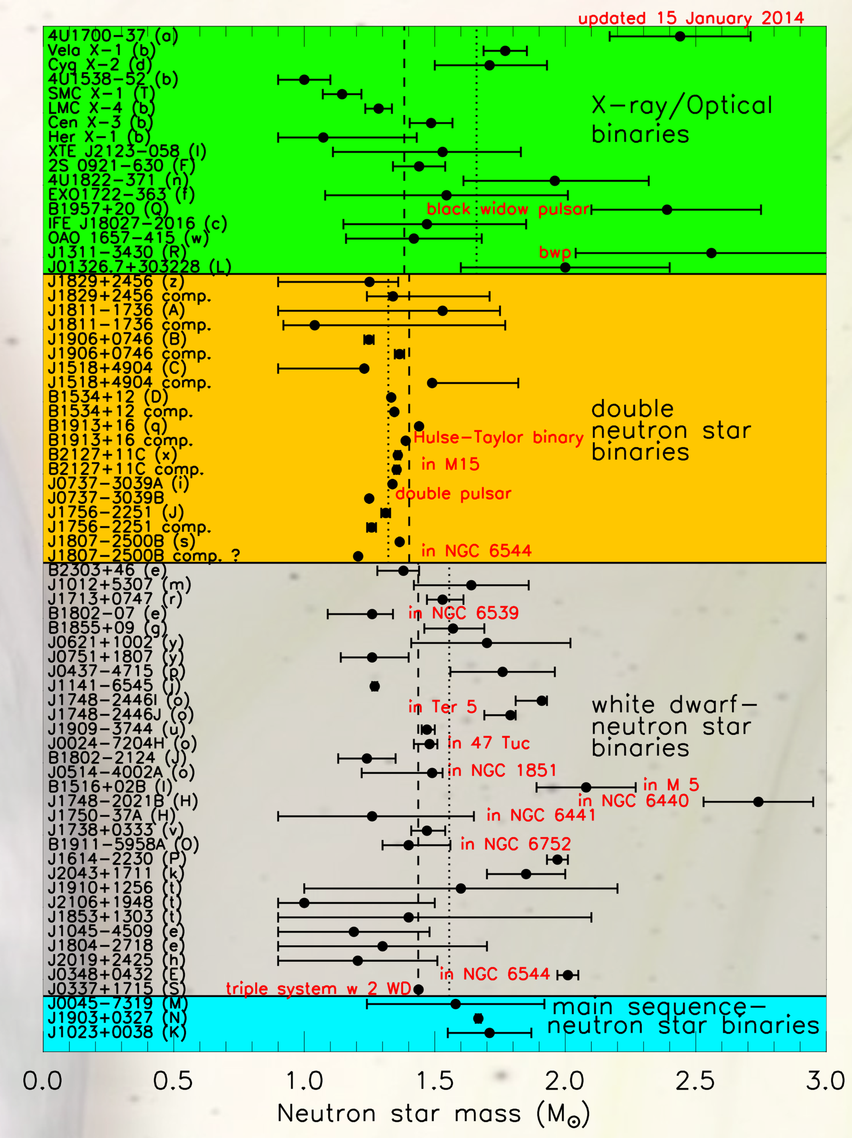


Fig. 2 Mass of neutron stars determination in a different type of objects (http://stellarcollapse.org/nsmasses) – new version of diagram, originally published in Lattimer & Parkash (2005).

<u>There are two ways to constrain the EOS</u>:

1. Astronomers seek more and more massive neutron stars. Such a discovery allows one to exclude EOS models, which predict a lower maximum mass than the measured mass. Comparison of both masses does not allow for the unique determination of the equation of state.

2. There exist methods, which allow for the simultaneous mass and radius determination, and consequently, to constrain EOS. One of these methods is modeling observed spectra by the model atmospheres. Some question is the accuracy of mass and radius determination. For this reason we need good quality observed spectra, like the LAD ones.

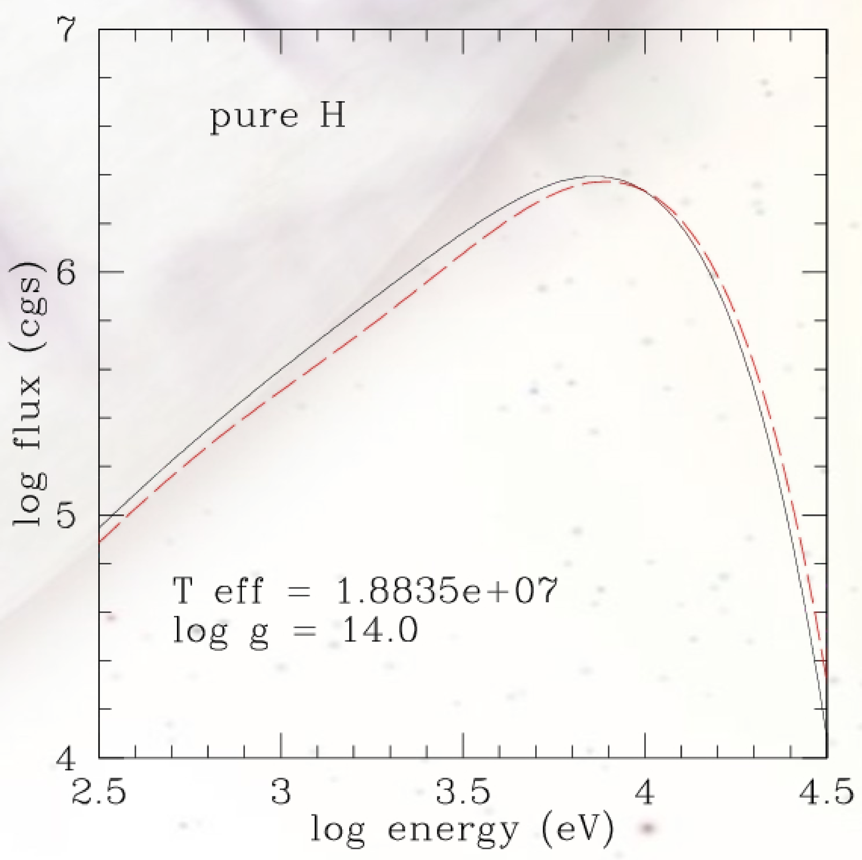
Our model atmospheres

Our grids of model atmospheres and X-ray spectra of hot neutron stars were computed with the ATM24 code, which computes model atmospheres with the account of Compton scattering on free electrons. The code assumes LTE equation of state of matter and the angle-averaged Compton scattering redistribution function of X-ray photons Φ(ν,ν'), where initial photon energies can approach the electron rest mass.

The equation of transfer was adopted from Sampson (1959), Pomraning (1973) and Madej (1991):

$$\mu\frac{dI_\nu}{d\tau_\nu}=\frac{k_\nu}{k_\nu+\sigma_\nu}(J_\nu+B_\nu)+\frac{k_\nu}{k_\nu+\sigma_\nu}J_\nu\int_0^\infty\Phi(\nu,\nu')\left(1+\frac{c^2}{2h\nu'^3}J_{\nu'}\right)d\nu' + \frac{k_\nu}{k_\nu+\sigma_\nu}\left(1+\frac{c^2}{2h\nu^3}J_\nu\right)\times\int_0^\infty\Phi(\nu,\nu')J_{\nu'}\left(\frac{\nu}{\nu'}\right)^3\exp\left[-\frac{h(\nu-\nu')}{kT}\right]d\nu'$$

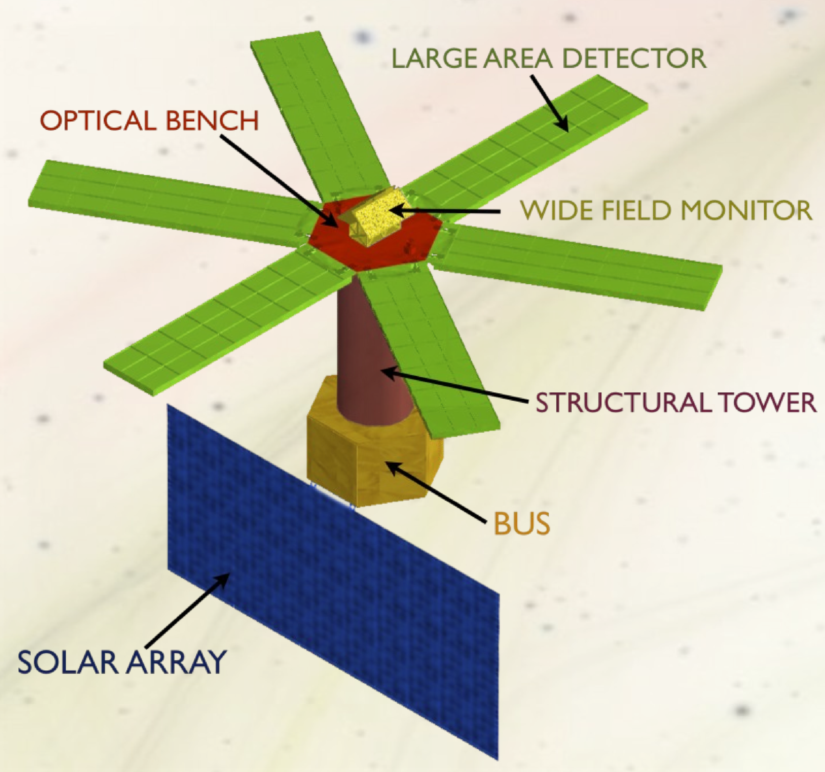
We extended computations of model atmospheres with iron lines up to ~400 iterations, when the relative temperature corrections were less than $\Delta T/T_{eff}$ = 0.0002. Our model spectra, computed with latter condition, generally fairly well agree with those in Suleimanov et al. (2012), see sample comparision of models in Fig. 3.



In the present day our grid includes about 4200 models for the single chemical composition consisting of hydrogen, helium and iron. We have chosen chemical composition of models in the present grid similar to one of compositions in Majczyna & Madej (2005). This is hydrogen-helium-iron mixture with the solar iron abundance (fe0). In our grid we assumed the effective temperatures T_{eff} ranging from 10^7 K to 3×10^7 K with step of $\Delta T = 2\times10^5$ K. Surface gravity log(g) was changed from the critical gravity $\log(g_{cr})$ up to log(g) = 15 with step of Δlog(g) = 0.02 (cgs units).

Fig. 3 Comparison of ATM24 model spectrum (black solid line) with model spectrum by Suleimanov et al. (2012) obtained from CDS Archive (red dashed line). Both spectra were computed for pure H atmosphere, very close to the Eddington limit.

LOFT satellite (Large Observatory for X-ray Timing)



Main scientific instruments:

- Wide Field Monitor (WFM):
  - energy range: 2-50 keV
  - energy resolution (@ 6 keV): < 500 eV
  - angular resolution: 5'
  - source location accuracy: 1'
- Large Area Detector (LAD):
  - energy range: 2-80 keV
  - field of view: ≤ 1°
  - energy resolution (@ 6 keV): ≤ 260 keV
  - time resolution: ~7 μs

Fitting procedure

1. We computed a fake spectrum for $T_{eff} = 2.2\times10^7$ K, log(g) = 14.3 and z = 0.3, using XSPEC 12.0.8 software.
2. We fitted synthetic spectrum by the grid of our models with parameters: T_{eff} ranging from 10^7 to 3×10^7 K with step 0.02×10^7 K, z = 0.1 – 0.6 with step 0.01, and log(g) up to 15.0 with Δlog(g) = 0.02.
3. We assumed that the mass of the neutron star is:

   $0.1\,M_\odot < M < 3\,M_\odot$.
4. Finally, we selected a set of log(g) and z, for which:

   $\chi^2_{\nu,min} < \chi^2_\nu < \chi^2_{\nu,min} + \Delta\chi^2_\nu$

   where χ^2_ν is chi square per one degree of freedom and the value of $\Delta\chi^2_\nu$ was defined as for 1, 2 and 3σ confidence levels for two free parameters.

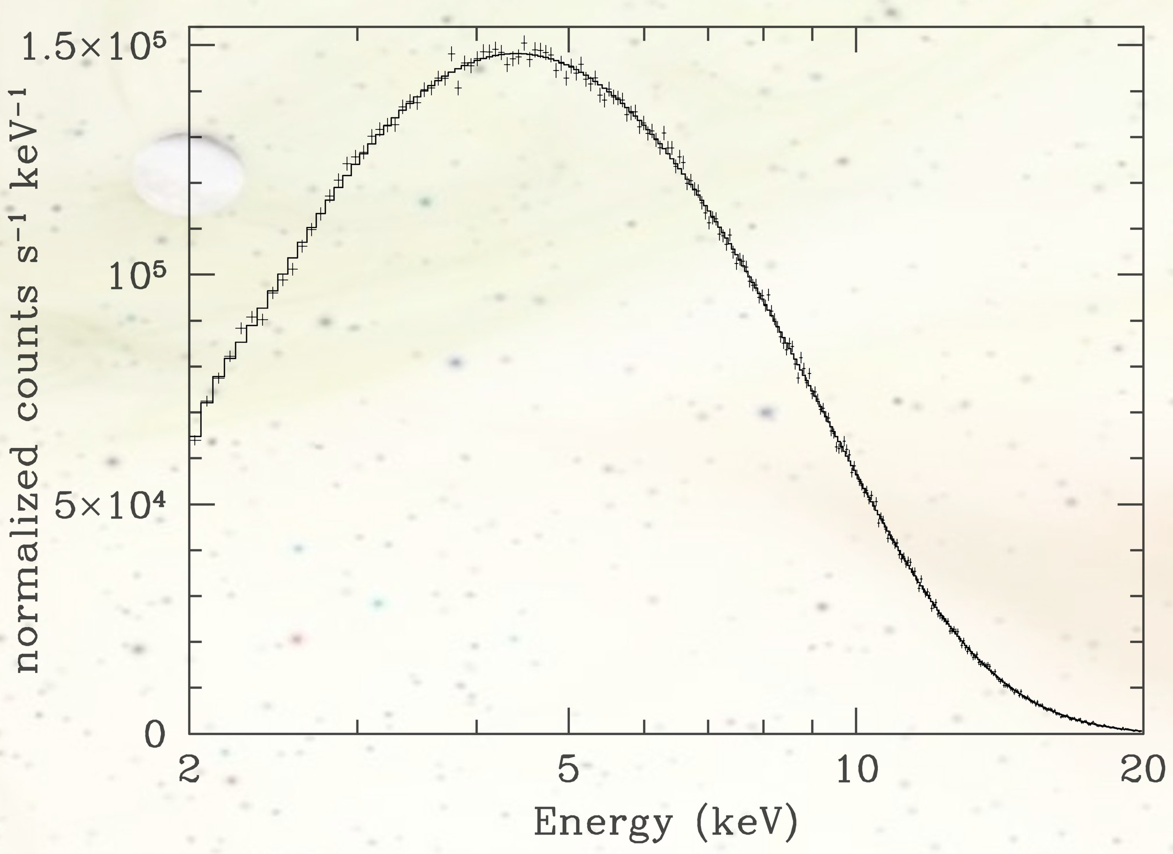
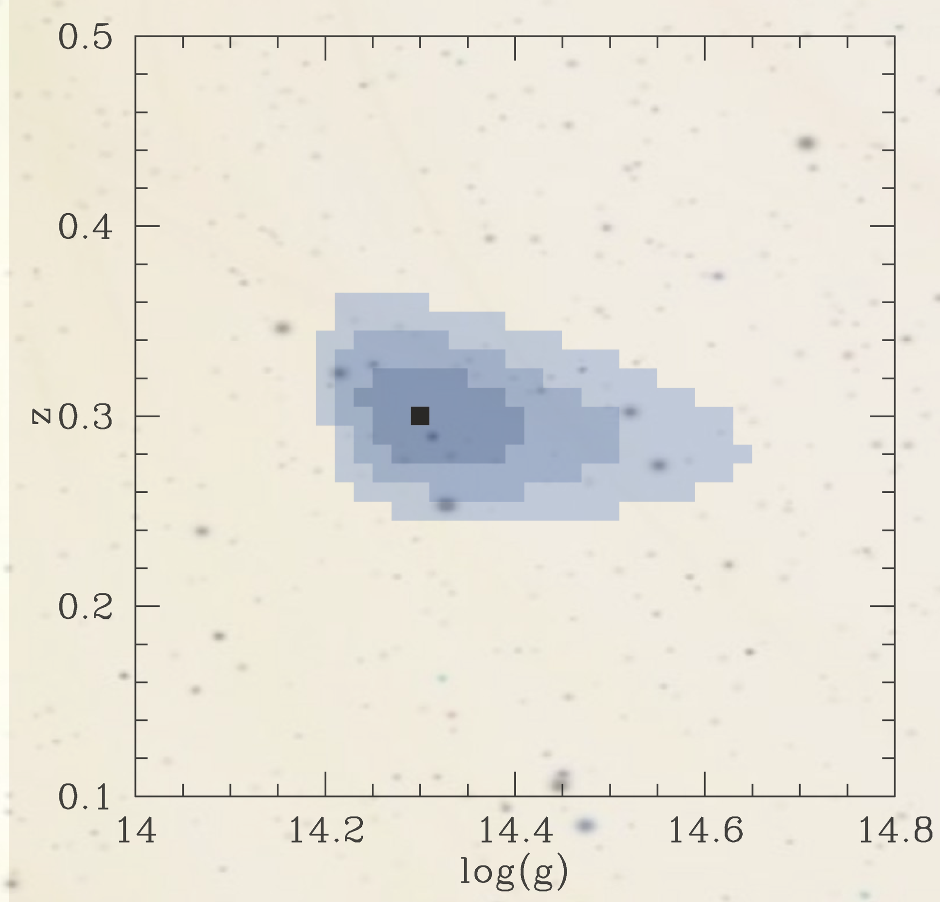


Fig. 4 Best fit of our model spectrum (solid line) to the simulated LOFT spectrum (series of crosses).



Results

Our values of log(g) and z, determined for the sample neutron star, as seen by LAD detector (1σ confidence level):

log(g) = 14.3±0.1
z = 0.30±0.02

Note, that our determinations reproduce an initial parameters of the simulated neutron star.

	log(g)	z
1σ	14.24 - 14.40	0.28 - 0.32
2σ	14.22 - 14.50	0.26 - 0.34
3σ	14.20 - 14.64	0.25 - 0.36

Fig. 5 1, 2 and 3σ confidence contours for fitting of model spectra to the simulated spectrum, as seen by the LAD detector, on board the LOFT satellite Dark square in the middle of 1σ contour shows initial parameters of the simulated neutron star.

Conclusions

We presented the simulations of log(g) and z determination from simulated X-ray spectrum of a bursting neutron star, as seen by the LOFT satellite. Our poster shows that the surface gravity and the gravitational redshift of a bright X-ray burster can be determined quite accurately. We showed that for a bursting neutron star with $T_{eff} = 2.2\times10^7$ K, log(g) = 14.3, z = 0.3 both latter parameters can be determined with the errors: δlog(g) = 0.1, δz = 0.02 (1σ error).

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