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Heavy metal neutron star atmosphere models

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1 Abstract

Context. Cooling of the neutron star (NS) atmospheres after type-I X-ray bursts from low-mass X-ray binaries can be used to study matter at supranuclear densities. By comparing the observed time-resolved spectra with the theoretical atmosphere models we can set constraints to the mass and radius of the NS.

Aims. In some energetic X-ray bursts nuclear burning ashes can be brought up into the NS photosphere (Weinberg et al. 2006). These heavy metals can have a big impact on the shape of the emerging spectrum and need to be taken into account.

Methods. To investigate the effects arising from these metals, we compute a detailed grid of hot NS atmosphere models using plane-parallel approximation in local thermodynamical equilibrium for different metal-rich chemical compositions.

Results. From the emerging model spectra we compute the colour correction factors f_c that can be compared to the observations to get information of the chemical composition and to constrain the mass and radius of the NS.

2 Method of computation

Our atmospheres are computed assuming planar geometry with hydrostatic and radiative equilibrium in local thermodynamical equilibrium.

Hydrostatic equilibrium

Firstly, from hydrostatic equilibrium we get

$$\frac{\mathrm{d}P_g}{\mathrm{d}m} = g - g_{\rm rad},$$

where P_g is gas pressure, g is the surface gravity, $g_{\rm rad}$ is the radiative acceleration and m is the column density found from $\mathrm{d}m = -\rho \mathrm{d}z$, where ρ is the gas density and z the vertical distance.

Radiative transfer

Secondly, by using the plane parallel approximation we get the radiative transfer equation for the specific intensity $I(x,\mu)$ and the source function $S(x,\mu)$ as

$$\mu \frac{\mathrm{d}I(x,\mu)}{\mathrm{d}\tau(x,\mu)} = I(x,\mu) - S(x,\mu),$$

where $\mu = \cos\theta$ is the cosine between the angles of the surface normal and the direction of propagation. The dimensionless photon energy x is given in the units of electron rest mass. Here the source function S accounts for photon emission as well as Compton scattering, which is taken into account using an exact angle-dependent relativistic Compton scattering redistribution function.

Energy balance

Our solution also needs to fulfill the energy balance

$$\int_0^\infty \int_{-1}^{+1} [\sigma(x,\mu) + k(x)][I(x,\mu) - S(x,\mu)] \mathrm{d}\mu = 0,$$

where $\sigma(x,\mu)$ is the electron scattering opacity and $k(x)$ is the "true" absorption opacity.

Ideal gas law

Finally, for the equation of state we use the ideal gas law

$$P_g = N_{\rm tot} kT,$$

where $N_{\rm tot}$ is the number density of all particles, k is the Boltzmann constant and T is the temperature. In addition equations for particle and charge conservation are needed.

The code

To solve these equations we have used our own version of the atmosphere modeling code ATLAS (Kurucz 1970, 1993) that is modified to deal with high temperatures (Suleimanov & Poutanen 2006; Suleimanov & Werner 2007) and to take exact relativistic Compton scattering into account (Suleimanov et al. 2012).

3 Atmosphere structure and emerging spectrum

We have computed a set of models for various relative luminosities $l = L/L_{\rm Edd}$ up to the Eddington limit where $g_{\rm rad}/g = 1$ (see Fig. 1 and 2). As a fiducial composition we use pure iron. Other compositions considered are solar ratios of hydrogen and helium where the number fraction of metals is enhanced by a factor of 10 or 100.

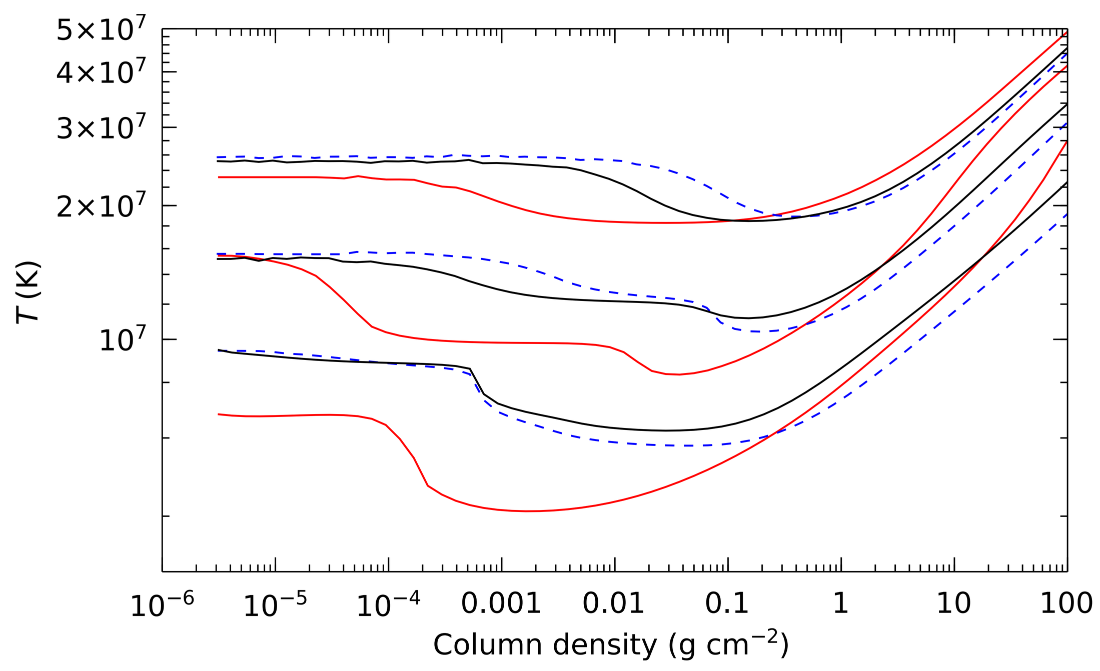

Figure 1: Temperature profiles of pure iron (red) and solar-like mixtures of H and He with $10\times$ (blue, dashed) and $100\times$ (black) the solar metallicity for $l = 0.01$, 0.1 and 0.5.

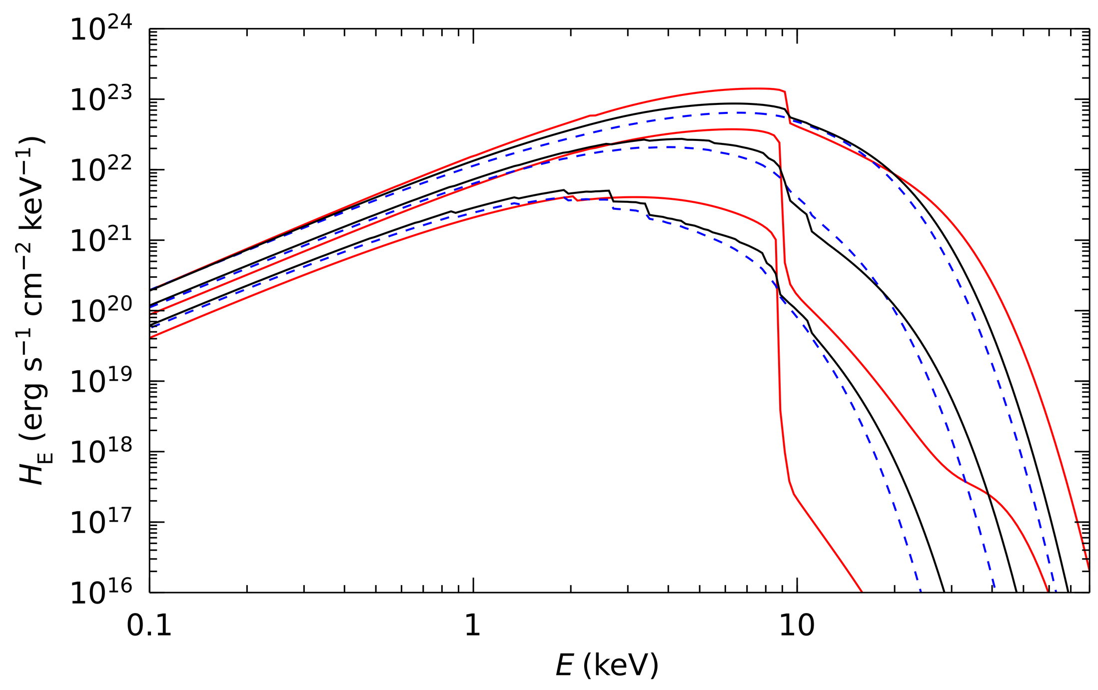

Figure 2: Emerging spectra from the hot NS atmospheres. Luminosities and compositions are the same as in Fig. 1.

4 Colour correction factors

Emerging spectra are well described by a diluted black body

$$F_E = \frac{1}{f_c^4} B_E(f_c T_{\rm eff}),$$

where f_c is the colour correction factor. Using the cooling tail method (see e.g. Suleimanov et al. (2012) for full description) the evolution of this factor (see Fig. 3) can be compared to the observations to obtain the mass and radius of the NS from the cooling of the atmosphere durning X-ray bursts.

This method is based on the fact that the observed spectra can also be fitted by the black body

$$\mathcal{F}_E = K \times B_E(T_{\rm bb}),$$

so we have a relation $K^{-1/4} \propto f_c$ between the normalization K of the black body and the colour correction factor f_c.

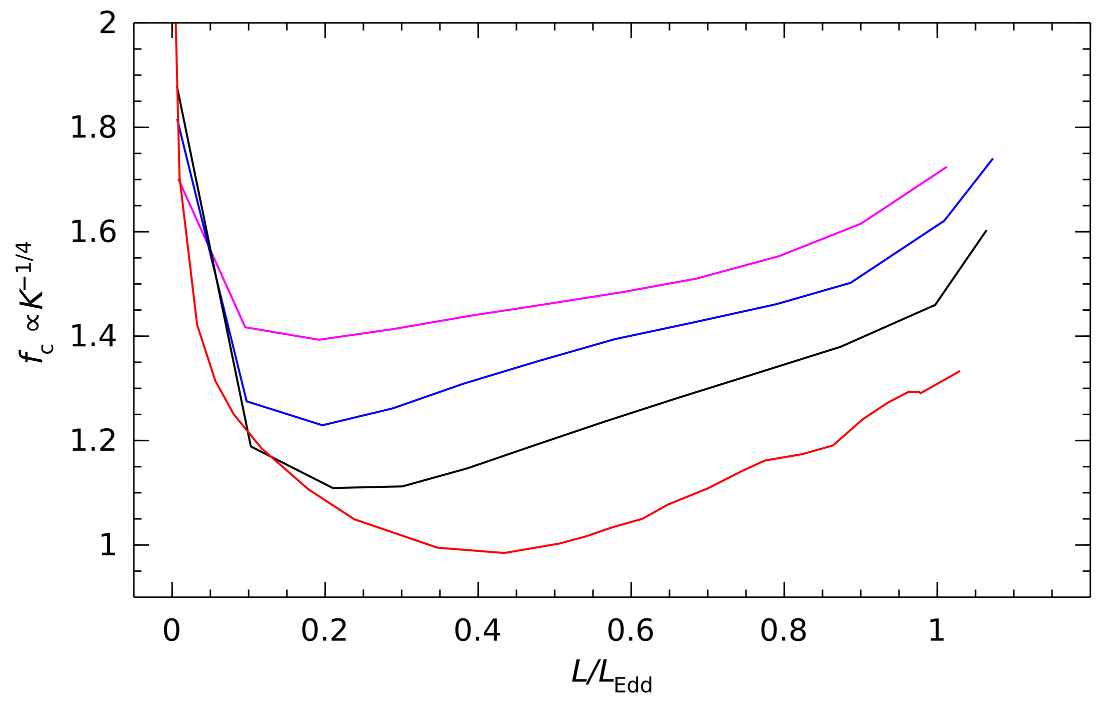

Figure 3: Evolution of the colour correction factor f_c for pure iron (red) and solar-like mixtures of H and He with $1\times$ (magenta), $10\times$ (blue) and $100\times$ (black) the solar metallicity.

5 Applications to observations

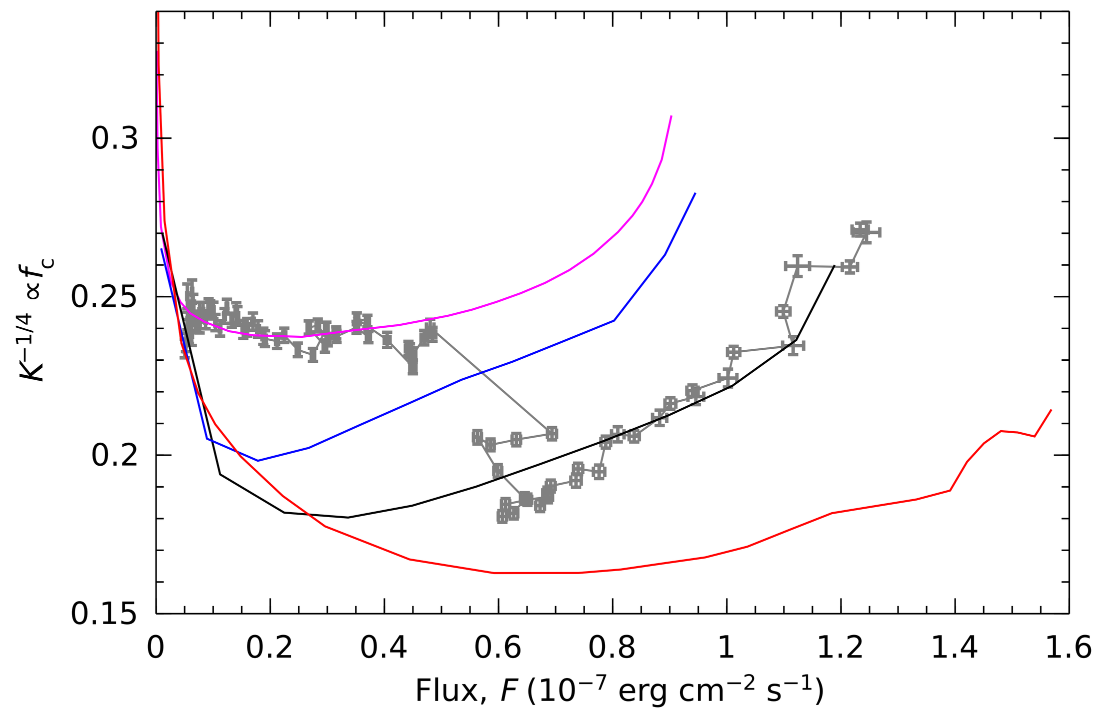

Figure 4: Evidence of changing composition from $100\times$ to $1\times$ of the solar metallicity durning a burst from HETEJ 1900.1—2455. Here the relation between the normalization K from the observations (gray crosses) and colour correction f_c from the models is used (colours are the same as in Fig. 3). Notice that the Eddington limit varies between compositions because it is related to the hydrogen mass fraction that changes from model to model.

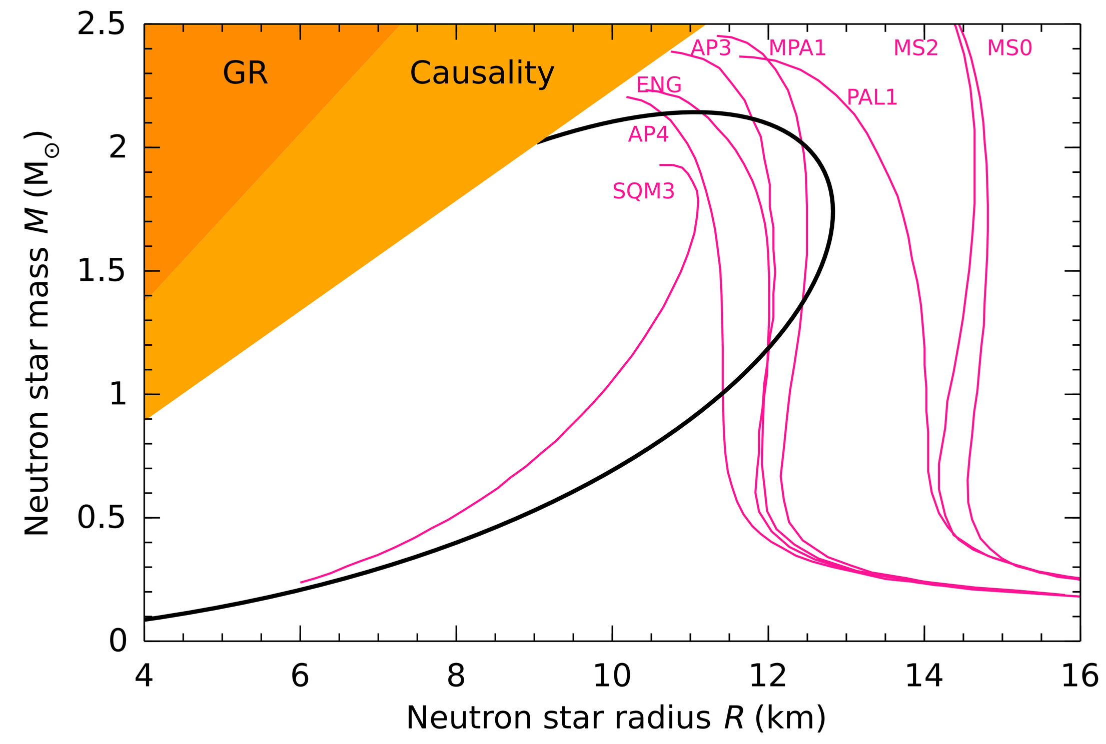

Figure 5: Mass and radius constraints for HETEJ 1900.1—2455 (using the cooling tail method) from the data presented in Fig. 4. The NS mass-radius relations for several equations of state of cold dense matter are shown by pink curves (Lattimer & Prakash 2007). Regime on the upper left corner is forbidden by the general relativity (GR) and causality conditions (Haensel et al. 2007).

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