Importance of Compton scattering for radiation spectra of isolated neutron stars

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Abstract Model atmospheres of isolated neutron stars with low magnetic field are calculated with Compton scattering taking into account. Radiation spectra computed with Compton scattering are softer than computed with Thomson scattering at high energies (E> 5 keV) for hot ($T_{\rm eff} > 1$ MK) atmospheres with hydrogen-helium composition. Compton scattering is more significant in models with low surface gravity. This fact resembles a new tool for the measurement of neutron star compactness. Compton scattering is less important in models with solar abundance of heavy elements.

1 Introduction

At present time the model atmospheres of neutron stars (NS) with various chemical composition are widely used for interpretation of isolated NS spectra (see review Pavlov, Zavlin and Sanwal (2002)). Such model atmospheres have been calculated by many authors for magnetized NSs as well as for nonmagnetic ones (see review Zavlin and Pavlov (2002) for details).

Spectra of light elements (H and He) model atmospheres without magnetic field show strong deviations from corresponding blackbody spectra due to strong dependency of the true opacity on photon energy and significant contribution of electron scattering to the opacity. Therefore, the Compton effect can change the emergent spectra most hot ($T_{\rm eff}$ > 1 MK) H and He NS atmospheres. In the previous works this effect is not taken into account and here we present a set of models with various chemical compositions which were calculated with the Compton effect taking into consideration.

2 The method of modelling

We computed model atmospheres of hot NSs subject to the constraints of hydrostatic and radiative equilibrium assuming planar geometry using standard methods (Mihalas 1978).

The model atmosphere structure for a hot NS with effective temperature $T_{\rm eff}$ and surface gravity g is described by the hydrostatic equilibrium equation,

$$\frac{dP_{\rm g}}{dm} = g - 4\pi \int_0^\infty H_\nu \frac{k_\nu + \sigma_{\rm e}}{c}\, d\nu, \qquad (1)$$

where k_ν is opacity per unit mass due to free-free, bound-free and bound-bound transitions, $\sigma_{\rm e}$ is the electron scattering opacity, H_ν is the Eddington flux, $P_{\rm g}$ is the gas pressure, and m is column mass.

Compton scattering is taken into account in the radiation transfer equation using the Kompaneets operator (Kompaneets 1957):

$$\frac{\partial^2 f_\nu J_\nu}{\partial \tau_\nu^2} = \frac{k_\nu}{k_\nu + \sigma_{\rm e}}(J_\nu - B_\nu) - \frac{\sigma_{\rm e}}{k_\nu + \sigma_{\rm e}} \frac{kT}{m_{\rm e}c^2} \times \\ x\frac{\partial}{\partial x}\left(x\frac{\partial J_\nu}{\partial x} - 3J_\nu + \frac{T_{\rm eff}}{T} x J_\nu \left(1 + \frac{CJ_\nu}{x^3}\right)\right), \qquad (2)$$

where $x = h\nu/kT_{\rm eff}$ is the dimensionless frequency, $f_\nu(\tau_\nu) \approx 1/3$ is the variable Eddington factor, J_ν is the mean intensity of radiation, B_ν is the blackbody (Planck) intensity, T is the local electron temperature, and $C = c^2h^2 \,/\, 2(kT_{\rm eff})^3$. The optical depth τ_ν is defined as $d\tau_\nu = (k_\nu + \sigma_{\rm e})\, dm$. These equations have to be completed by the energy balance equation

$$\int_0^\infty k_\nu (J_\nu - B_\nu)\, d\nu - \sigma_{\rm e} \frac{kT}{m_{\rm e}c^2} \times \\ \left(4\int_0^\infty J_\nu\, d\nu - \frac{T_{\rm eff}}{T}\int_0^\infty x J_\nu \Big(1 + \frac{CJ_\nu}{x^3}\Big)\, d\nu\right) = 0, \qquad (3)$$

the ideal gas law, and also by the particle and charge conservation equations. We assume local thermodynamical equilibrium (LTE) in our calculations, so the number densities of all ionisation and excitation states of all elements have been calculated using Boltzmann and Saha equations. We take into account the pressure effects on the atomic populations using the occupation probability formalism (Hummer & Mihalas 1988).

For solving the above equations and computing the model atmosphere we used a version of the computer code ATLAS (Kurucz 1993), modified to deal with high temperatures; see Ibragimov et al. (2003). This code was also modified to account for Compton scattering; see Suleimanov & Poutanen (2006) for further details.

3 Results

We calculated the set of pure H, He and solar abundance NS model atmospheres with $T_{\rm eff}$ = 1, 3 and 5 MK, and $log\ g$ = 14.3 and 13.9. Results are presented in Figs. 1-4.

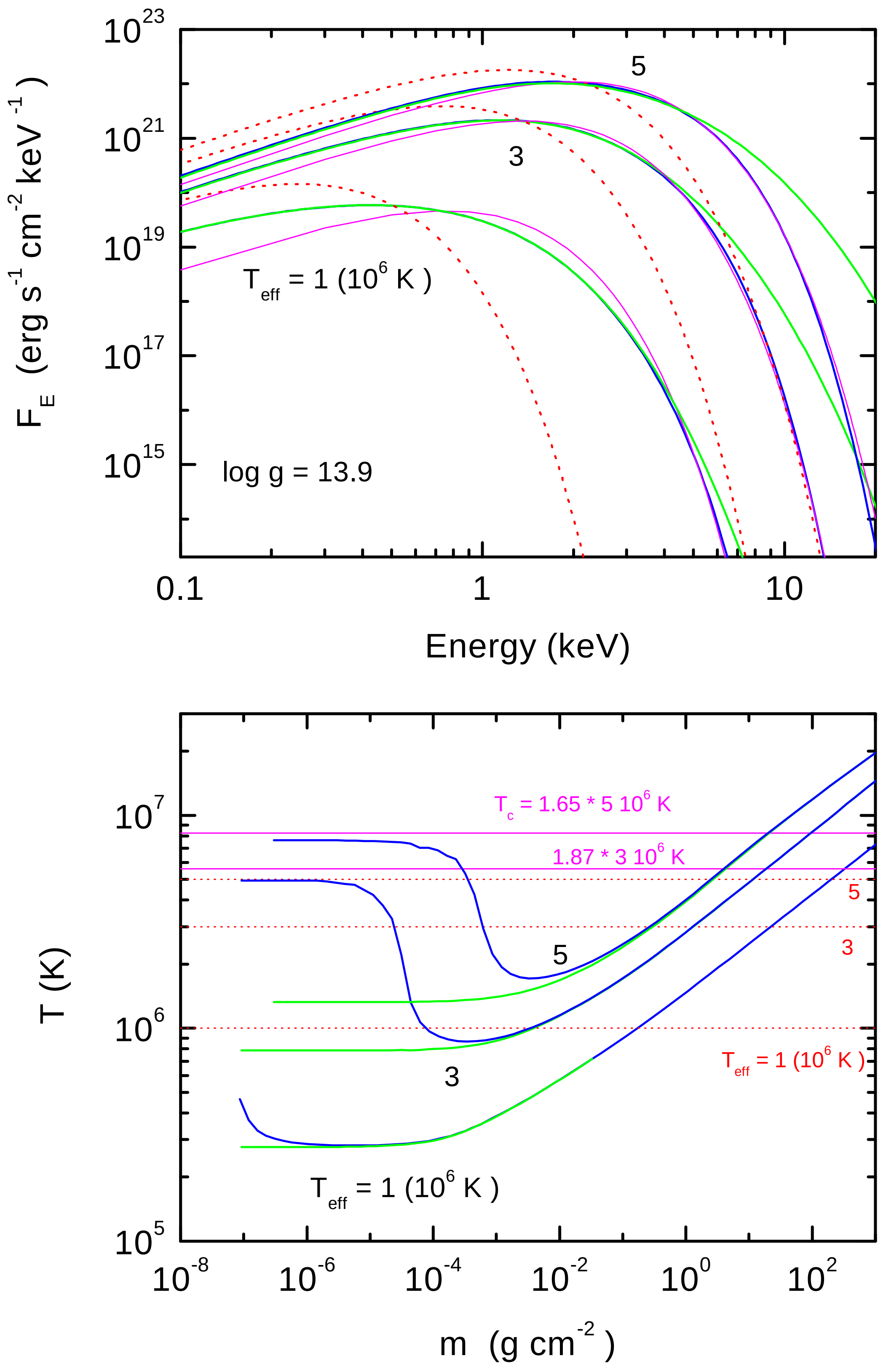

Figure 1: *Top panel:* Emergent (unredshifted) spectra of pure H low gravity NS model atmospheres. Blue lines - with Compton effect, green lines - without Compton effect, red dotted lines - blackbody spectra, magenta - diluted blackbody spectra with hardness factors 3.1, 1.87 and 1.65 for models with $T_{\rm eff}$= 1, 3 and 5 MK. *Bottom panel:* Temperature structures of the corresponding model atmospheres. Effective and color temperatures are shown by red and magenta lines.

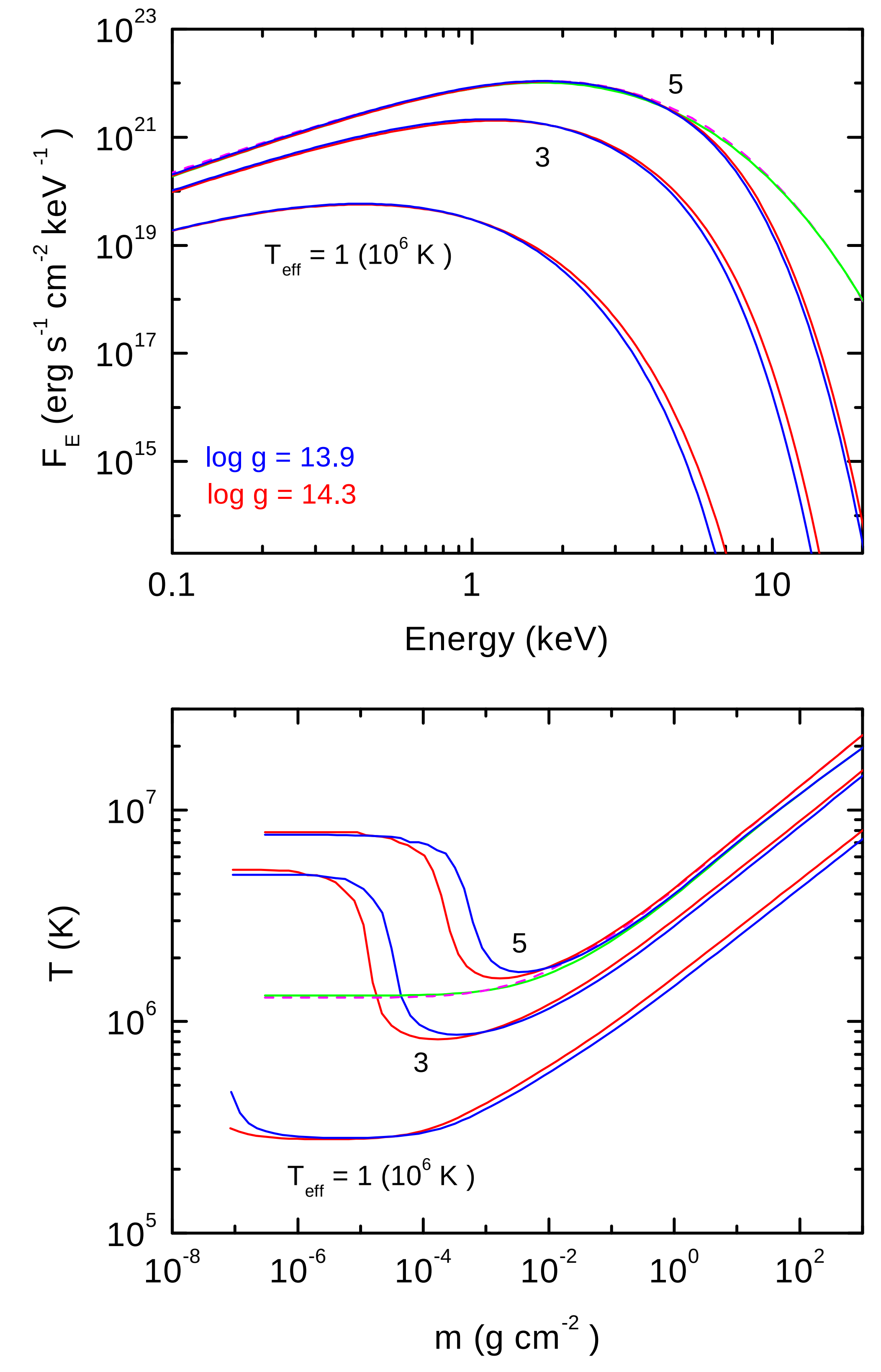

Figure 2: *Top panel:* Emergent (unredshifted) spectra of pure H NS model atmospheres with different surface gravities. For comparison the model spectra without Compton effect are shown for hottest model (green line - low gravity model, magenta dashed line - high gravity model). *Bottom panel:* Temperature structures of the corresponding model atmospheres.

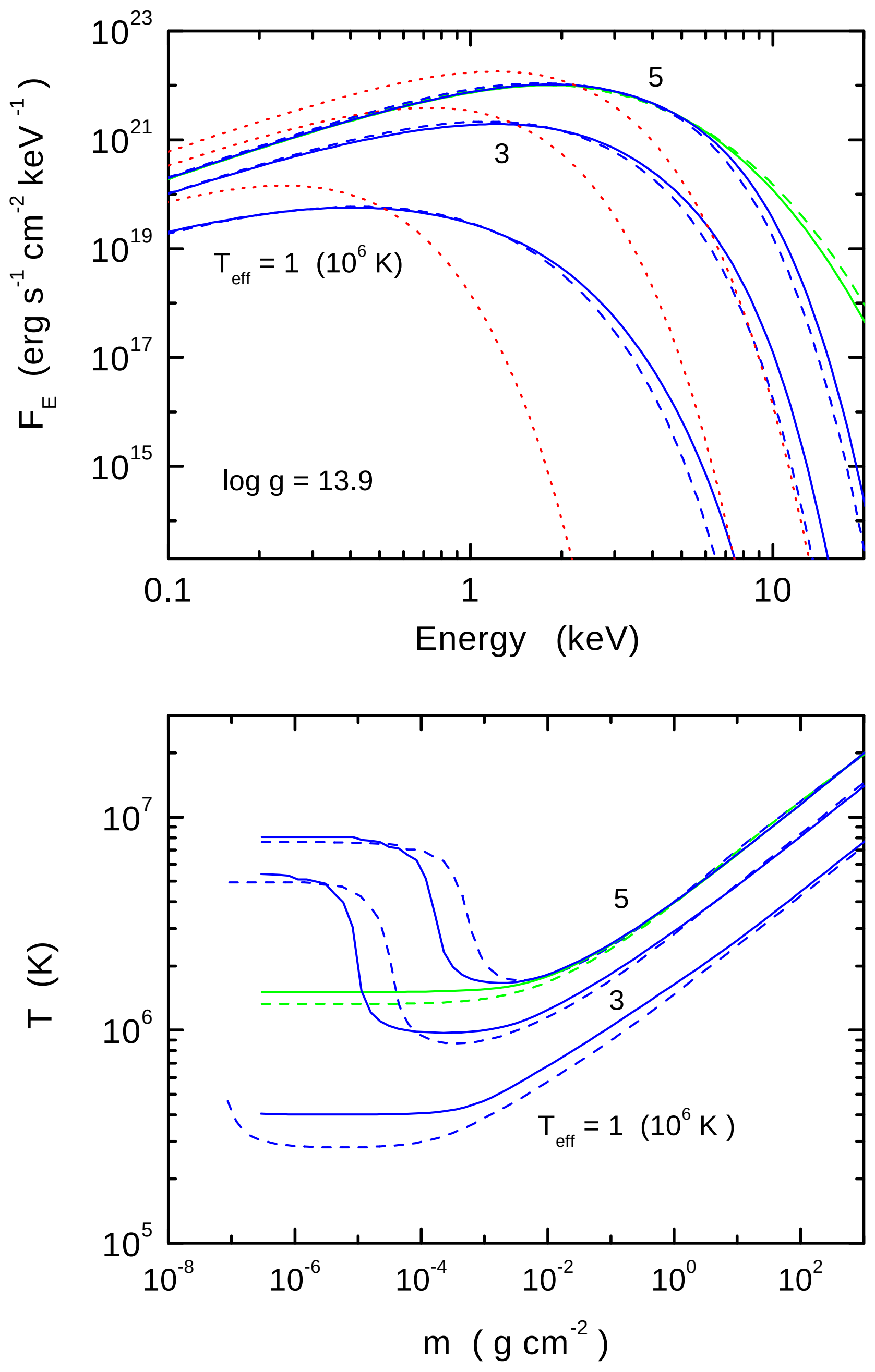

Figure 3: *Top panel:* Emergent (unredshifted) spectra of pure He low gravity NS model atmospheres. For comparison the model spectra of pure H atmospheres are shown by dashed lines. The model spectra of hottest atmospheres without Compton effect are shown by green lines. *Bottom panel:* Temperature structures of the corresponding model atmospheres.

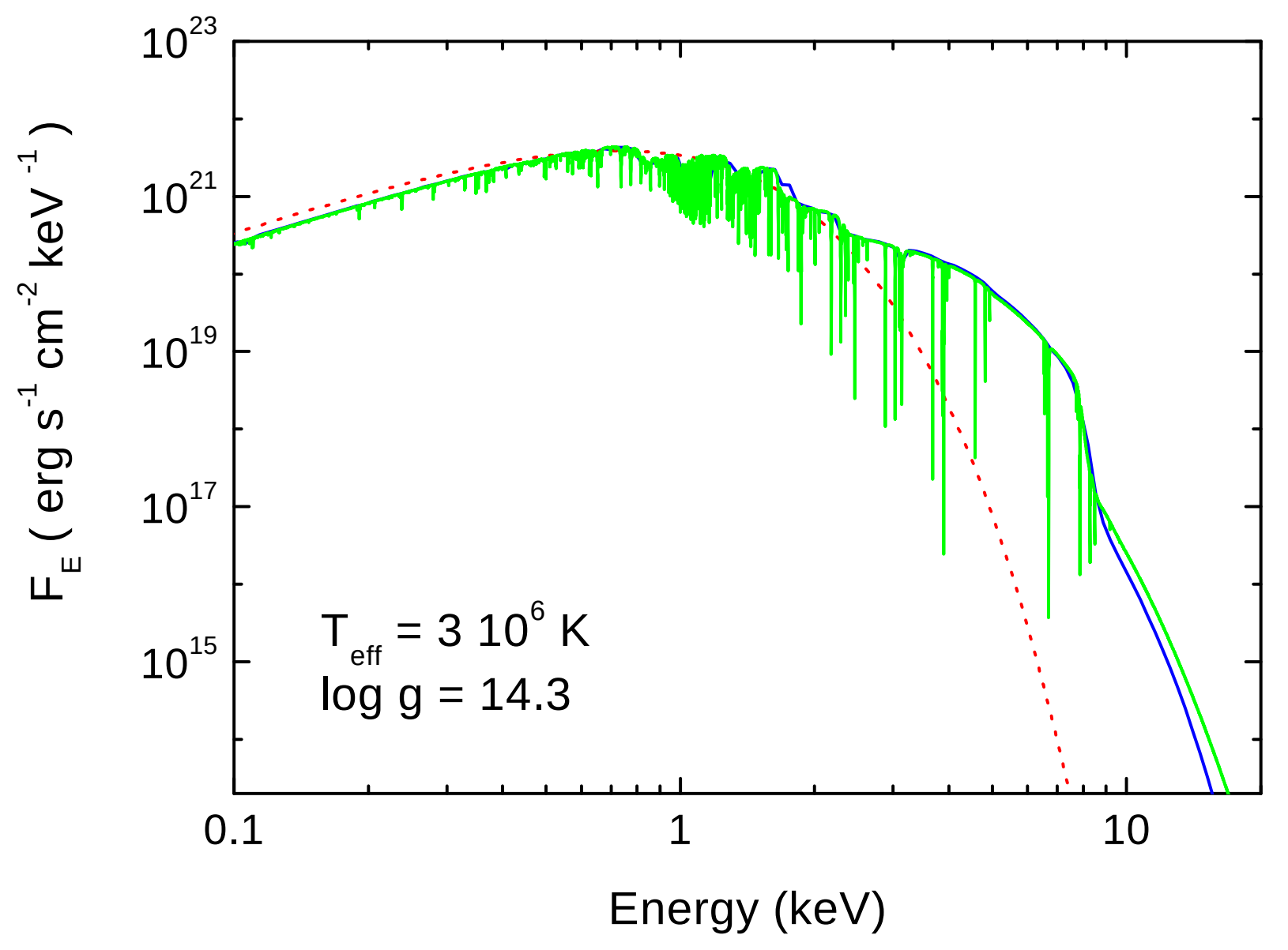

Figure 4: Emergent (unredshifted) model spectra of high gravity NS atmospheres with solar abundance of 15 most abundant heavy elements with (blue line) and without (green line) Compton scattering.

4 Conclusions

Emergent spectra of light elements NS model atmospheres with $T_{\rm eff} > 1$ MK are changed by the Compton effect and spectra of hottest model atmospheres can be described by diluted blackbody spectra with hardness factors $\sim$ 1.6 - 1.9. The Compton effect is less significant in He model atmospheres and high gravity model atmospheres, but differences in the emergent spectra for models with different gravities are reduced by different gravitational redshifts. Emergent model spectra of NS atmospheres with solar abundance are changed by Compton effect only very slightly.

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