Importance of Compton scattering for radiation spectra of isolated neutron stars

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Neutron Stars and Pulsars: About 40 years after the discovery

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Outline

- Model atmospheres of neutron stars
- Importance of Compton scattering for hot atmospheres of neutron stars
- Method of modeling
- Results
- Conclusions

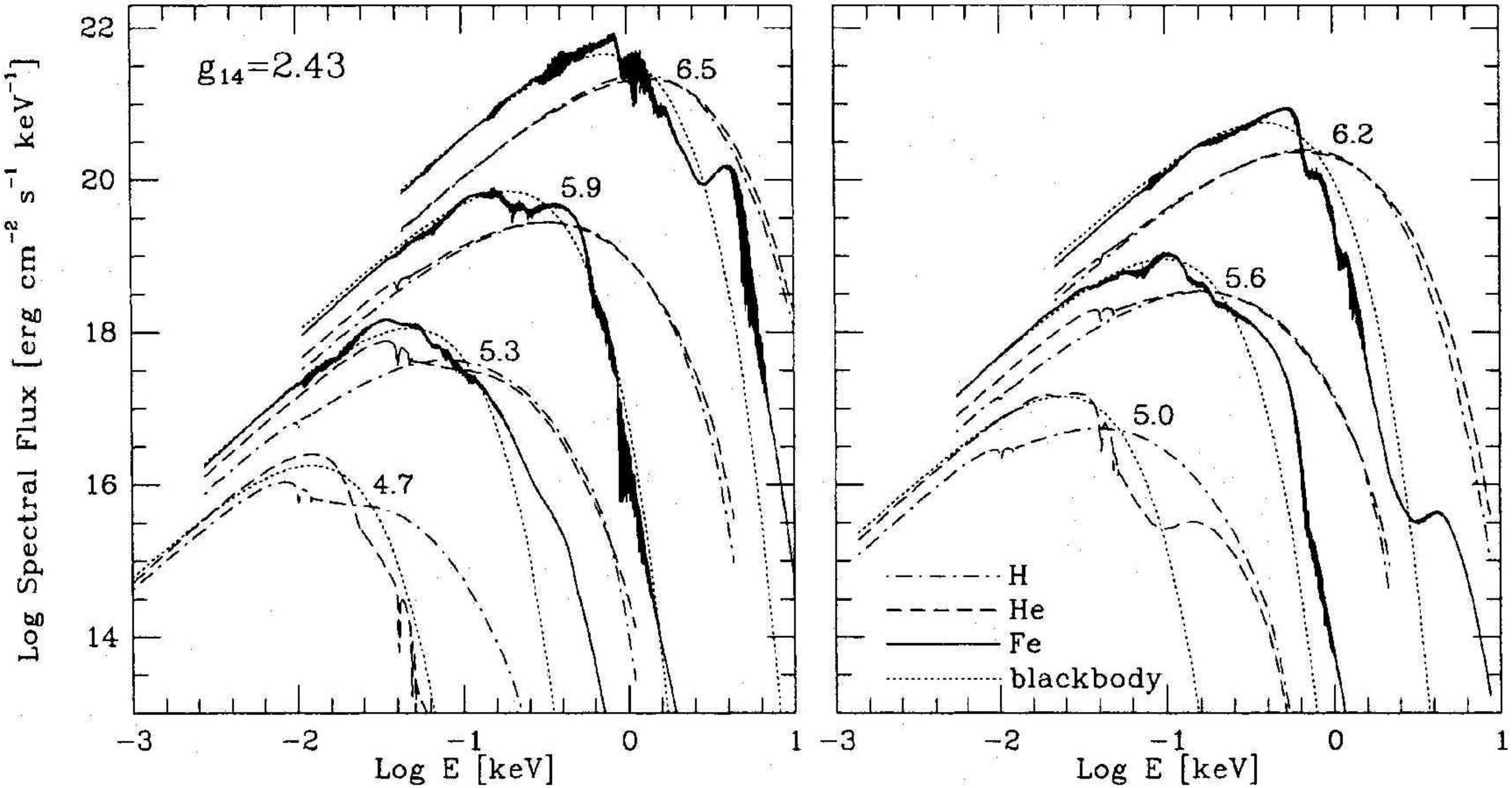


Fig. 5. Spectral fluxes of emergent radiation for hydrogen, helium and iron atmospheres with different values of $\log T_{\rm eff}$ (numbers near the curves). Dotted curves show the corresponding blackbody fluxes $\pi B_\nu(T_{\rm eff})$.

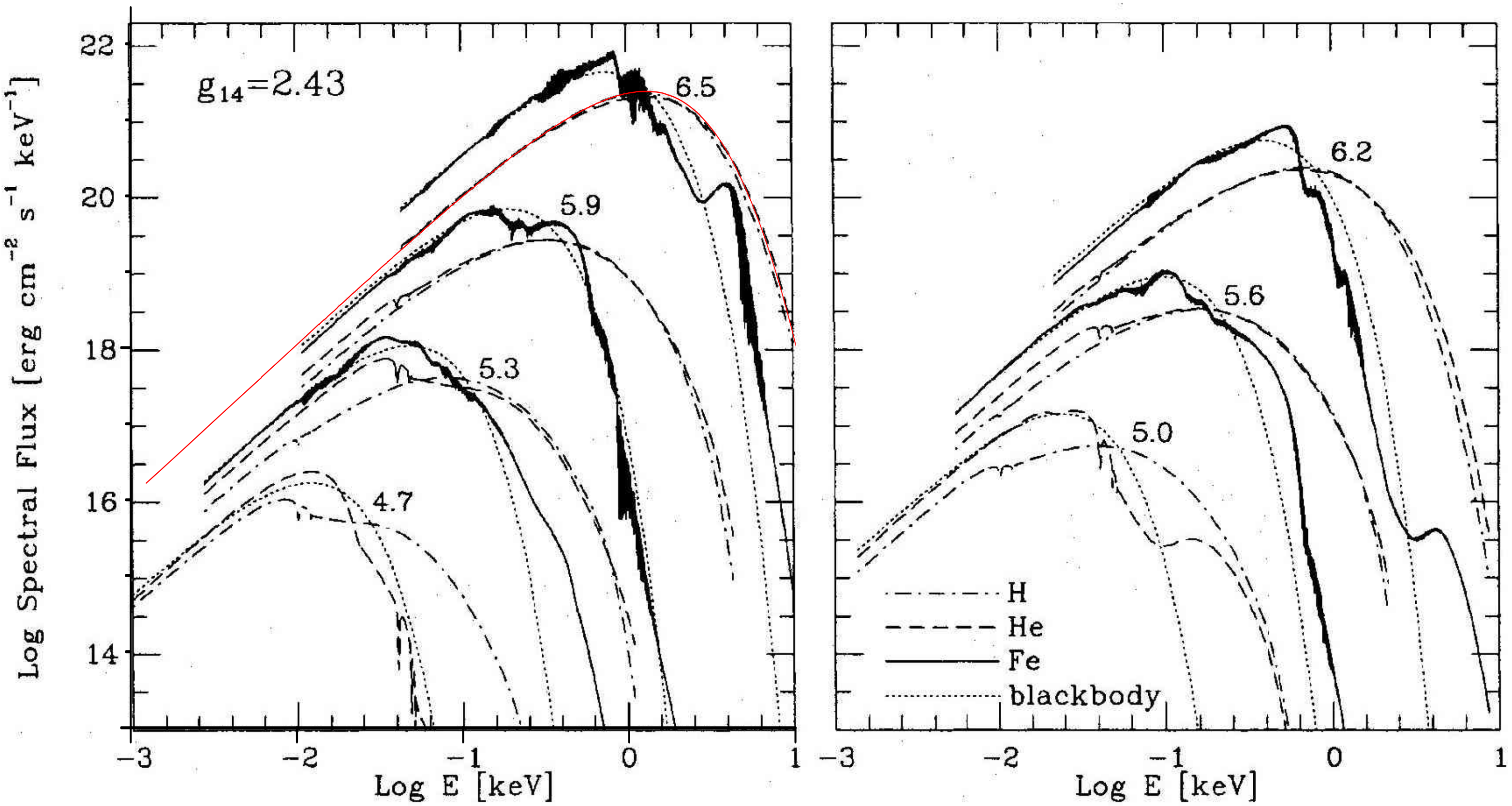


Fig. 5. Spectral fluxes of emergent radiation for hydrogen, helium and iron atmospheres with different values of $\log T_{\rm eff}$ (numbers near the curves). Dotted curves show the corresponding blackbody fluxes $\pi B_\nu(T_{\rm eff})$.

Compton scattering can be important!

$$k_{ff} << \sigma_e \quad at \quad x = \frac{h\nu}{kT_{eff}} > 10 - 100$$

Hard photons which we observe are emitted from the depth

$$\tau_{eff} = \sqrt{\tau_{ff}\tau_T} \approx 1$$ - thermalization depth

At this depth, electron scattering optical depth $\tau_T >> 1$

During one Compton down-scattering relative changing of a photon energy $E = h\nu$ is

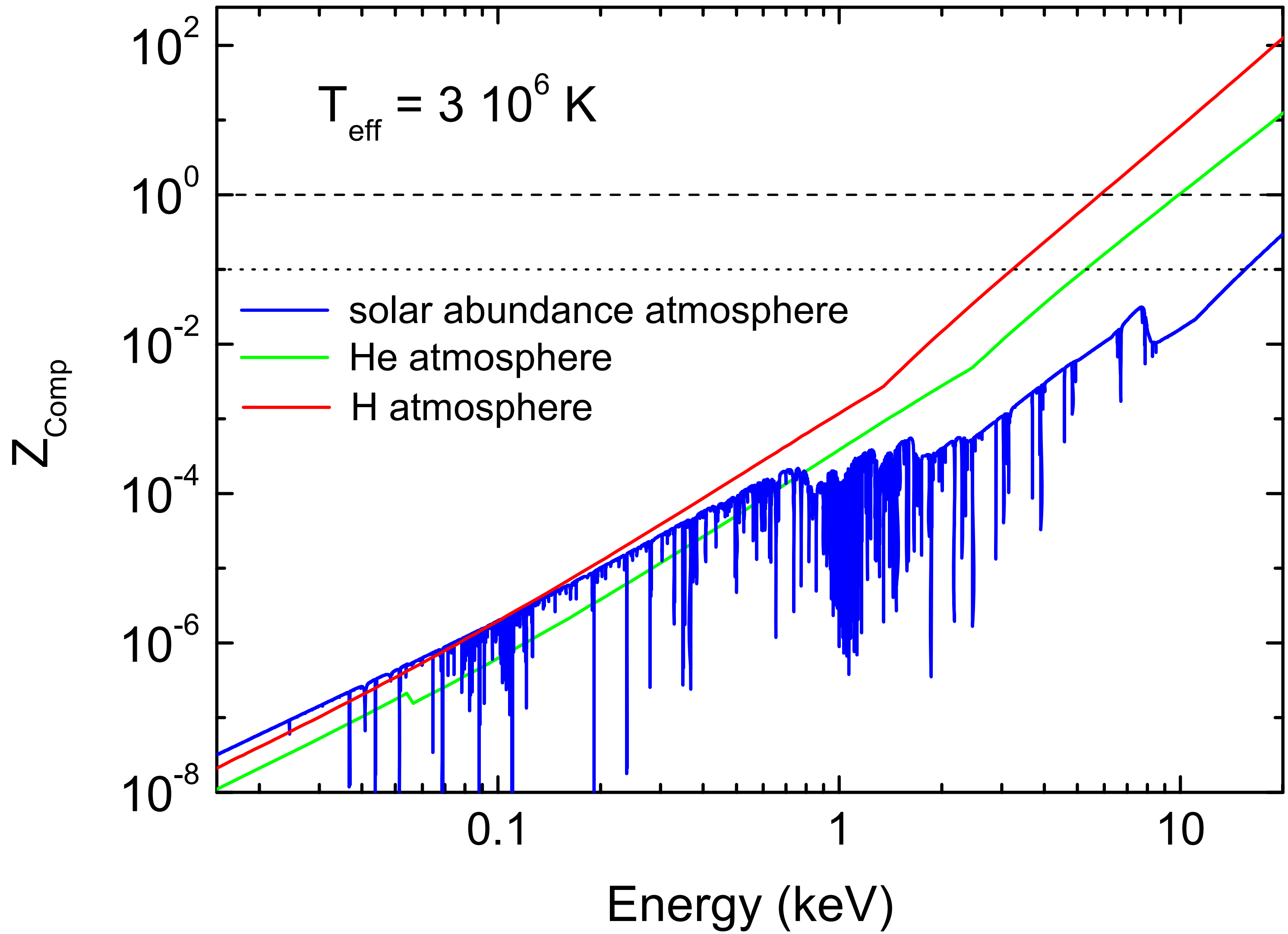
$$\Delta E / E \approx h\nu / m_e c^2$$

Therefore at energies where $$Z_{Comp} = \frac{h\nu}{m_e c^2} \max(\tau_*, \tau_*^2) \geq 0.1 - 1$$

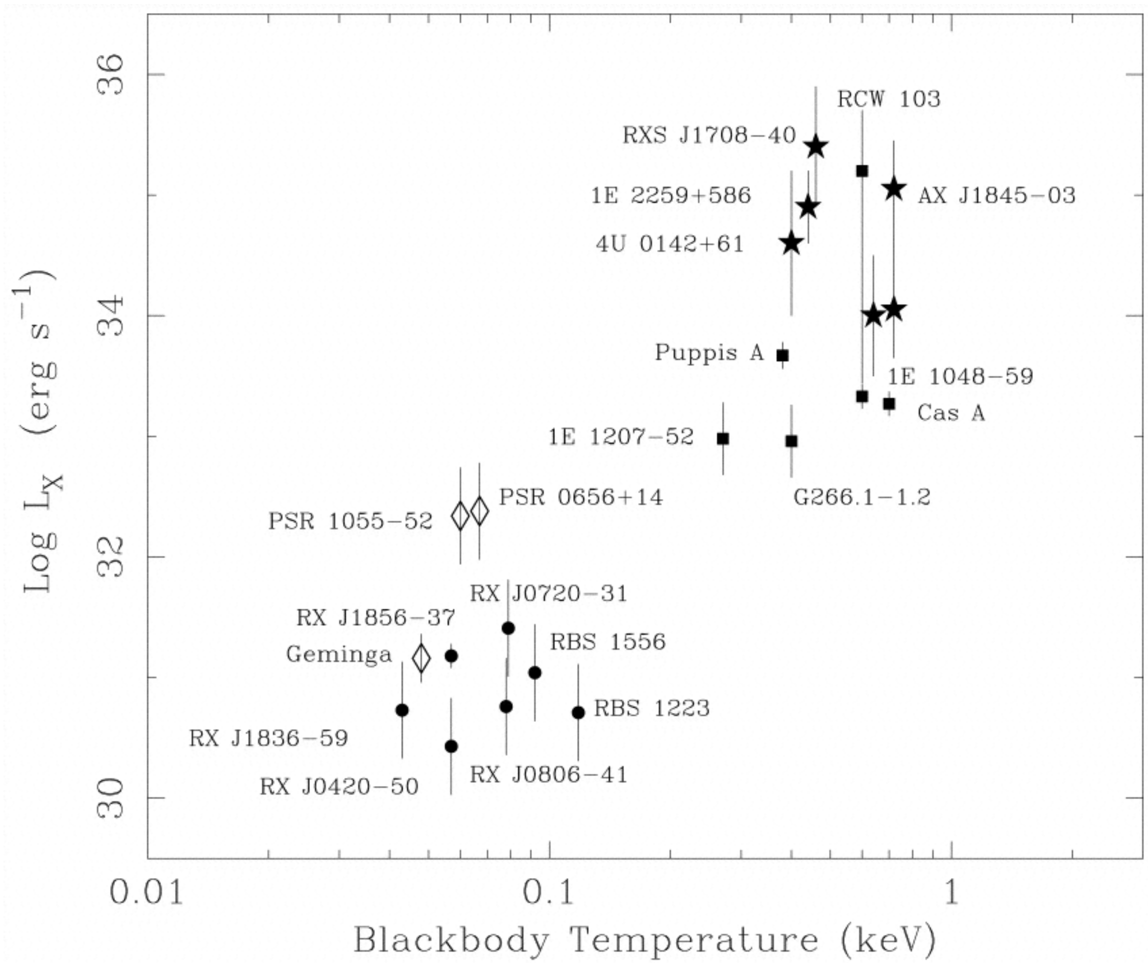
we can expect significant effect of the Compton scattering on the emergent spectrum.

$\max(\tau_*, \tau_*^2)$ is mean number of scatterings of the photon from creation to escape.

Here $\tau_* = \tau_T(\tau_{eff} = 1)$



Comptonization parameter Z_{Comp} vs. photon energy for neutron star model atmospheres with different chemical abundance



Temperature – luminosity diagram for different classes of neutron stars: AXPs (stars), supernova remnant CCOs (squares), XDINSs (circles), and radio pulsars (diamonds) (from Mereghetti et al. 2002).

Basic equations

Hydrostatic equilibrium

$$\frac{1}{\rho}\frac{dP_{gas}}{dr} = -\frac{GM_{NS}}{R_{NS}^2(1-R_g/R_{NS})^{1/2}} + \frac{4\pi}{c}\int H_\nu (k_{ff} + \sigma_e)\, d\nu$$

Radiation transfer

$$\frac{\partial^2(f_\nu J_\nu)}{\partial \tau_\nu{}^2} = \frac{k_{ff}}{k_{ff}+\sigma_e}(J_\nu - B_\nu) - \frac{\sigma_e}{k_{ff}+\sigma_e}\frac{kT}{m_e c^2} x \frac{\partial}{\partial x}\left(\frac{\partial J_\nu}{\partial x} - 3J_\nu + \frac{T_{eff}}{T} x J_\nu \left(1 + C\frac{J_\nu}{x^3}\right)\right)$$

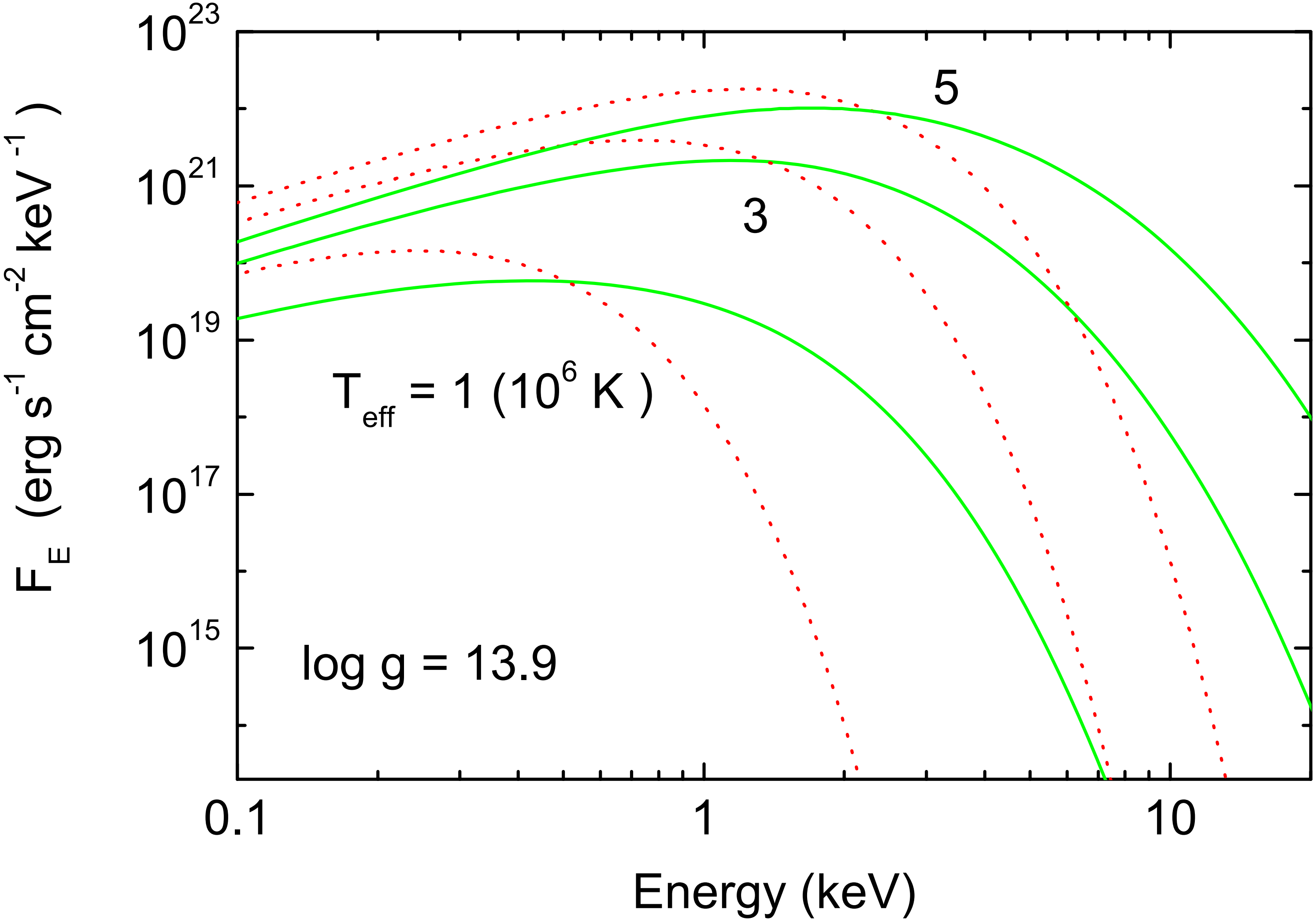
$$x = \frac{h\nu}{kT_{eff}} \qquad C = c^2 h^2 / 2(kT_{eff})^3$$

Radiation equilibrium

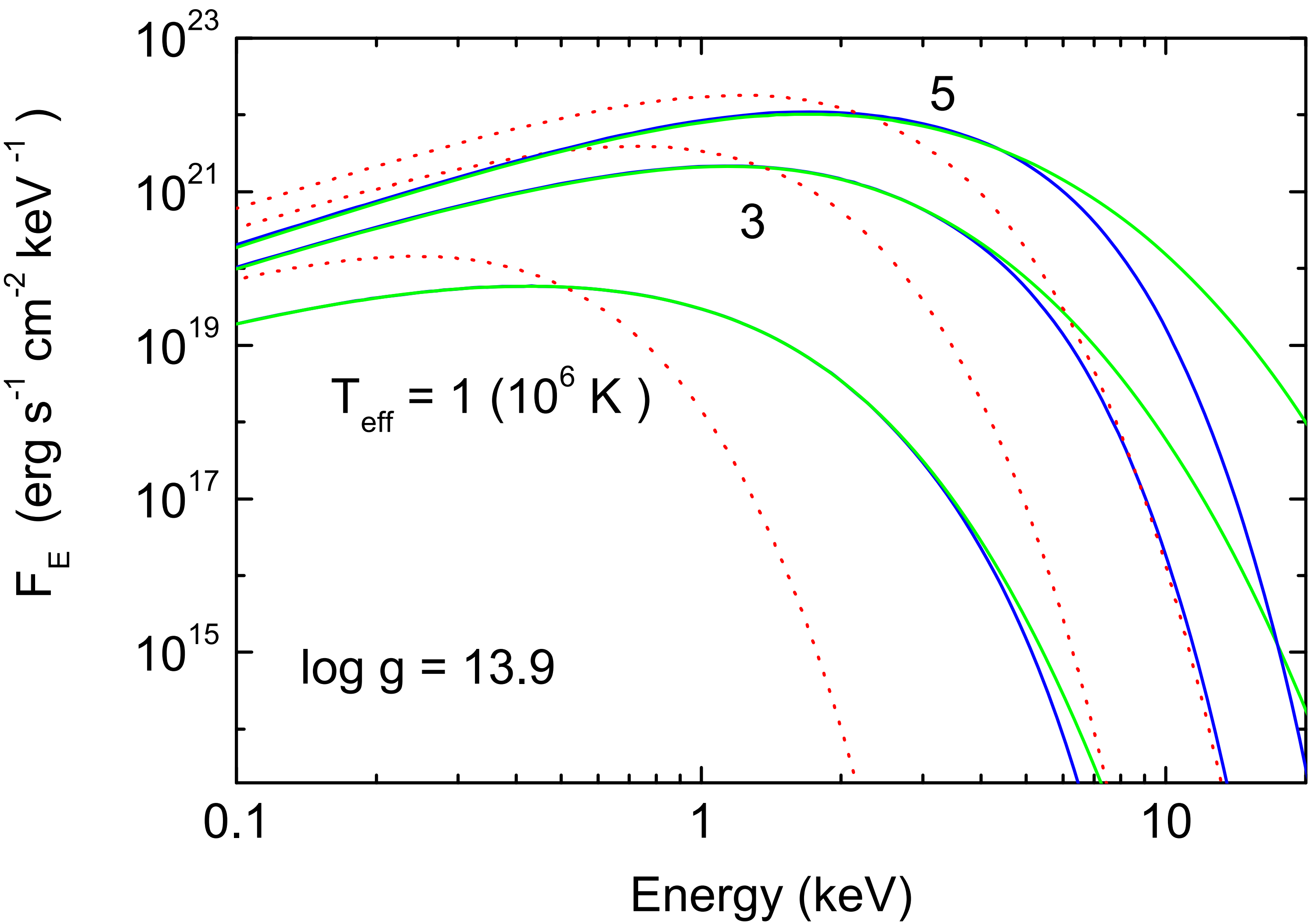
$$\int k_{ff}(J_\nu - B_\nu)dx - \sigma_e \frac{kT}{m_e c^2}\int \left(4J_\nu - \frac{T_{eff}}{T} x J_\nu \left(1 + \frac{CJ_\nu}{x^3}\right)\right)dx = 0$$

k_{ff} - true absorption opacity (mainly free-free transitions)

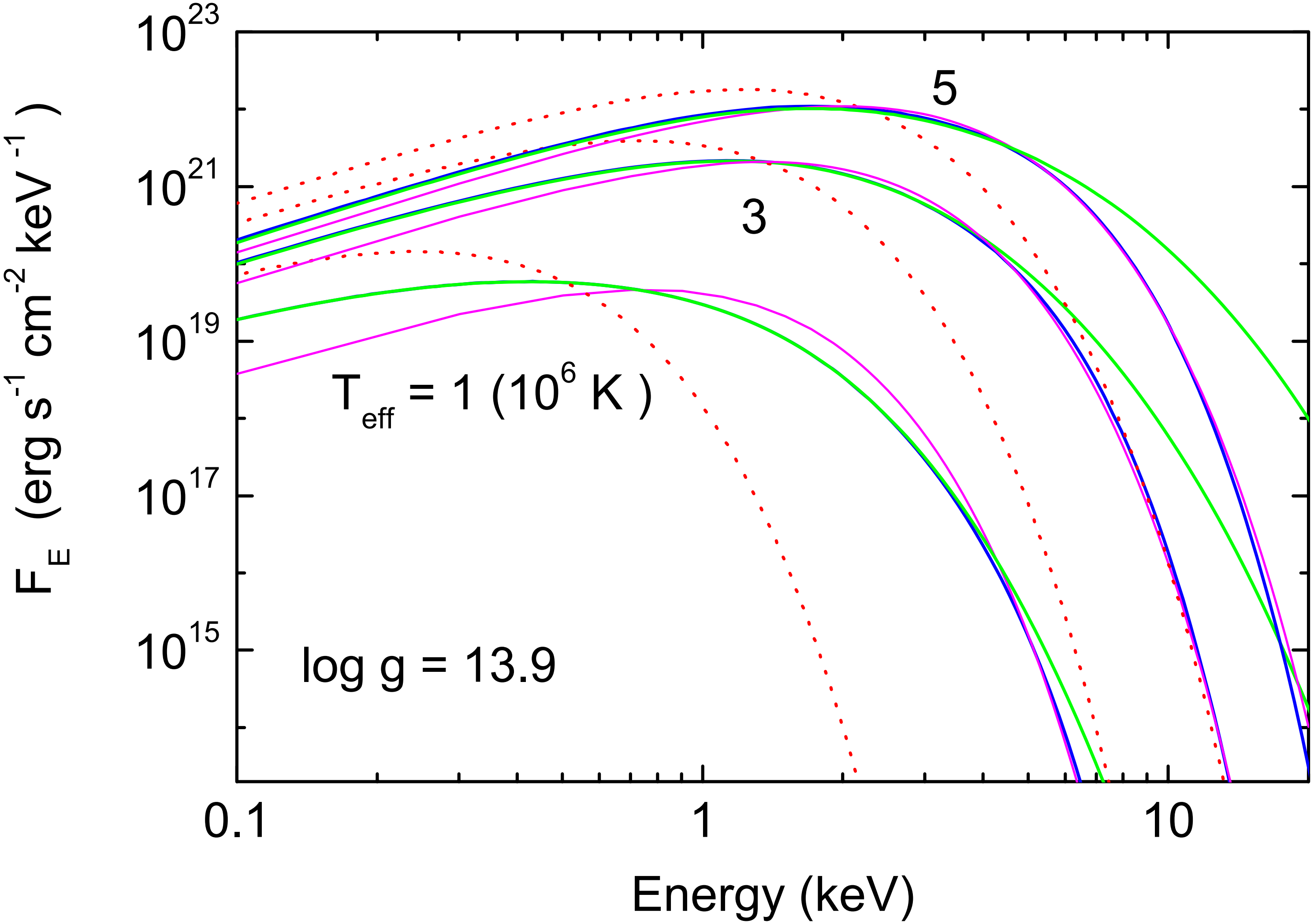
σ_e - Thomson electron scattering opacity



Emergent model spectra of H neutron star atmospheres without Compton scattering (green lines). Red dotted lines are blackbody spectra.



Emergent model spectra of H neutron star atmospheres without Compton scattering (green lines). Red dotted lines are blackbody spectra. Blue lines are spectra with Compton scattering.



Emergent model spectra of H neutron star atmospheres without Compton scattering (green lines). Red dotted lines are blackbody spectra. Blue lines are spectra with Compton scattering. Magenta lines are diluted blackbody spectra.

Compton scattering is important!

In the case of Thomson scattering, the radiation and the gas are weakly coupled in the surface layers of atmosphere → low surface temperature.

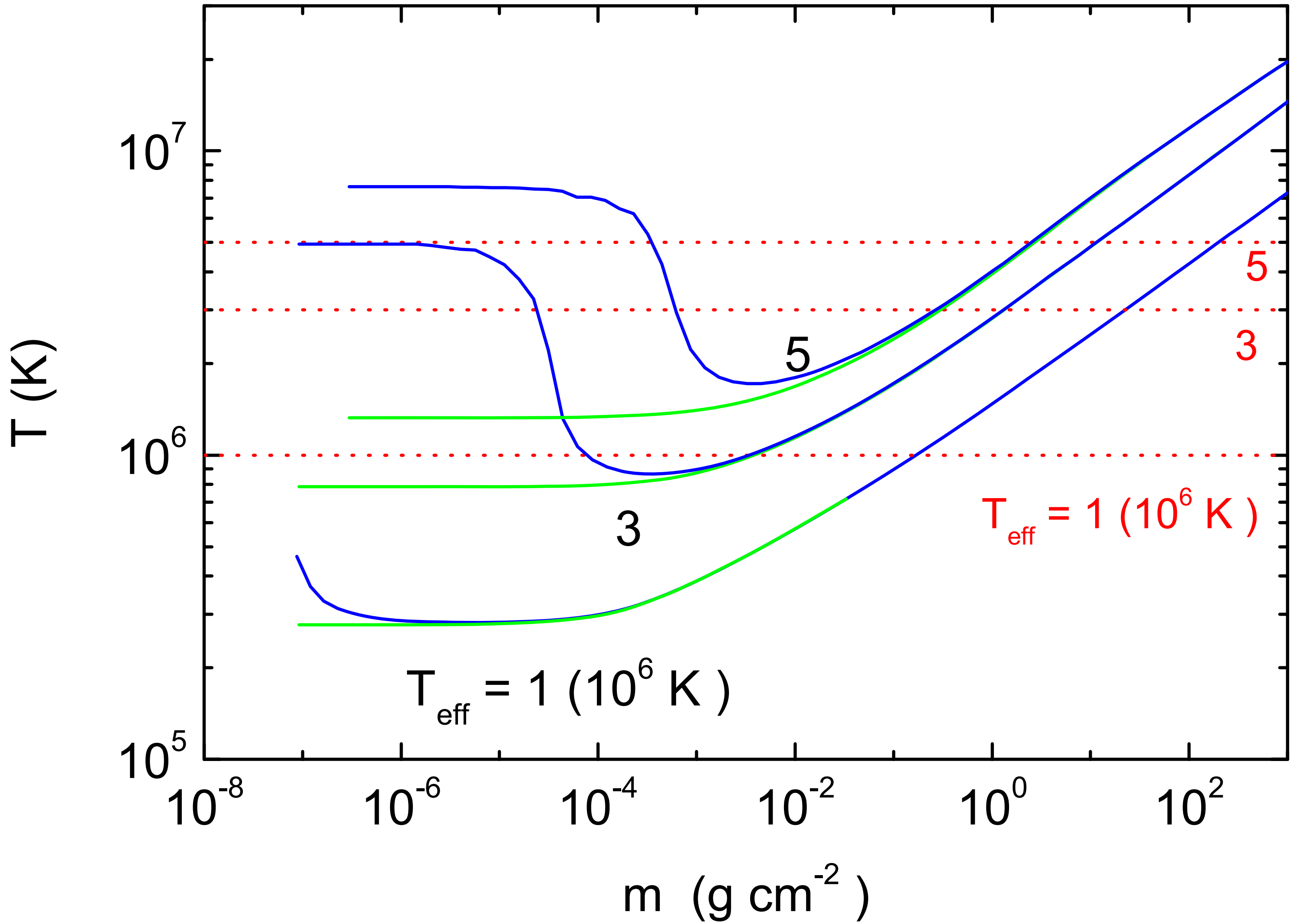
If Compton scattering is taken into account, hard photons heat electrons at the surface up to $T>T_{eff}$. This results in the emergent spectrum close to the diluted black body:

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

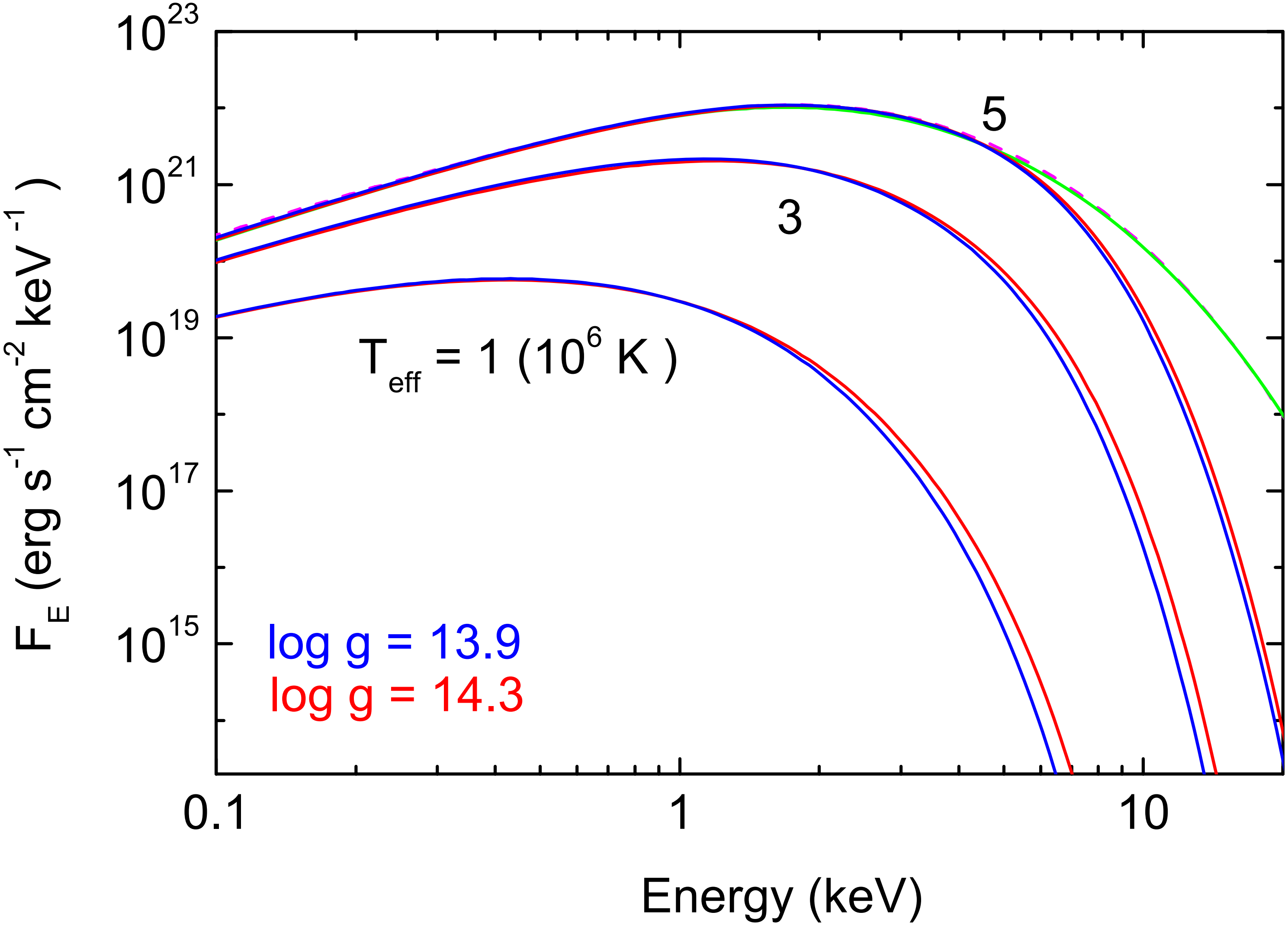
f_c is hardness factor.

f_c = 1.87 for model with $T_{eff} = 3\ 10^6$ K

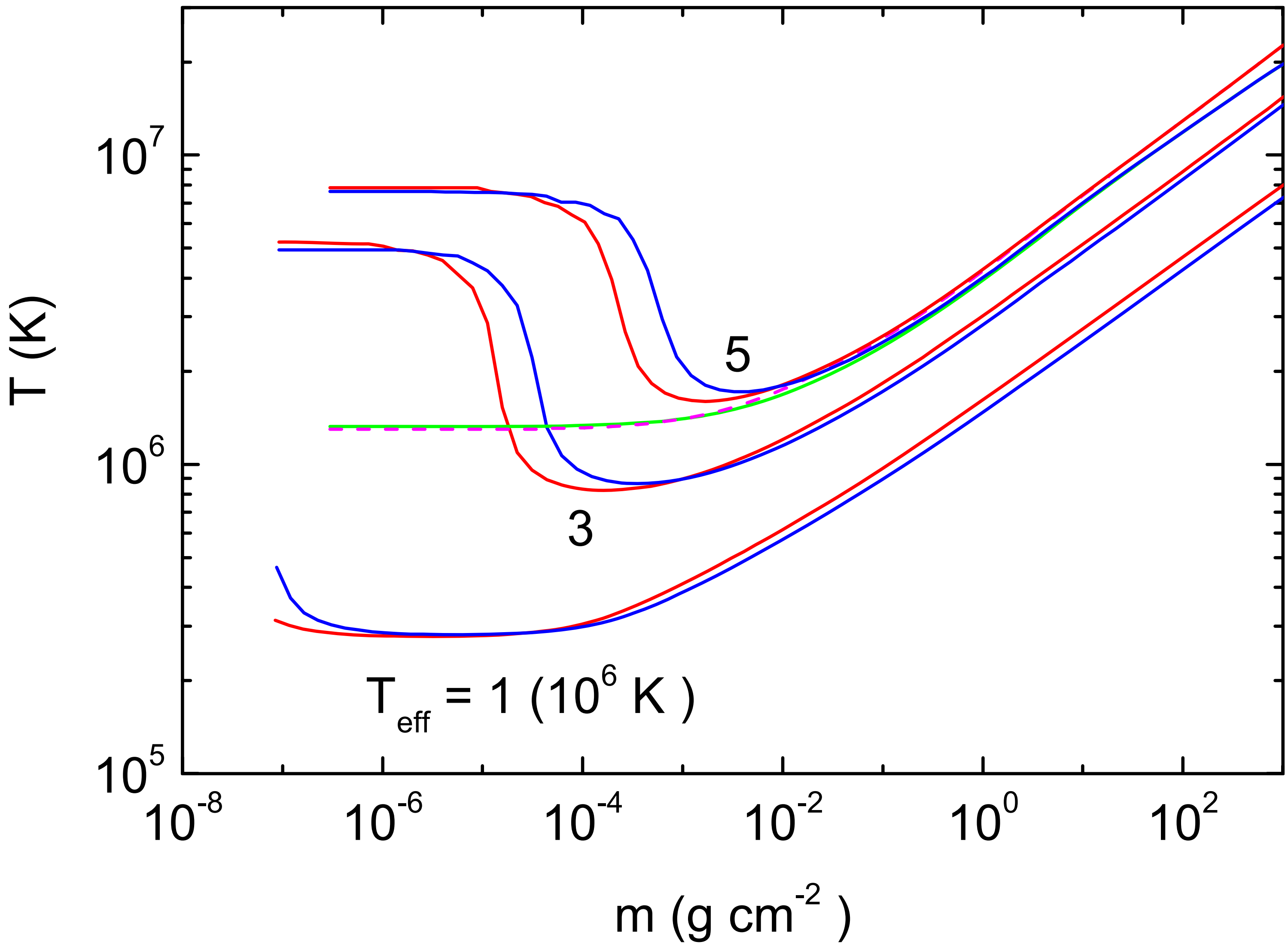
f_c = 1.65 for model with $T_{eff} = 5\ 10^6$ K



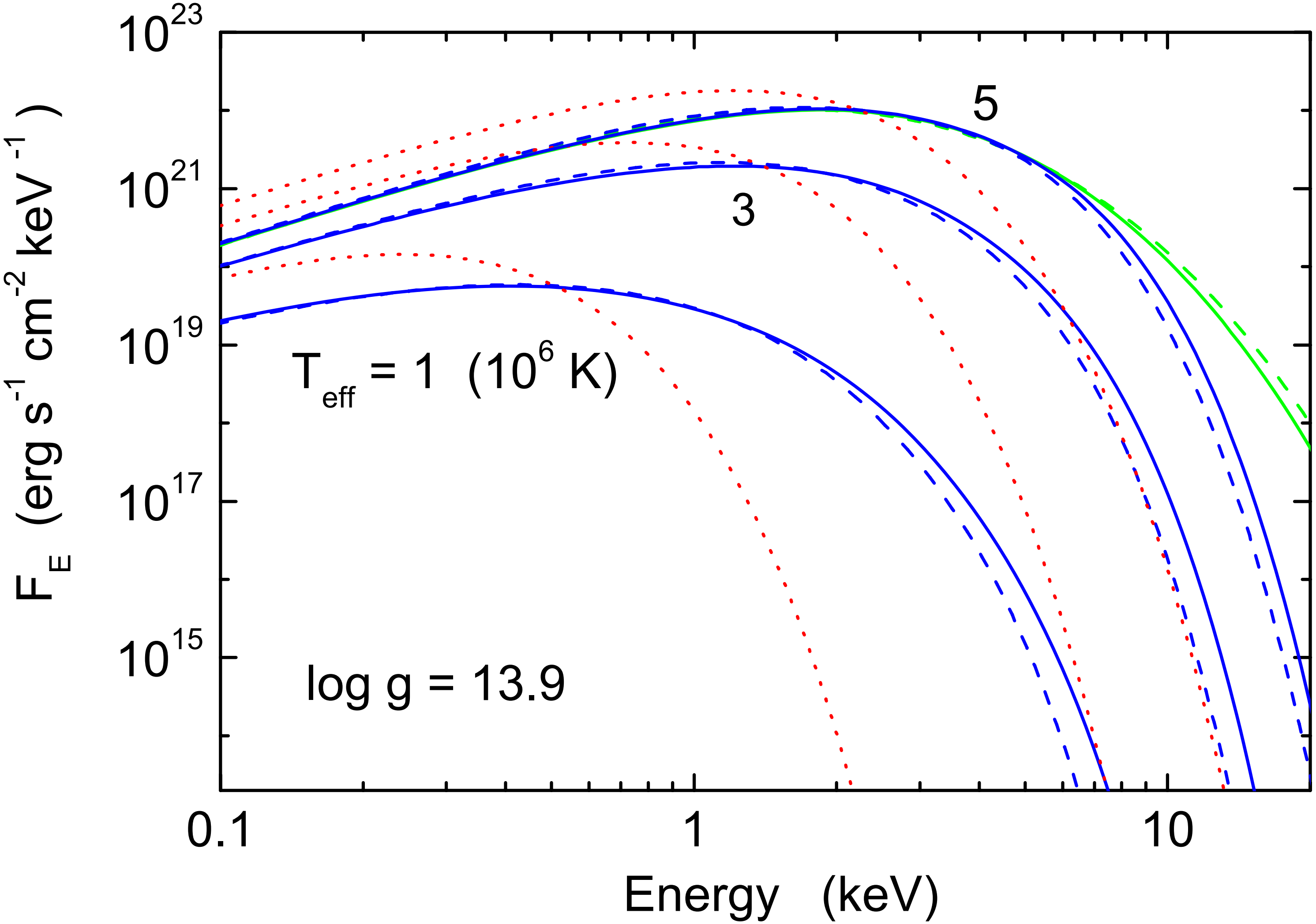
Temperature structures of H neutron star model atmospheres with and without Compton scattering. The effective temperatures are also shown.



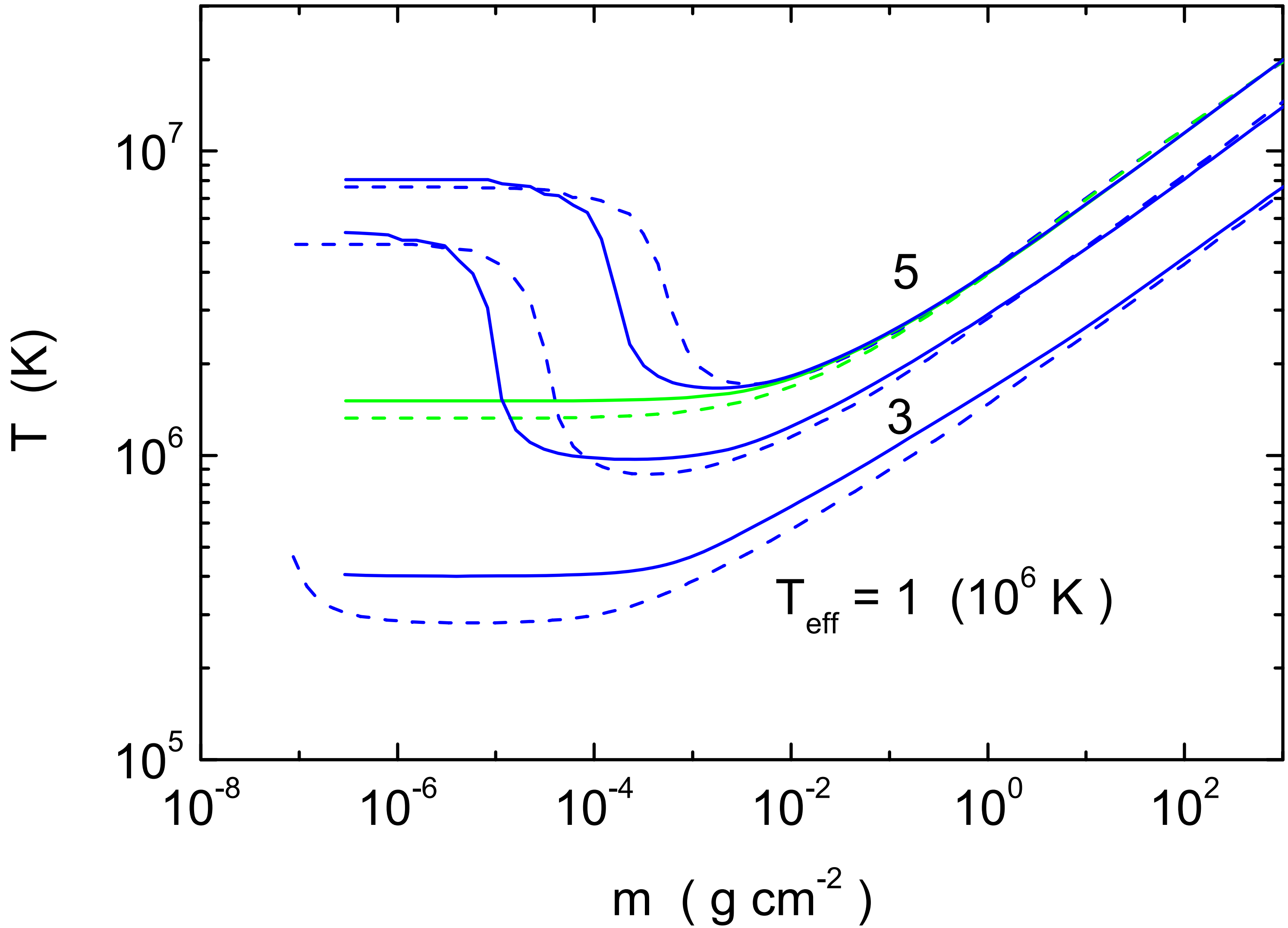
Emergent model spectra of H neutron star atmospheres with different surface gravities.



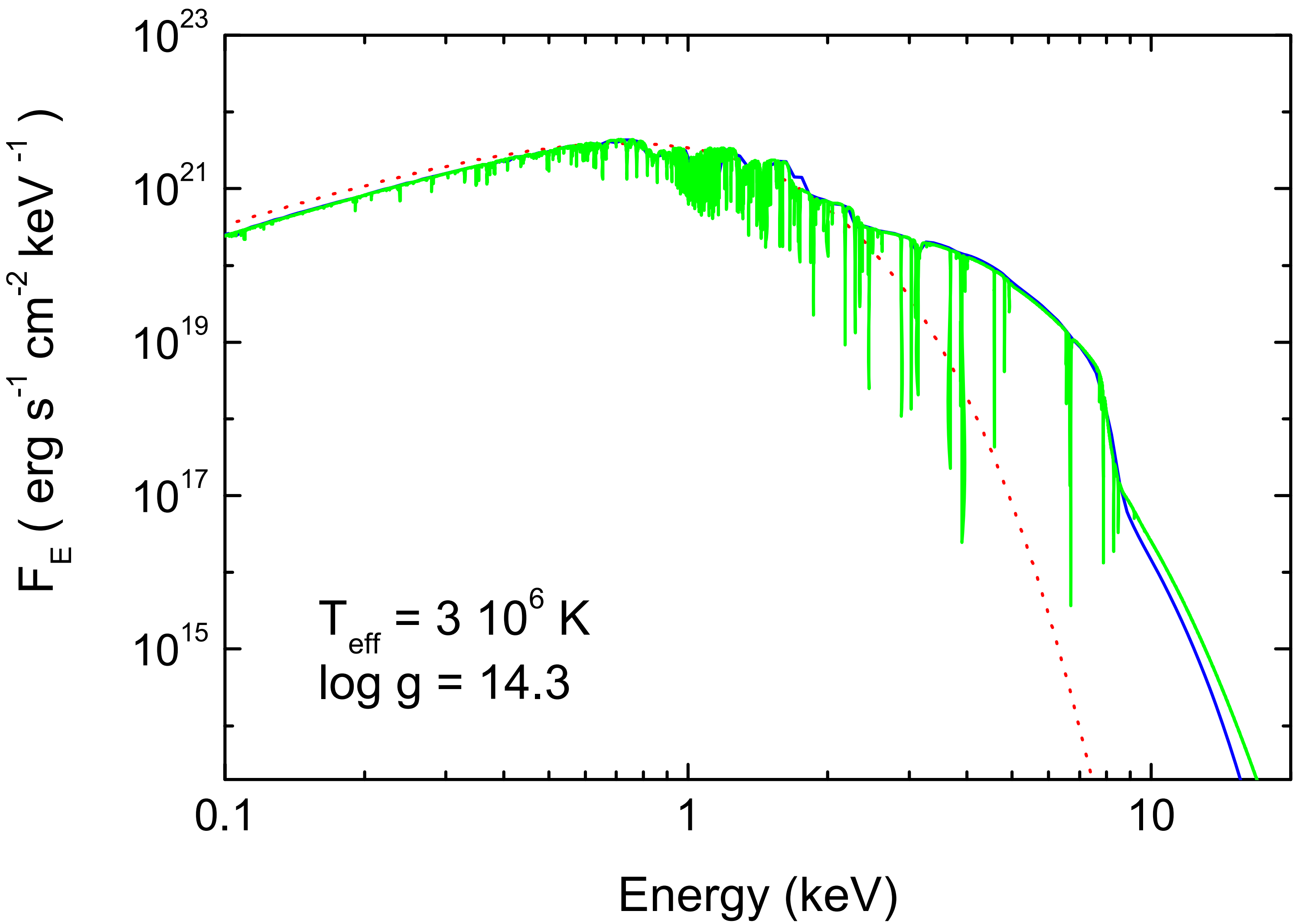
Temperature structures of H model neutron star atmospheres with different gravities.



Emergent model spectra of H (dashed lines) and He (solid lines) neutron star atmospheres with and without (hottest only) Compton scattering.



Temperature structures of H (dashed lines) and He (solid lines) model neutron star atmospheres with and without (hottest model only) Compton scattering.



Emergent model spectra of high gravity neutron star model atmosphere with solar abundance of 15 most abundant heavy elements with and without Compton scattering.

Conclusions

- Emergent spectra of light elements NS model atmospheres with T_{eff} > 1 MK are changed by the Compton effect.
- Spectra of hottest models (T_{eff} > 3 MK) can be described by diluted blackbody spectra with hardness factors ~ 1.6 – 1.9
- The Compton effect is less significant in He model atmospheres and high gravity model atmospheres.
- Emergent model spectra of NS atmospheres with solar abundance are changed by the Compton effect very slightly.