Model atmosphere and spectra computations of X-ray burst sources

by

Agnieszka Majczyna

Jerzy Madej

Introduction

In hot atmosphere and in X-ray energy band the most important opacity sources are:

- Compton scattering on free electrons
- free-free absorption.

Our model assumptions

1. We use equation of transfer with Compton scattering redistribution functions which trace scattering of photons with energies exeeding electron rest mass.
2. Compton scattering is isotropic.
3. Photons are scattered on thermal electrons with relativistic thermal velocities.
4. Zero magnetic field and non rotating neutron star.
5. Effects of linear polarization during Compton scattering are ignored.
6. By assumption general relativistic corrections are not included.

Equation of transfer with Kompaneets approximation

$$\mu \frac{\partial I_\nu}{\partial z} = \kappa_\nu (B_\nu - I_\nu) - \sigma_T I_\nu + \sigma_T J_\nu$$

$$+ \sigma_T \left[\frac{kT}{mc^2} \nu^2 \frac{\partial^2}{\partial \nu^2} + \left(\frac{h\nu}{mc^2} - 2\frac{kT}{mc^2} \right) \nu \frac{\partial}{\partial \nu} + \frac{h\nu}{mc^2} \right] J_\nu$$

$$- \sigma_T \frac{c^2}{h\nu^3} \frac{h\nu}{mc^2} J_\nu \left(1 - \nu \frac{\partial}{\partial \nu} \right) J_\nu$$

Model equations

$$\mu \frac{\partial I_\nu(z,\nu)}{\mu\, \partial z} = \kappa'_\nu \left(1 - e^{\frac{-h\nu}{kT}}\right)\left(B_\nu - I_\nu\right)$$

$$+ \left(1 + \frac{c^2}{2h\nu^3} I_\nu\right) \oint_{\omega'} \frac{d\omega}{4\pi} \int_0^\infty \frac{\nu}{\nu'} \sigma\left(\nu' \to \nu, \vec{\nu'} \cdot \vec{\nu}\right) I_\nu\left(z, \vec{n'}\right) d\nu$$

$$- I_\nu(z,\mu) \oint_{\omega'} \frac{d\omega}{4\pi} \int_0^\infty \sigma\left(\nu \to \nu', \vec{\nu} \cdot \vec{\nu'}\right)\left(1 + \frac{c^2}{2h\nu'^3} I_{\nu'}\right) d\nu'.$$

μ - cosine of zenithal angle

I_ν – specific intensity of radiation

h – Planck constant

B_ν – Planck function

σ – differential cross section for Compton scattering

κ_ν – thermal absorption coefficient

ν,ν' – initial and final frequencies

$n \cdot n'$ – cosine of scattering angle

Model equations

We made a few very important assumptions:

- we treat the stimulated thermal emission in simplified way, as in thermodynamical equilibrium.
- on the right hand side of the transfer equation we replace specific intensity I_ν by mean intensity J_ν in both stimulated scattering terms.
- we use approximation formula:

$$\oint_{\omega'} \frac{d\omega}{4\pi} \int_0^\infty \sigma\left(\nu \to \nu', \vec{n} \cdot \vec{n}'\right)\left(1 + \frac{c^2}{2h\nu'^3} I_{\nu'}\right) d\nu' \approx \int_0^\infty d\nu' \oint_{\omega'} \frac{d\omega}{4\pi} \sigma\left(\nu \to \nu', \vec{n} \cdot \vec{n}'\right) \oint_{\omega'} \frac{d\omega}{4\pi} \left(1 + \frac{c^2}{2h\nu'^3} I_{\nu'}\right)$$

- we require that the right hand side of the equation is linear with respect to I_{ν}.

Model equation

Hydrostatic equilibrium:

$$\frac{dP_{gas}}{d\tau} = \frac{g}{(\kappa + \sigma)_{std}} - \frac{dP_{rad}}{d\tau} = \frac{g}{(\kappa + \sigma)_{std}} - \frac{4\pi}{c}\int_0^\infty \eta_\nu H_\nu \, d\nu$$

Arbitrarily chosen standard wavelength: 3.5 Å

Model equation

Radiative equilibrium

$$\frac{dF_{bol}}{dz} = 0$$

$$\int_0^\infty \eta_\nu \varepsilon_\nu (J_\nu - B_\nu^*) d\nu + \int_0^\infty \eta_\nu (1-\varepsilon_\nu) J_\nu d\nu \int_0^\infty \Phi_1^*(\nu,\nu') d\nu'$$

$$-\int_0^\infty \eta_\nu (1-\varepsilon_\nu) d\nu \int_0^\infty J_{\nu'} \Phi_2^*(\nu,\nu') d\nu' = 0$$

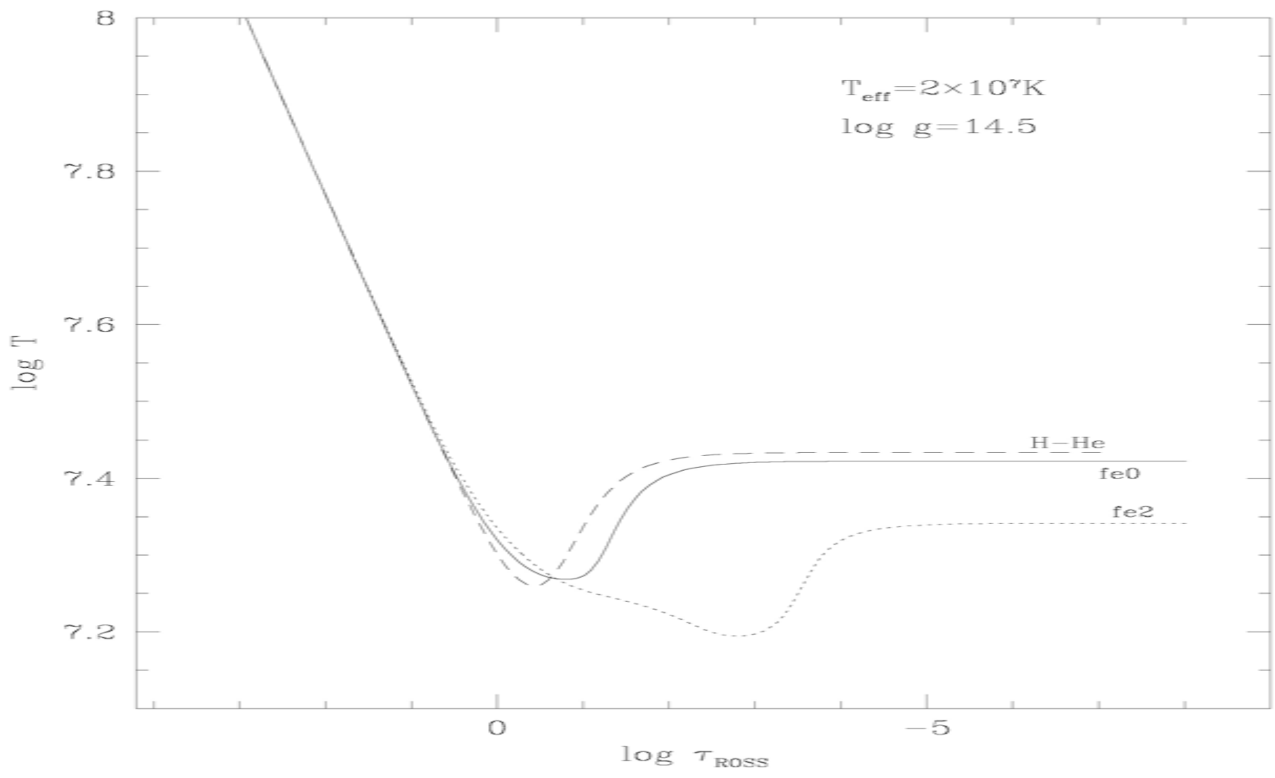
Model equation

The final form of transfer equation, which is adopted in numerical calculation:

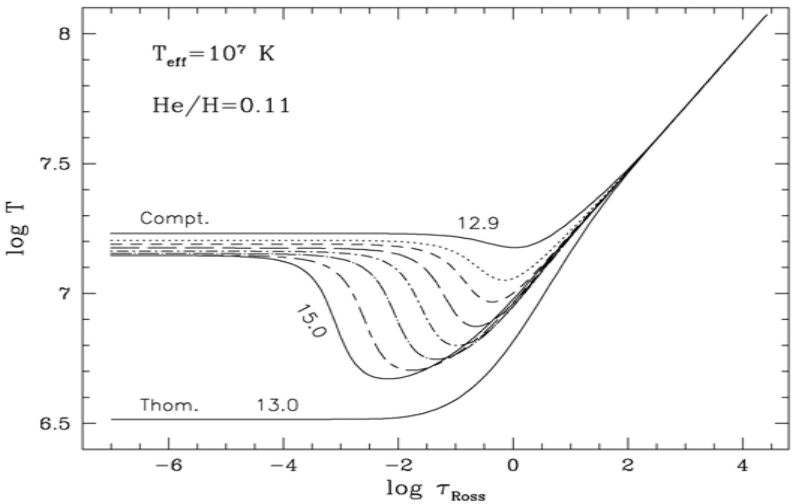
$$\frac{d^2}{d\tau_\nu^2}(f_\nu J_\nu) = \varepsilon_\nu (J_\nu - B_\nu) + (1-\varepsilon_\nu) J_\nu \int_0^\infty \Phi_1(\nu,\nu') d\nu' - (1-\varepsilon_\nu) \int_0^\infty J_{\nu'} \Phi_2(\nu,\nu') d\nu'$$

$$-\left[\varepsilon_\nu \frac{\partial B_\nu}{\partial T} - (1-\varepsilon_\nu) J_\nu \int_0^\infty \frac{\partial \Phi_1}{\partial T} d\nu' + (1-\varepsilon_\nu) \int_0^\infty J_{\nu'} \frac{\partial \Phi_2}{\partial T} d\nu'\right] \times$$

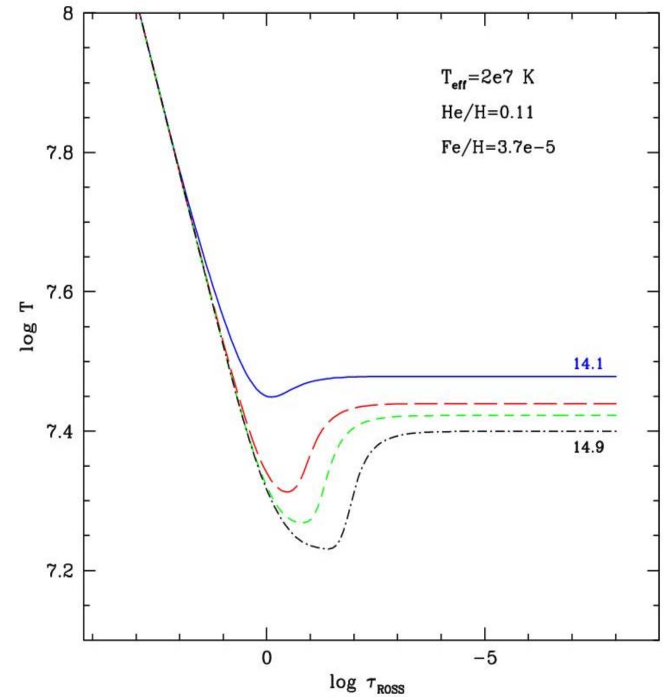
$$\times \frac{\int_0^\infty \eta_\nu \varepsilon_\nu (J_\nu - B_\nu) d\nu + L}{\int_0^\infty \eta_\nu \varepsilon_\nu (\partial B_\nu / \partial T)_\tau d\nu - L'}$$



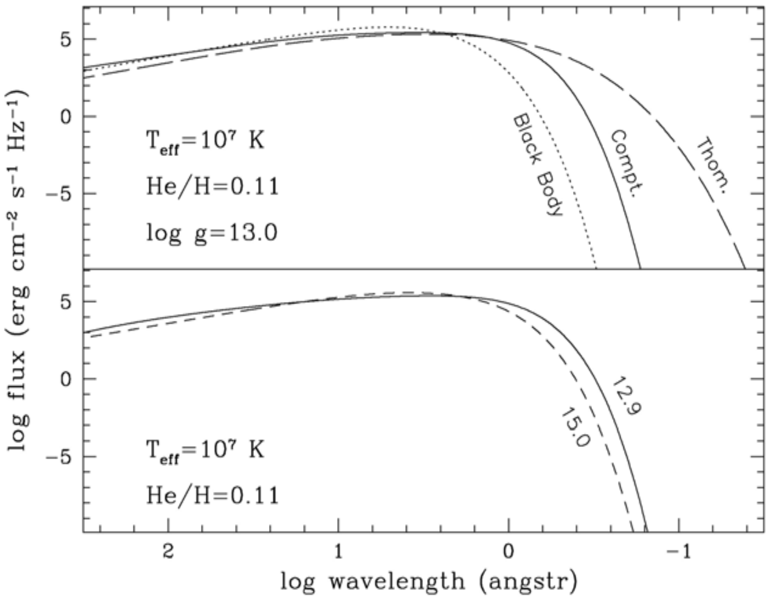
$T_{eff}=2\times10^7$K
log g=14.5
H−He
fe0
fe2
8
7.8
7.6
7.4
7.2
log T
0
−5
log τ_{ROSS}



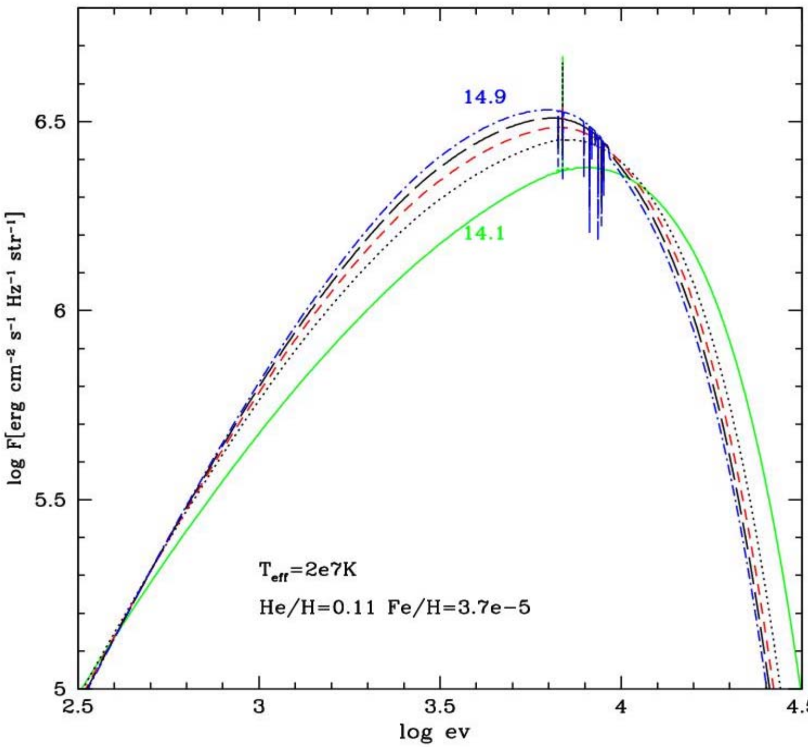
T_{eff}=10⁷ K
He/H=0.11
Compt.
12.9
15.0
Thom.
13.0
log T
log τ_{Ross}



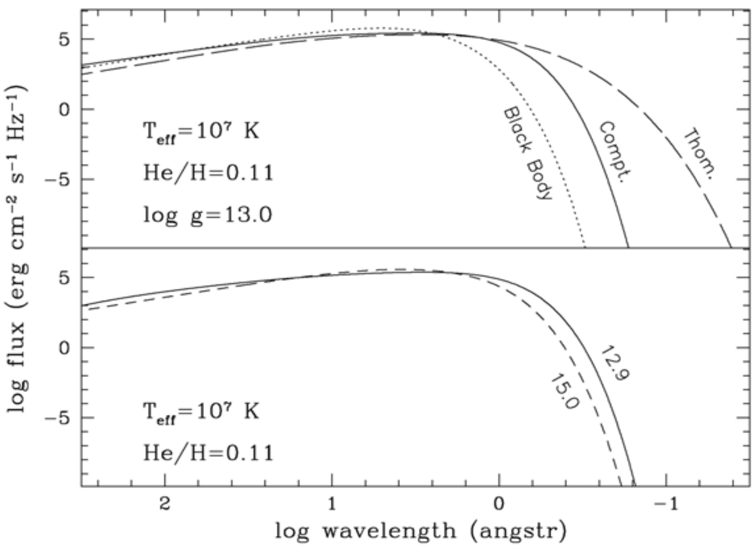
T_{eff}=2e7 K
He/H=0.11
Fe/H=3.7e-5
14.1
14.9
log T
log τ_{ROSS}



log flux (erg cm⁻² s⁻¹ Hz⁻¹)
$T_{eff}=10^7$ K
He/H=0.11
log g=13.0
Black Body
Compt.
Thom.
12.9
15.0
log wavelength (angstr)



log F[erg cm⁻² s⁻¹ Hz⁻¹ str⁻¹]
14.9
14.1
T_{eff}=2e7K
He/H=0.11 Fe/H=3.7e-5
log ev



log flux (erg cm⁻² s⁻¹ Hz⁻¹)
log wavelength (angstr)
T_eff=10⁷ K
He/H=0.11
log g=13.0
Black Body
Compt.
Thom.
T_eff=10⁷ K
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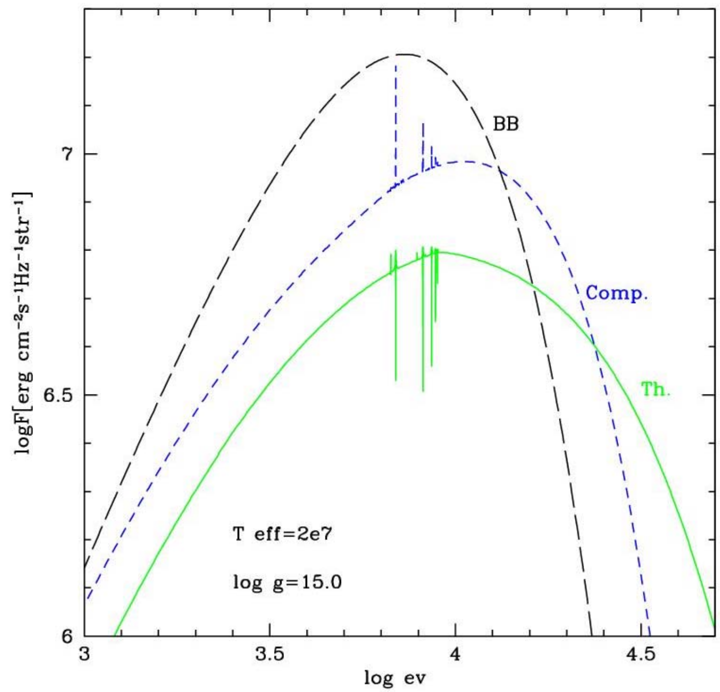
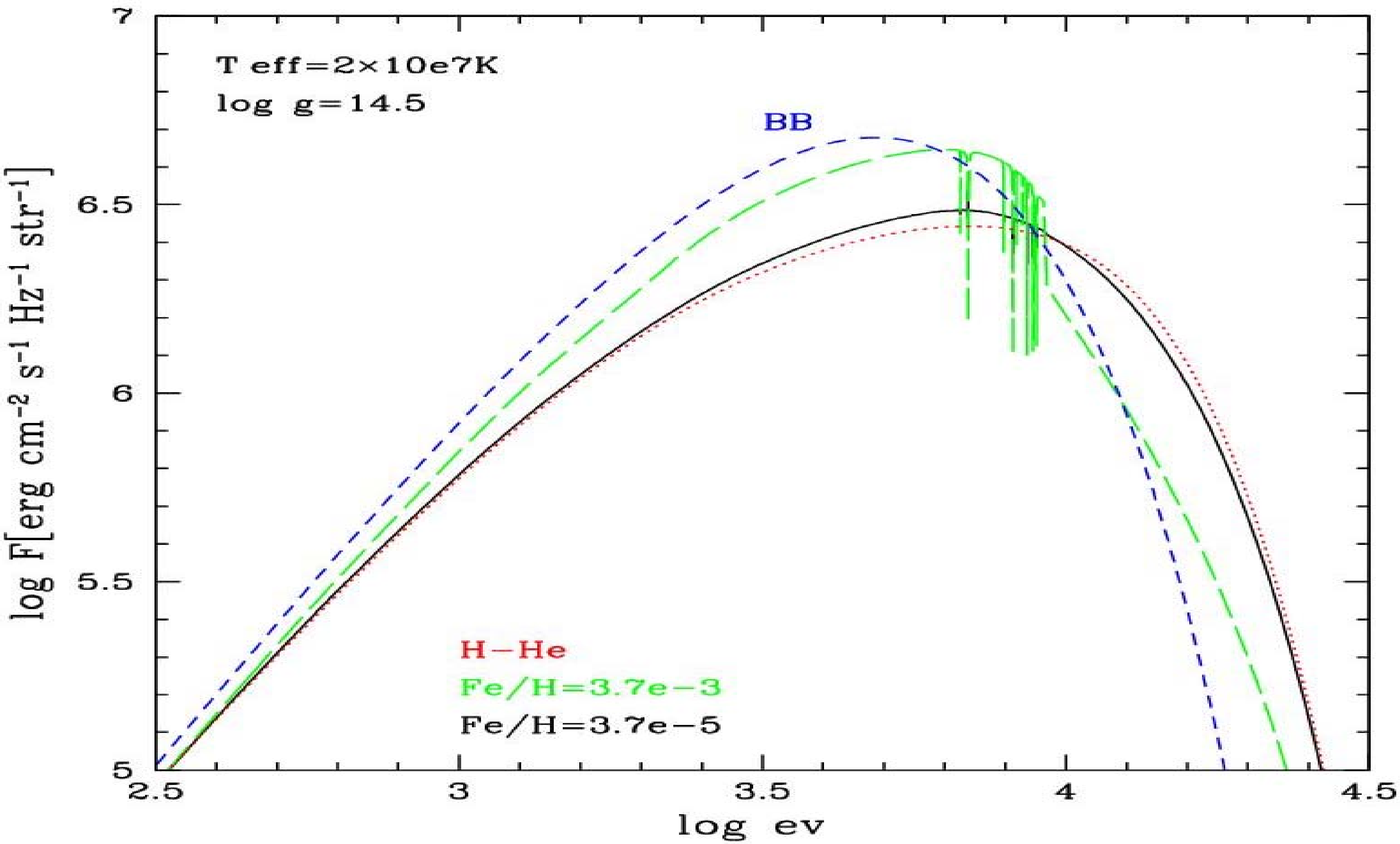


logF[erg cm⁻²s⁻¹Hz⁻¹str⁻¹]
log ev
BB
Comp.
Th.
T eff=2e7
log g=15.0


T eff=2×10e7K
log g=14.5
BB
H−He
Fe/H=3.7e−3
Fe/H=3.7e−5
log F[erg cm-2 s-1 Hz-1 str-1]
log ev
7
6.5
6
5.5
5
2.5
3
3.5
4
4.5

Summary and conclusions

- I presented outline of model equations applicable to X-ray burst sources and results of numerical calculations of spectra.
- We reject Kompaneets approximation.
- Our calculations show that all model spectra of X-ray bursters differ from the blackbody spectra.
- Model spectra with iron exhibit numerous absorption edges and iron spectral lines.
- Our numerical code can be used to calculate model atmospheres with wide range of effective temperatures and physical conditions (e.g. external illumination).
- Our models can be used for reliable fitting of the observed continuum X-ray burst spectra, and therefore for attempts to mass and radius determination of bursting neutron stars.