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. Models with effective temperatures 1, 3 and 5 MK, with two values of surface gravity (log g = 13.9 and 14.3), and different chemical compositions are calculated. Radiation spectra computed with Compton scattering are softer than the 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 to hydrogen models with low surface gravity. The emergent spectra of the hottest ($T_{\rm eff} > 3$ MK) model atmospheres can be described by diluted blackbody spectra with hardness factors $\sim$ 1.6 - 1.9. Compton scattering is less important for models with solar abundance of heavy elements.

1. Introduction

Relatively young neutron stars (NSs) with age $\leq 10^6$ yr are sufficiently hot ($T_{\rm eff} \sim 1$ MK) and can be observed as soft X-ray sources. Indeed, at present time the thermal radiation of few tens different kind of isolated NSs, from anomalous X-ray pulsars to millisecond pulsars are detected. The thermal spectra of these objects can be described by blackbody spectra with (color) temperatures from 40 to 700 eV (see, for example, Mereghetti et. al 2002).

The plasma envelope of a NS (if it exists) can be considered as a NS atmosphere, and structure and emergent spectrum of this atmosphere can be calculated by using stellar model atmosphere methods (Mihalas 1978). Such modelling was performed by many scientific groups, beginning with Romani (1987), for NS model atmospheres without magnetic field as well as for models with strong ($B > 10^{12}$ G) magnetic field (see review by Zavlin & Pavlov 2002). These model spectra were used to fit the observed isolated NSs X-ray spectra (see review by Pavlov et al. 2002).

One of the important results of these works is as follows. Emergent model spectra of light elements (hydrogen and helium) NS atmospheres with low magnetic field are significantly harder than corresponding blackbody spectra. These elements are fully ionized in atmospheres with $T_{\rm eff} \geq 1$ MK. Therefore, the true opacity in these atmospheres (mainly due to free-free transitions) decreases with photon energy as E^{-3}. At high energies electron scattering is larger than true opacity and photons emitted deep in the atmosphere (where $T > T_{\rm eff}$) escape after few scatterings on electrons. In previous works, concerning isolated NS model atmospheres, coherent (Thomson) electron scattering is considered. As a result, emergent spectra are very hard. But such a situation is very favorable to change the photon energy due to Compton down-scattering.

It is well known that the Compton down-scattering determines the shape of emergent model spectra of hotter NS atmospheres with $T_{\rm eff} \sim 20$ MK and close to Eddington limit (London et al. 1986; Lapidus et al. 1986; Ebisuzaki 1987). These model spectra describe the observed X-ray spectra of X-ray bursting NSs in Low-Mass X-ray Binaries (LMXBs), and they are close to diluted blackbody spectra with a hardness factor $f_c \sim$ 1.5 - 1.9 (London et al. 1986; Lapidus et al. 1986, Madej 1991; Pavlov et al. 1991). But these model atmospheres with Compton scattering taken into account are not calculated for relatively cool atmospheres with $T_{\rm eff} < 10$ MK. Therefore, the effect of Compton scattering on emergent spectra of isolated NS model atmospheres with $T_{\rm eff} < 5$ MK is not well known up to now.

Here we present model atmospheres of isolated NSs with Compton scattering taken into consideration and investigate the Compton effect on the emergent spectra of these atmospheres.

2. Importance of Compton scattering

First of all we consider the Compton scattering effect on emergent model spectra of isolated NS atmospheres qualitatively. It is well known that in the non-relativistic approximation ($h\nu, kT_{\rm e} << m_{\rm e}c^2$) the relative photon en-
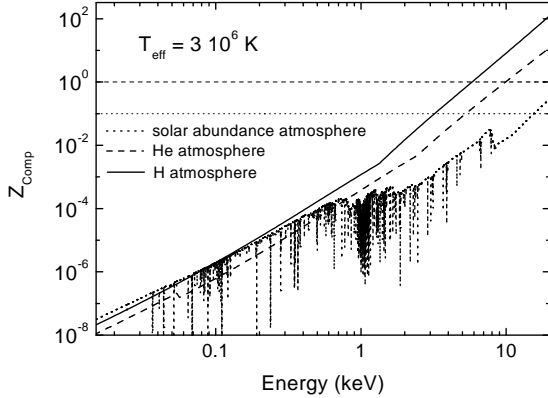
Fig. 1. Comptonization parameter Z_{Comp} vs. photon energy for neutron star model atmospheres with different chemical composition.

ergy lost due to a scattering event on a cool electron is:

$$\frac{\Delta E}{E} \approx \frac{h\nu}{m_{\mathrm{e}}c^2}. \tag{1}$$

Each scattering event changes the relative photon energy by this value. It is clear that the Compton scattering effect can be significant, if the final photon energy change is comparable with the initial photon energy. Therefore, we can define the Comptonisation parameter Z_{Comp} (see also Suleimanov et al. 2006):

$$Z_{\mathrm{Compt}} = \frac{h\nu}{m_{\mathrm{e}}c^2} \max((\tau_{\mathrm{e}}^*)^2, \tau_{\mathrm{e}}^*), \tag{2}$$

where $\max((\tau_{\mathrm{e}}^*)^2, \tau_{\mathrm{e}}^*)$ is the number of scattering events the photon undergoes before escaping, τ_{e}^* is the Thomson optical depth, corresponding to the depth where escaping photons of a given frequency are emitted. We can expect that Compton effects on emergent spectra of isolated NS model atmospheres are significant if the Comptonisation parameter approaches unity (Rybicki & Lightman 1979). Because of this we compute Z_{Comp} at different photon energies (see Fig. 1) for hot NS model atmospheres with different chemical compositions. These models were computed by using the method described in the next section, with the Thomson electron scattering. It is seen from Fig. 1 that the Comptonisation parameter is larger (0.1 - 1) at high photon energies ($E > 4 - 5$ keV) for H and He model atmospheres. Therefore, we can expect a significant effect of Compton scattering on the emergent spectra of these models. On the other hand, Z_{Comp} is low for the model with solar chemical composition of heavy elements. The Compton scattering effect has to be weak on the emergent spectrum of this model.

This qualitative analysis shows that Compton scattering can be significant for light element model atmospheres of isolated NS we have investigated in more detail.

3. Method of calculations

We computed model atmospheres of isolated NSs assuming planar geometry using standard methods (Mihalas 1978).

The model atmosphere structure for a isolated NS with effective temperature T_{eff}, surface gravity g, and given chemical composition, is described by the hydrostatic equilibrium equation, the radiation transfer equation, and the energy balance equation. These equations have to be completed by the equation of state, 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 pressure ionisation effects on the atomic populations using the occupation probability formalism (Hummer & Mihalas 1988) as described by Hubeny et al. (1994).

Compton scattering is taken into account in the radiation transfer equation using the Kompaneets operator (Kompaneets 1957; Zavlin & Shibanov 1991; Grebenev & Sunyaev 2002). The energy balance equation also accounts for Compton scattering.

For computing the model atmospheres we used a version of the computer code ATLAS (Kurucz 1970; Kurucz 1993), modified to deal with high temperatures; see Ibragimov et al. (2003) for further details. This code was also modified to account for Compton scattering (Suleimanov & Poutanen 2006; Suleimanov et al. 2006).

Our method of calculation was tested by comparing models for X-ray bursting neutron star atmospheres (Pavlov et al. 1991; Madej et al. 2004), with very good agreement.

4. Results

Using this method the set of hydrogen and helium NS model atmospheres with effective temperatures 1, 3, and 5 MK and surface gravities log $g = 13.9$ and 14.3 were calculated. Models with Compton scattering and Thomson scattering were computed for comparison. Part of the obtained results are presented in Figs. 2-4.

The Compton effect is significant for spectra of hot ($T_{\mathrm{eff}} \geq 3$ MK) hydrogen model atmospheres at high energies (Fig. 2). The hard emergent photons lost energy and heat the upper layers of the atmosphere due to interactions with electrons. As a result the high energy tails of the emergent spectra become close to Wien spectra, and chromosphere-like structures with temperatures close to color temperatures of the Wien spectra in the upper layers of the model atmospheres appear. Moreover, the overall emergent model spectra of high temperature atmospheres in first approximation can be presented as diluted blackbody spectra with color temperatures that are close to
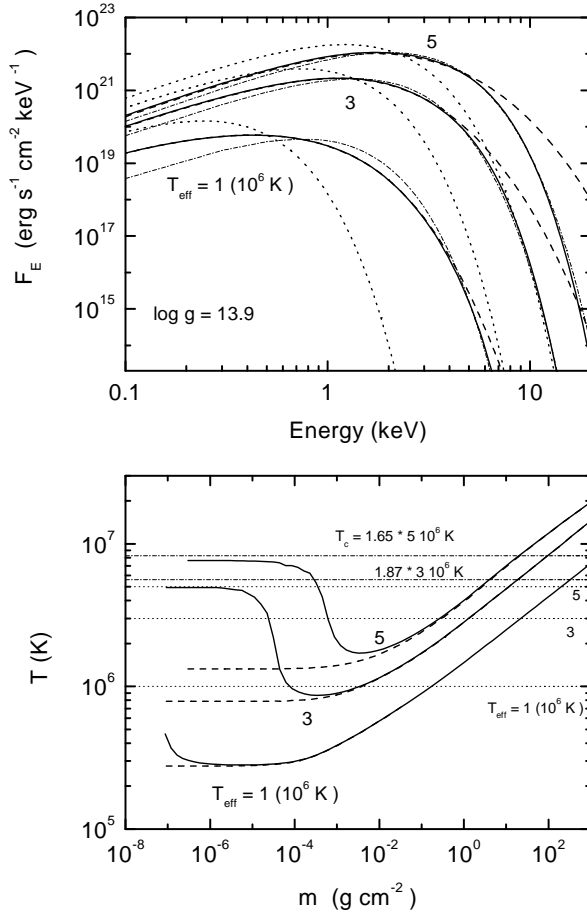
Fig. 2. *Top panel:* Emergent (unredshifted) spectra of pure H low gravity NS model atmospheres. Solid curves - with Compton effect, dashed curves - without Compton effect, dotted curves - blackbody spectra, thin dash-dotted curves - diluted blackbody spectra with hardness factors 3.1, 1.87 and 1.65, 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 dotted and dash-dotted lines.

Wien tail color temperatures:

$$F_{\rm E} = \frac{\pi}{f_{\rm c}^4} B_{\rm E}(T_{\rm c}), \qquad T_{\rm c} = f_{\rm c}T_{\rm eff}, \qquad (3)$$

where $f_{\rm c}$ is hardness factor. These results are similar to those obtained for model atmospheres and emergent spectra of X-ray bursting NS in LMXBs (see Pavlov et al. 1991; Madej et al. 2004).

The Compton scattering effect on the emergent model spectra of high gravity atmospheres is less significant (Fig. 3). The reason is a relatively small contribution of electron scattering to the total opacity in high gravity atmospheres compared to low gravity ones.

The Compton scattering effect on helium model atmospheres is also less significant than on hydrogen model
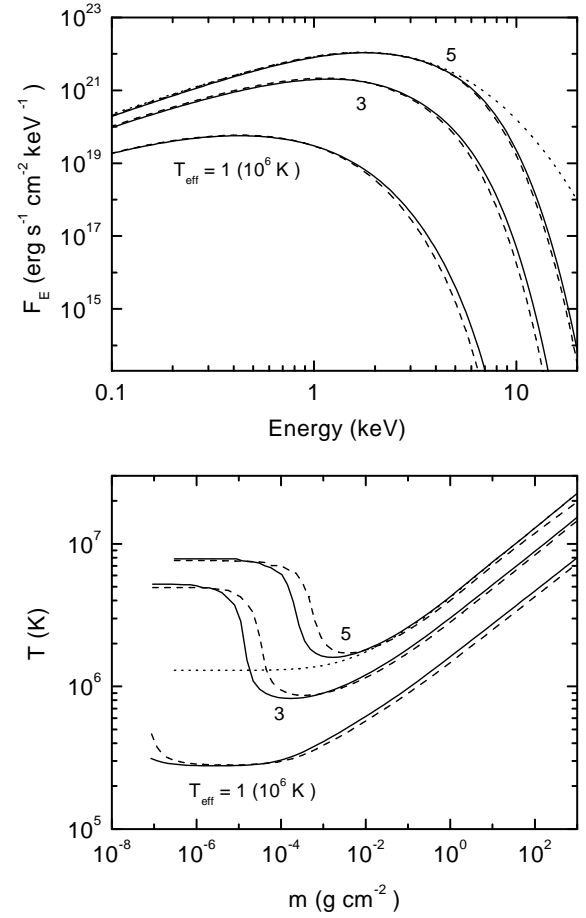
Fig. 3. *Top panel:* Emergent (unredshifted) spectra of H NS model atmospheres with different surface gravities (solid curves - high gravity models, dashed curves - low gravity models). For comparison the model spectra without Compton effect are shown for hottest high gravity model (dotted curve). *Bottom panel:* Temperature structures of the corresponding model atmospheres.

atmospheres with the same $T_{\rm eff}$ and log g (Fig. 4). The reason is the same as in the case of high gravity models. The contribution of electron scattering to the total opacity is less in the helium models.

We also computed one isolated NS model atmosphere with solar metal abundances and $T_{\rm eff}$ = 3 MK and log g=14.3 (see Fig. 5). The model was calculated with Thomson and Compton scattering and we found that the Compton effect on the emergent spectrum is very small.

5. Conclusions

Emergent model spectra of hydrogen and helium NS atmospheres with $T_{\rm eff}$ > 1 MK are changed by the Compton effect at high energies (E > 5 keV), and spectra of the hottest ($T_{\rm eff} \geq 3$ MK) model atmospheres can be described by diluted blackbody spectra with hardness fac-
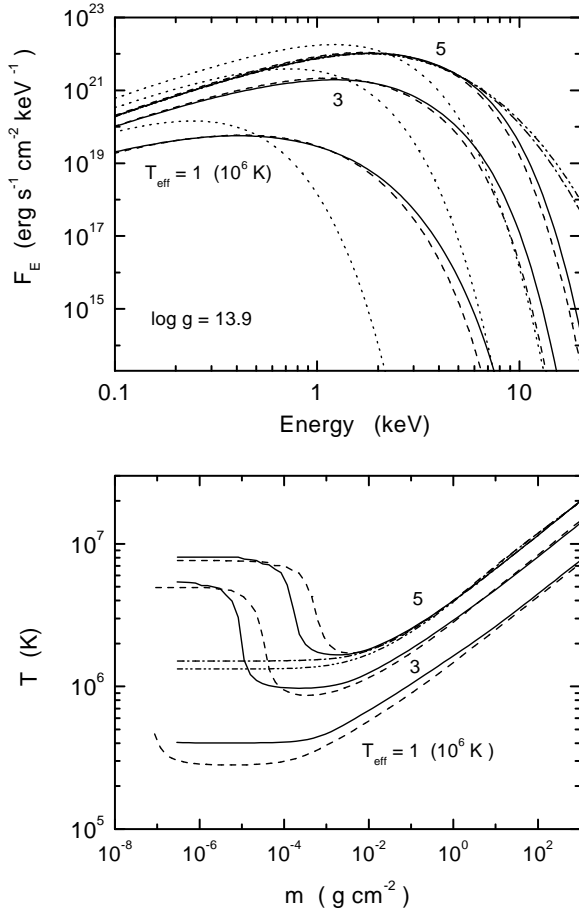
Fig. 4. *Top panel:* Emergent (unredshifted) model spectra of pure He low gravity NS model atmospheres. For comparison the model spectra of pure H atmospheres are shown by dashed curves. The model spectra of hottest atmospheres without Compton effect are shown by dash-dotted and dash-dot-dotted curves. *Bottom panel:* Temperature structures of the corresponding model atmospheres.

tors ∼ 1.6 - 1.9. But at the same time the spectral energy distribution of these models are not significantly changed at the maximum of the SED (at energies 1-3 keV), and effects on the color temperatures are not large.

The Compton effect is most significant for hydrogen model atmospheres and to low gravity models. Emergent model spectra of NS atmospheres with solar metal abundances are changed by Compton effects very slightly.

References

Ebisuzaki T., 1987, PASJ 39, 287
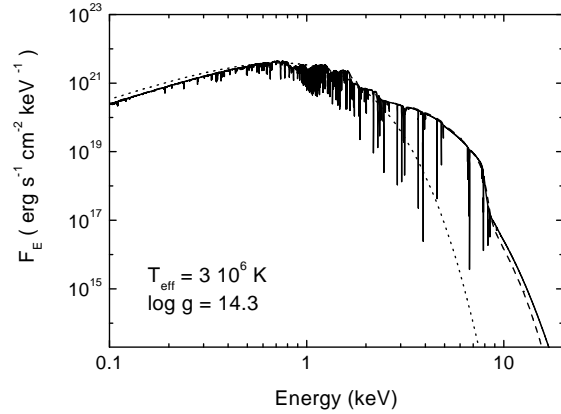Grebenev S.A., & Sunyaev R.A., 2002, Astr. Lett. 28, 150

Fig. 5. Emergent (unredshifted) model spectra of high gravity NS atmospheres with solar abundance of 15 most abundant heavy elements with (dashed curve) and without (solid curve) Compton scattering. The dotted curve is the corresponding blackbody spectrum.

Hubeny I., Hummer D.G., & Lanz T., 1994, A&A 282, 151
Hummer D.G., & Mihalas D., 1988, ApJ 331, 794
Ibragimov A., Suleimanov V., Vikhlinin A., et al., 2003, Astr. Rep. 47, 186
Kompaneets A.S., 1957, Sov. Phys. JETP 4, 730
Kurucz R., 1970, SAO Spec. Rep. 309, 1
Kurucz R. CD-ROMs, 1993, Smithsonian Astrophysical Observatory, Cambridge, Mass.
Lapidus I.I., Sunyaev R.A., & Titarchuk L.G., 1986, Sov. Astr. Lett. 12, 383
London R.A., Taam R.E., & Howard W.M., 1986, ApJ 306, 170
Madej J., 1991, ApJ 376, 161
Madej J., Joss P.C, & Rozanska A., 2004, ApJ 602, 904
Mereghetti S., Tiengo A. & Israel G.L., 2002, ApJ 569, 275
Mihalas D. Stellar Atmospheres, 1978, W.H. Freeman and Co., San Francisco
Pavlov G.G., Shibanov Y.A. & Zavlin V.E., 1991, MNRAS 253, 193
Pavlov G.G., Zavlin V.E., & Sanwal D., 2002, in The Proceedings of the 270th WE-Heraeus Seminar on Neutron Stars, Pulsars, and Supernova Remnants, Becker, W., Lesch, H., Trümper, J. (eds.) Garching bei München, MPE Report 278, p.273
Rybicki G.B. & Lightman A.P., Radiative processes in astrophysics, 1979, (New York, Wiley-Interscience)
Romani R.W., 1987, ApJ 313, 718
Suleimanov V., & Poutanen J., 2006, MNRAS 369, 2036
Suleimanov V., Madej J., Drake J.J., et al., 2006, A&A (in press) (astro-ph/0605318)
Zavlin V.E., & Shibanov Y.A., 1991, Sov. Astr. 35, 499
Zavlin V.E., & Pavlov G.G., 2002, in The Proceedings of the 270th WE-Heraeus Seminar on Neutron Stars, Pulsars, and Supernova Remnants, Becker, W., Lesch, H., Trümper, J. (eds.) Garching bei München, MPE Report 278, p.263