MODEL ATMOSPHERES OF MAGNETIC NEUTRON STARS

Nondiffusional Transport and Anisotropic Emission

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Abstract. An efficient method is presented which allows one to obtain an accurate numerical solution of the radiative transfer in atmospheres of cooling neutron stars (NS) with strong magnetic fields. It is a combination of the diffusion approach and subsequent iterative solution of the anisotropic radiative transfer equations. The method is applied to the computation of the spectral flux, pulse profile and modulation index of X-ray radiation from a rotating NS with a small polar hot spot on the surface. The results are compared with the corresponding blackbody and nonmagnetic atmosphere models.

Key words: Radiative transfer. Cooling neutron stars. Pulsar thermal emission.

Computation of the magnetized NS atmosphere model can be split in two parts: (i) construction of a diffusion approximation model (Shibanov *et al.*, 1992; Pavlov *et al.*, 1994); (ii) correction of the diffusion model with an iterative procedure. For this we use a generalization of the so-called Λ-iteration method (Mihalas, 1978) for the case of anisotropic photon transfer. The diffusion approximation offers the simplest and quickest way for obtaining an appropriate initial knowledge of the source function (temperature and density profiles, etc.) for the radiation in the extraordinary polarization mode, which emerges from optically deep, hot atmospheric layers, giving the main contribution to the escaping intensity. The iterative corrections change mainly the structure of cooler surface layers (cf. Fig. 1) and the related emission in the ordinary mode coming from these layers, whose contribution to the overall escaping flux is small. Thus, one can obtain rather accurate solutions for the escaping radiation after only few iterations.

The formal solution of the radiative transfer equations for the angle-dependent

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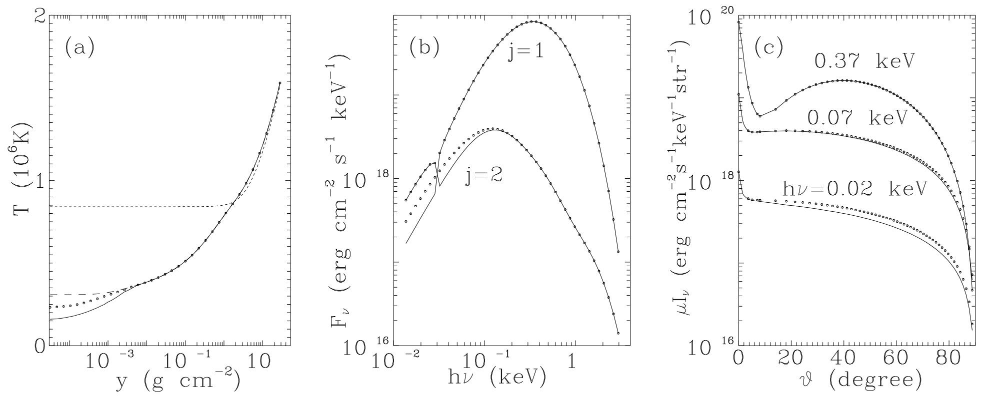

Fig. 1. Illustration of the convergence of the method for the temperature depth profile (a), the spectral (b) and angular (c) dependences of the emerging flux at various steps of solution. Solid curves show the "exact" final solution, long dashes correspond to the diffusion approach, dots and short dashes denote the results after first correction and the gray atmosphere temperature profile, respectively.

intensities of two polarization (normal) modes I_j (Kaminker *et al.*, 1982) reads

$$I_j^+(\mathbf{n},y) = \frac{1}{\mu}\int\limits_y^{y_{max}} dy' S_j(\mathbf{n},y')\exp(-\frac{1}{\mu}\int_y^{y'} K_j(\mathbf{n},y'')dy'')+$$

$$+I_j^+(y_{max})\exp(-\frac{1}{\mu}\int_y^{y_{max}} K_j(\mathbf{n},y')dy'), \quad \mu \geq 0 \tag{1}$$

$$I_j^-(\mathbf{n},y) = -\frac{1}{\mu}\int\limits_{y_{min}}^{y} dy' S_j(\mathbf{n},y')\exp(\frac{1}{\mu}\int_{y'}^{y} K_j(\mathbf{n},y'')dy''), \quad \mu \leq 0 \tag{2}$$

where $j = 1,2$ stands for the extraordinary and ordinary modes, respectively, μ is the cosine of the angle θ between the wave vector direction $\mathbf{n}$ and the normal to the emitting surface, and $dy = -\rho dz$ is the column density variable. The extinction coefficient, K_j is the sum of the absorption and scattering coefficients K_j^a and K_j^s. The source function for the j-th mode is

$$S_j = K_j^a \frac{B_\nu(T)}{2} + \sum_{i=1}^{2}\int d\mathbf{n}' K_{ji}^s(\mathbf{n},\mathbf{n}')I_i(\mathbf{n}') \tag{3}$$

where $B_\nu(T)$ is the Planck function, K_{ji}^s is the scattering conversion coefficient of the mode i into the mode j.

The conservation of the outward flux H throughout the atmosphere,

$$H = \int d\nu \int d\mathbf{n}\mu \sum_{j=1}^{2}(I_j^+ + I_j^-) = \sigma T_{\rm eff}^4, \tag{4}$$

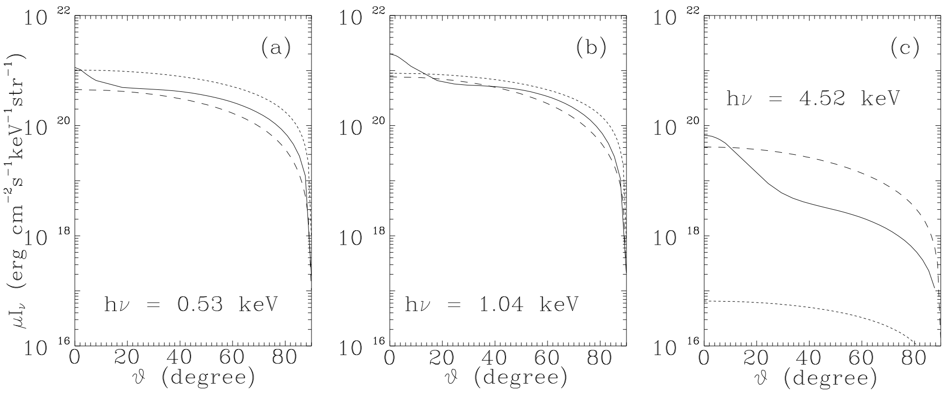

Fig. 2. Specific fluxes at different photon energies for the hot spot models with $B = 4.7 \times 10^{12}$ G (solid curves), with $B = 0$ (long dashes), and for the blackbody model (short dashes).

leads to the following condition for the radiative equilibrium

$$f = \int d\nu \int d\mathbf{n} \sum_{j=1}^{2} K_j^a \left(I_j^+ + I_j^- - \frac{B_\nu(T)}{2} \right) = 0, \tag{5}$$

which is used to obtain a correction to the temperature profile

$$\Delta T = -\frac{f}{df/dT}. \tag{6}$$

To compute the model, one should close the above system by the hydrostatic and ionization equilibrium equations.

To obtain the solution, we start with the source function obtained in the diffusion approximation, solve Eqs. (1) and (2), and find the temperature corrections from Eq. (6). Then, we find a new hydrostatic and ionization equilibrium in the atmosphere, solve the radiative transfer equations (1) and (2) anew, and iterate until convergence is reached. If scattering is negligible (at $T_{\rm eff} \lesssim 10^6 K$ for hydrogen atmospheres), then the solution of the radiative transfer problem is directly given by Eqs. (1) and (2), since the source function, Eq. (3) with $K_{ij}^s = 0$, is known. At higher effective temperatures, the source function depends on the intensities, and Eqs. (1) and (2) themselves need to be solved iteratively.

The convergence of the method is demonstrated in Figure 1, for a hydrogen model atmosphere with the surface gravity $g = 2.43 \times 10^{14}$ cm s^{-2}, magnetic field $B = 4.7 \times 10^{12}$ G normal to the surface, and effective temperature $T_{\rm eff} = 10^6$ K. At such high temperatures the atmosphere is almost fully ionized so that contribution to the opacity from nonionized atoms was neglected (cf. Shibanov *et al.*, 1992). It is seen that, the initial (diffusion) and final temperature profiles differ only in the very surface layers leading only to small changes in the low-energy emergent fluxes, while at moderate and higher photon energies the first correction to the flux gives an accuracy (few %) acceptable for comparing theoretical results with observations.

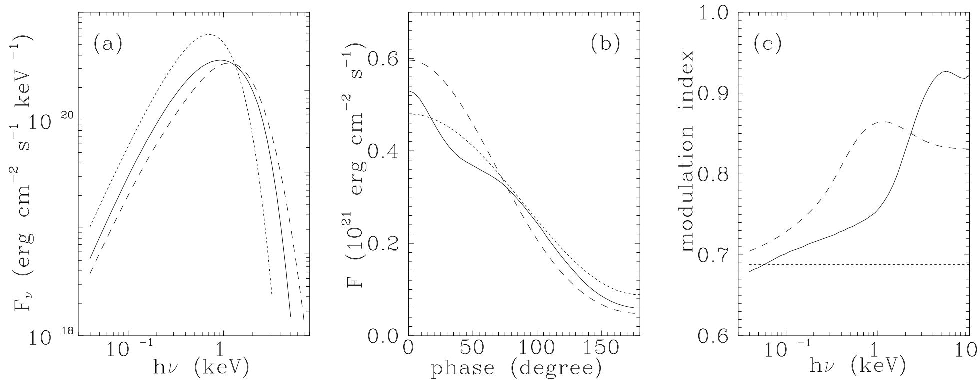

Fig. 3. Spectra averaged over the NS rotation (a), pulse profiles integrated over photon energies (b), and the modulation indices (c) for the hot spot corresponding to the geometry of PSR 1929+10. See Fig. 2 for notations.

ROSAT observations of radio pulsars have revealed that at least some of them may have a small polar hot spot responsible for the hard radiation in the few keV range. The angular charcteristics of radiation from such a spot with the parameters $T_{\rm eff} = 2.9 \times 10^6$K, $g = 2.43 \times 10^{14}$ cm s^{-2}, $B = 1.18 \times 10^{12}$ G are shown in Figure 2. It is seen that the magnetic field should influence the pulse shape and its dependence on photon energy, in comparison with the blackbody and nonmagnetic atmosphere models. Figure 3 shows the application of the model to the geometry obtained from radio observations of PSR 1929+10 (Phillips, 1990). The angles between the NS rotation and magnetic axes and the line of sight are equal to 31° and 51°, respectively. It is clear that quite different conclusions can be reached when these different models are used in interpreting the observational data on thermal X-ray radiation from NSs. Note that the energy dependence of the modulation index $(F_{max} - F_{min})/(F_{max} + F_{min})$ for the nonmagnetic model may have some relation to the observed energy dependence of pulsed X-rays from the millisecond pulsar PSR J0437-4715 (Becker and Trümper, 1993).

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