Radiative Opacities and Photosphere Models for Soft Gamma-Ray Repeaters

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We consider the radiative processes for conditions expected in photospheres of neutron stars (NSs) with magnetic fields $B \sim 10^{14} - 10^{16}$ G. The radiative opacities are employed to construct model photospheres and to calculate the spectral flux and specific intensity emitted by these objects which are thought to be associated with Soft Gamma-Ray Repeaters (SGRs).

INTRODUCTION

The presence of superstrong magnetic fields, $B \sim 10^{14} - 10^{16}$ G, in radiating layers of SGRs has been suggested in (1) to explain the apparent super-Eddington luminosities observed from these enigmatic sources of thermal-like radiation with spectral temperatures $T_{\rm sp} \sim 10$ keV. This hypothesis is based on strong suppression of the electron Thomson scattering cross section for radiation polarized perpendicular to the magnetic field at photon energies lower than the electron cyclotron energy $E_{\rm Be} = 11.6 B_{15}$ MeV. According to (1–5), this effect can substantially reduce the radiative force and increase the critical luminosity above the observed SGR luminosities, $L \sim 10^{42}$ erg/s.

If the SGR magnetic fields are indeed so strong, the opacity can be significantly contributed by protons, especially if the energy $E_{\rm Bp} = 6.3 B_{15}$ keV of the proton cyclotron resonance gets into the X-ray range. Besides, for B exceeding the QED critical value $B_{\rm c} = 4.414 \times 10^{13}$ G, the polarized electron-positron vacuum strongly affects interaction of radiation with particles. We shall calculate the radiative opacities and construct SGR photosphere models with allowance for these effects.

RADIATIVE OPACITIES

We consider the radiative processes in a completely ionized, nondegenerate, strongly magnetized electron-proton plasma of a temperature $T \sim 10$ keV.

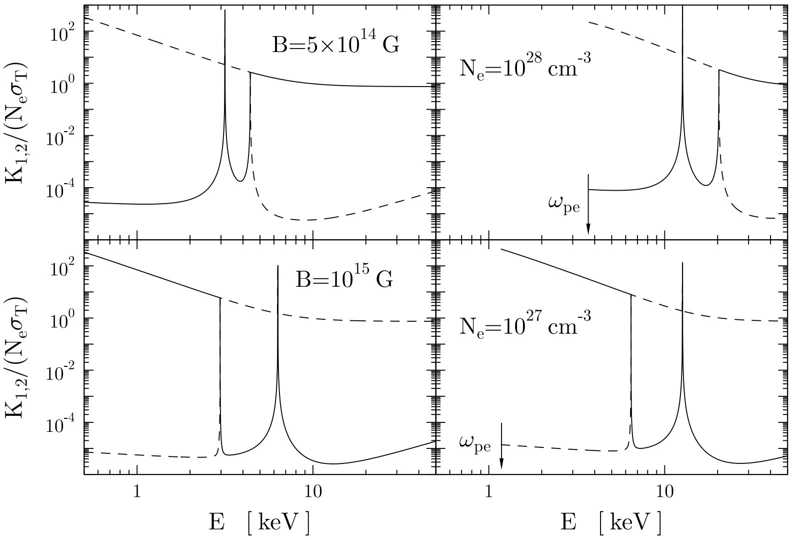

FIG. 1. Spectral opacities for two normal modes at $T = 10$ keV and $\vartheta = 60°$. Left panels show the opacities at the electron number density $N_e = 10^{26}$ cm^{-3} for different values of the magnetic field. Right panels correspond to $B = 2 \times 10^{15}$ G and different N_e. The arrows indicate the electron plasma frequencies.

Radiation propagates in such a plasma in form of two normal modes (NMs) – see (6). The *Thomson scattering* of photons on electrons and protons, as well as absorption and emission of photons in the *free-free transitions* of these particles, is included into the NM opacities as described in (7). To calculate the NM polarizations, we take into account the polarizabilities of both the electron-proton plasma and electron-positron vacuum (8). As a result, the NMs are polarized linearly in a wide domain of the photon energies E and angles ϑ between the direction of propagation and the magnetic field; the polarizations are nearly circular near the proton cyclotron resonance and a *"vacuum feature"*. The latter appears at the energy $E_{\rm vac}$ due to the compensation of the plasma and vacuum contributions to some components of the polarizability tensor (9). Our analysis shows that the vacuum feature energy is determined by the electron number density $N_{\rm e}$ and magnetic field strength B; $E_{\rm vac} \approx 0.89 N_{\rm e\,25}^{1/2} B_{15}^{-1/2}$ keV if $B \gg B_{\rm c}$ and $E_{\rm vac}$ is not too close to $E_{\rm Bp}$.

FIG. 1 demonstrates that the extinction coefficients of two NMs are remarkably different, by 4–8 orders of magnitude. Their energy dependences show strong proton cyclotron resonances and cross each other at the vacuum feature energies. At higher energies and lower densities the opacities are dominated by Thomson scattering, while the free-free transitions dominate at lower energies. Our approach is applicable at $E \gg \hbar\omega_{\rm pe} = 0.12 N_{e\,25}^{1/2}$ keV, where $\omega_{\rm pe}$ is the electron plasma frequency.

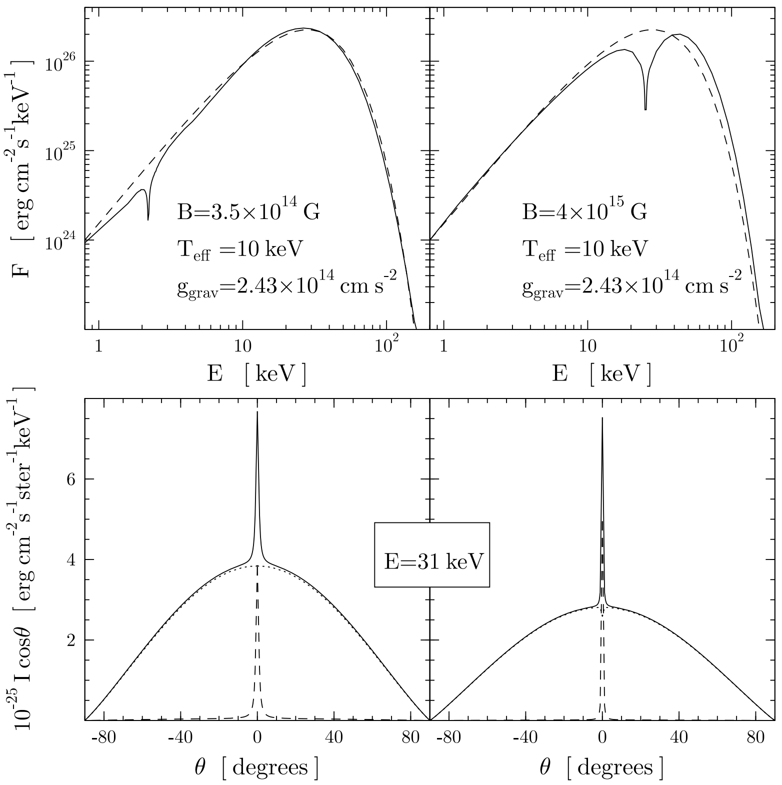

FIG. 2. Emergent spectral fluxes (top plots) and angular dependences of the specific fluxes (bottom plots) for two NS photosphere models with different strengths of the magnetic field (left and right) directed along the NS radius. The dashed lines in the top plots show the blackbody spectra with the same effective temperature. Dotted and dashed curves in the bottom panels show the angular diagrams in two polarization modes; solid lines show the total specific flux.

PHOTOSPHERE MODELS

The above radiative opacities can be used to model NS photospheres. We assume that the energy is produced at deep subphotospheric layers, so that the photosphere is in radiative equilibrium. We solve the coupled radiative transfer equations for the NMs, hydrostatic and radiative equilibrium equations, and equation of state to calculate the temperature T, density ρ and radiative acceleration $g_{\rm rad}$ at different depths y, as well as the NM spectral intensities $I_{1,2}(E,\theta)$ and fluxes $F_{1,2}(E) = 2\pi \int_0^\pi I_{1,2}(E,\theta)\, \cos\theta\, \sin\theta\, {\rm d}\theta$ (7). Here θ is the angle between the photosphere normal and the direction of emission.

We have computed two models for $T_{\rm eff} = 10$ keV and gravitational acceleration $g_{\rm grav} = 2.43\times 10^{14}$ cm s^{-2} which corresponds to the NS mass $M = 1.4 M_\odot$

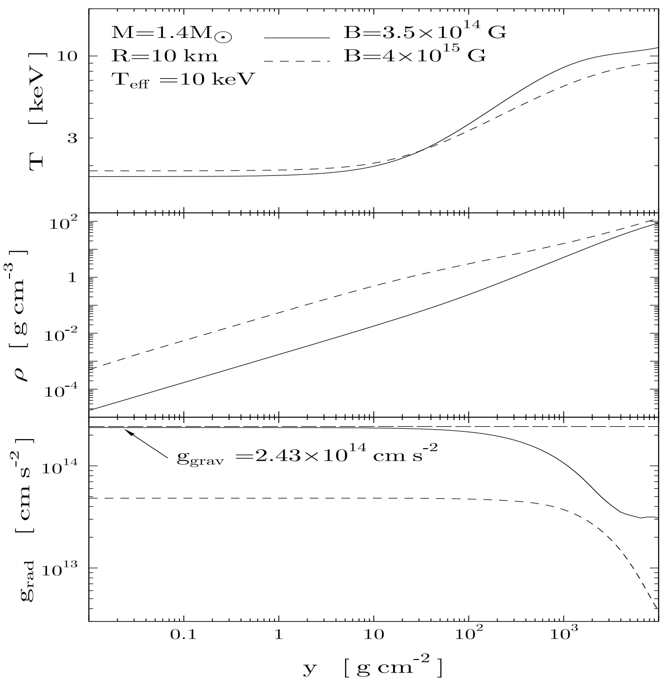

FIG. 3. The depth dependences of the temperature T, density ρ, and radiative acceleration $g_{\rm rad}$, for two NS photosphere models shown in FIG. 2.

and radius $R = 10$ km. In both models the magnetic field is directed along the NS radius (the magnetic pole region), but the strengths of the field are different: 3.5×10^{14} G and 4×10^{15} G. FIG. 2 demonstrates the emergent spectral flux $F = F_1 + F_2$ and the angular distribution of the specific fluxes $I \cos\theta$. The spectra show strong *proton cyclotron absorption lines*, at $E = 2.2$ keV and 25.2 keV for the two models, while the continuum components are remarkably close to the *blackbody spectrum* of the same effective temperature. The angular distributions consist of two components: nearly isotropic in one NM, and highly anisotropic (beamed along the magnetic field) in other NM. Therefore, the radiation is almost 100% linearly polarized (perpendicular to the magnetic field) in a wide domain of energies and directions. The vacuum spectral feature, which would be clearly seen in absorption if the density were uniform, is practically indiscernible in the emergent spectrum. It is smeared out by the strong density gradients in the radiating layers (FIG. 3).

Both models take into account the *radiative force* (10), which must be smaller than the gravitational force for the photosphere to be in hydrostatic equilibrium. The results show that at $T_{\rm eff} = 10$ keV, the outer layers of the photosphere are stable ($g_{\rm grav} > g_{\rm rad}$) for $B \geq 3.5 \times 10^{14}$ G (the lower field model is just on the verge of stability), and for $B = 4 \times 10^{15}$ G we obtain $g_{\rm rad}/g_{\rm grav} \simeq 0.2$ at the NS surface. This allows us to assume the approximate scaling law to be $g_{\rm rad} \propto B^{-0.66}$.

CONCLUSIONS

Modeling of NS photospheres with the accurate opacities of the NMs and with allowance for the radiative force, shows the following:

- Blackbody-like spectra with spectral temperatures $T_{\rm sp} \sim 10$ keV observed from SGRs can be produced in NS photospheres with superstrong magnetic fields and with $T_{\rm eff} \simeq T_{\rm sp}$.
- The photospheres at the NS magnetic poles can be in hydrostatic equilibrium if the magnetic field exceeds $\sim 10^{14} - 10^{15}$ G; in particular, $B \geq 3.5 \times 10^{14}$ G for $T_{\rm eff} = 10$ keV.
- The strength of the field can be evaluated from the energy of the absorption proton cyclotron line which can be observed with a moderate spectral resolution in the X-ray range.
- If the observed duration of a SGR burst exceeds the NS rotation period, and the SGR radiation is emitted by a fraction of the NS surface, a modulation of the SGR light curve with the rotation period can be observed; the modulation is expected to be smooth unless the direction of the local magnetic field coincides with the line of sight at some phases, which would result in short spikes of the observed flux.
- The SGR radiation is expected to be linearly polarized.

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REFERENCES

1. B. Paczyński, Acta Astron. **42**, 145 (1992).
2. C. Thompson and R.C. Duncan, ApJ **408**, 194 (1993).
3. C. Thompson and R.C. Duncan, MNRAS **275**, 255 (1995).
4. A. Ulmer, ApJ **437**, L111 (1994).
5. M.C. Miller, ApJ **448**, L29 (1995).
6. Yu.A. Gnedin and G.G. Pavlov, Sov. Phys. JETP **39**, 301 (1974).
7. G.G. Pavlov, Yu.A. Shibanov, V.E. Zavlin and R.D. Meyer, in The Lives of the Neutron Stars, eds. M. A. Alpar, Ü. Kiziloğlu and J. van Paradijs (Dordrecht: Kluwer), 71 (1995).
8. W. Tsai and T. Erber, Phys. Rev. D **12**, 1132 (1975).
9. G.G. Pavlov and Yu.A. Shibanov, Sov. Phys. JETP **49**, 741 (1979).
10. I.G. Mitrofanov and G.G Pavlov, MNRAS **200**, 1033 (1982).