

Magnetized neutron star atmospheres: beyond the cold plasma approximation

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All magnetized neutron star model atmospheres hitherto computed use opacities calculated in the cold plasma approximation. Here we present models of hydrogen neutron star atmospheres with the thermal cyclotron opacities taken into account. The parameters of the atmospheres are typical for the so-called central compact objects in supernova remnants, such as 1E 1207.4–5209 in PKS 1209–51/52. We show that the Doppler cores of the first three cyclotron harmonics can be significant for the interpretation of observable absorption features, in addition to the quantum oscillations in magnetic free-free opacity. The absorptions due to the quantum oscillations determine the total equivalent widths, but the relative contributions of the Doppler cores grow with increasing quantization parameter $b_{\text{eff}} \equiv E_{c,e}/kT_{\text{eff}}$ and harmonic number. The total equivalent widths of the features can reach $\sim 100\text{--}250$ eV; they increase with growing b_{eff} and are smaller for higher harmonics.

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1. Opacities in electron cyclotron line and harmonics

Our consideration of the thermal cyclotron opacities is based on the work of Pavlov, Shibano and Yakovlev [1]. The relativistic quantum description of the cyclotron opacities in that work is performed in collisionless approximation, applicable to Doppler cores of the cyclotron lines only. Therefore, we use the following approach here. We calculate separately the opacities in cold plasma approximation with quantum oscillations in magnetic free-free opacities taken into account (see details in [2,3]) and the opacities in cyclotron line and harmonics in quantum collisionless approximation. Then we compare both opacities at each used photon energy and take the largest one as the actual opacity. We perform all calculations in LTE approximation for the cyclotron radiation. This means that cyclotron opacities are considered as a true absorption only, without scattering, and we assume that the source function for the cyclotron radiation is equal to the Planck function.

We calculate opacities for the extraordinary (X) and the ordinary (O) modes. An example of computed continuum opacities, together with opacities at cyclotron line and harmonics for various angles θ between magnetic field and photon propagation direction, are shown in Fig. 1. It is important that, at some angles, opacities at fundamental resonance and first two harmonics are larger than continuum opacities in both modes.

2. Results of atmosphere modeling

We calculate the magnetic NS hydrogen atmosphere models using our recently developed code [2,3], assuming the magnetic field normal to the stellar surface. We also assume full ionization and neglect vacuum polarization.

We calculated two sets of atmosphere models with the surface gravitational acceleration $g = 10^{14} \text{ cm s}^{-2}$. In the first set the magnetic field strength was fixed ($B = 7 \times 10^{10} \text{ G}$) and models with three different effective temperatures ($T_{\text{eff}} = 1, 1.5 \text{ and } 3 \text{ MK}$) were computed (see Fig. 2, left panels). The second set consists of four models with different magnetic field strengths ($B = 1, 4, 7, \text{ and } 10 \times 10^{10} \text{ G}$) at the same effective temperature ($T_{\text{eff}} = 1.5 \text{ MK}$) (see Fig. 2, right panels).

Spectra of emergent specific intensity for the model with $T_{\text{eff}} = 1.5 \text{ MK}$ and $B = 7 \times 10^{10} \text{ G}$ for various angles θ between the line of sight and the surface normal are shown in the bottom panel of Figure 3.

In the top panel of the same Figure 3 angular distributions of the emergent intensity at five photon energies (near the fundamental resonance, the first harmonic, and three continuum energies) are shown. The specific intensities at cyclotron cores are strongly peaked along the surface normal in comparison with those in the continuum.

3. Conclusions

- Taking into account the thermal cyclotron opacities leads to the appearance of deep Doppler cores of the first cyclotron harmonics in the emergent spectra of the considered model atmospheres.

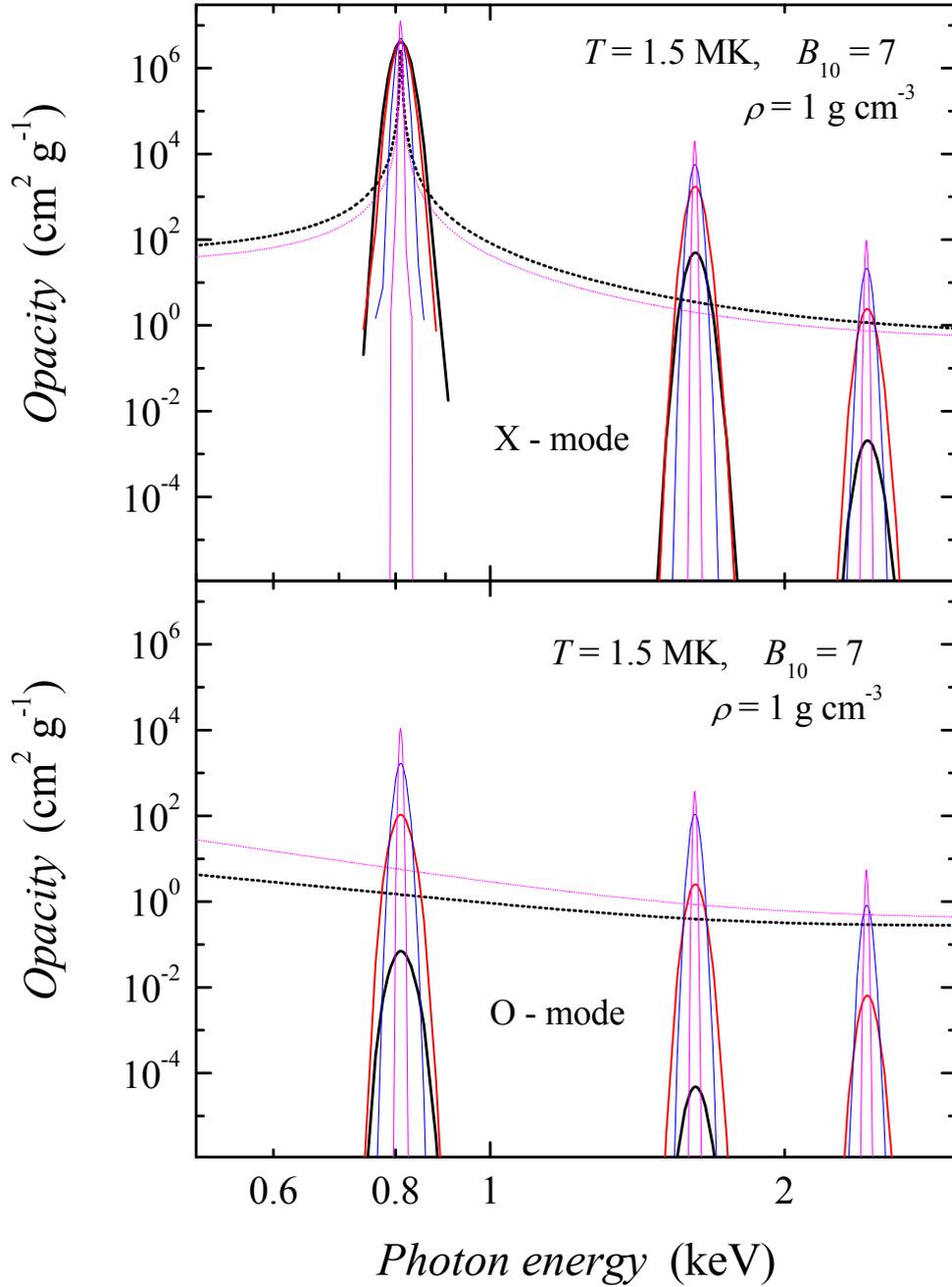


Figure 1: Opacities in cyclotron lines and continuum opacities in both modes (top and bottom panels) in a magnetized plasma with $T = 1.5 \text{ MK}$, $\rho = 1 \text{ g cm}^{-3}$, and $B_{10} = 7$ ($B_{10} \equiv B/10^{10} \text{ G}$) and various angles θ (5° - thickest black curves, 30° - thick red curves, 60° - thin blue curves, and 80° - thinnest magenta curves) between magnetic field and photon propagation. Continuum opacities are shown by short-dashed curves (thick black curves for $\theta = 5^\circ$ and thin magenta curves for 80°).

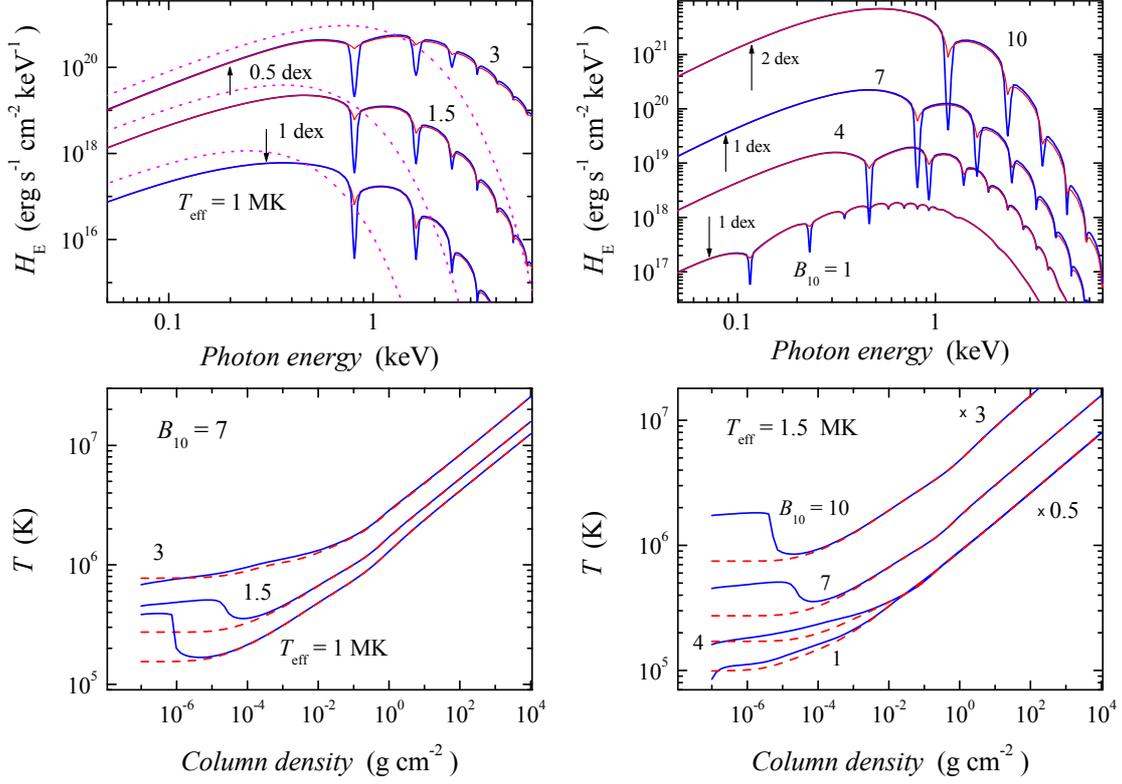


Figure 2: *Left panels:* In the top panel we show the emergent spectra for NS atmospheres with magnetic field $B = 7 \times 10^{10}$ G with thermal cyclotron opacities (thick solid curves) and without thermal cyclotron opacities (thin solid curves) for three effective temperatures, $T_{\text{eff}} = 1, 1.5,$ and 3 MK. For clarity, the spectra for $T_{\text{eff}} = 3$ and 1 MK are shifted along the ordinate axis by factors $10^{+0.5}$ and 10^{-1} . The dotted curves show the blackbody spectra for the same temperatures. In the bottom panel we show the temperature structures of the same models. Solid and dashed curves correspond to the models with and without thermal cyclotron opacities, respectively. *Right panels:* In the top panel we show the emergent spectra for magnetic NS atmospheres with $T_{\text{eff}} = 1.5$ MK and different magnetic fields ($B = 1, 4, 7$ and 10×10^{10} G), calculated with (thick solid curves) and without (thin solid curves) thermal cyclotron opacities. For clarity, the spectra for $B_{10} = 10, 7$ and 1 are shifted along the ordinate axis by factors $10^{+2}, 10^{+1}$ and 10^{-1} . In the bottom panel we display the temperature structures of the models with (solid curves) and without (dashed curves) thermal cyclotron opacities, for the same parameters. For clarity, the temperature structures for $B_{10} = 10, 4$ and 1 are shifted along the ordinate axis by factors $3, 0.5$ and 0.5 .

- The total equivalent widths of the absorption features reach $100 - 250$ eV; they decrease with increasing harmonic number and/or decreasing quantization parameter b_{eff} .
- The harmonically spaced absorption features in the X-ray spectrum of the CCO 1E 1207 [4,5] must be interpreted with the allowance for thermal cyclotron opacities.

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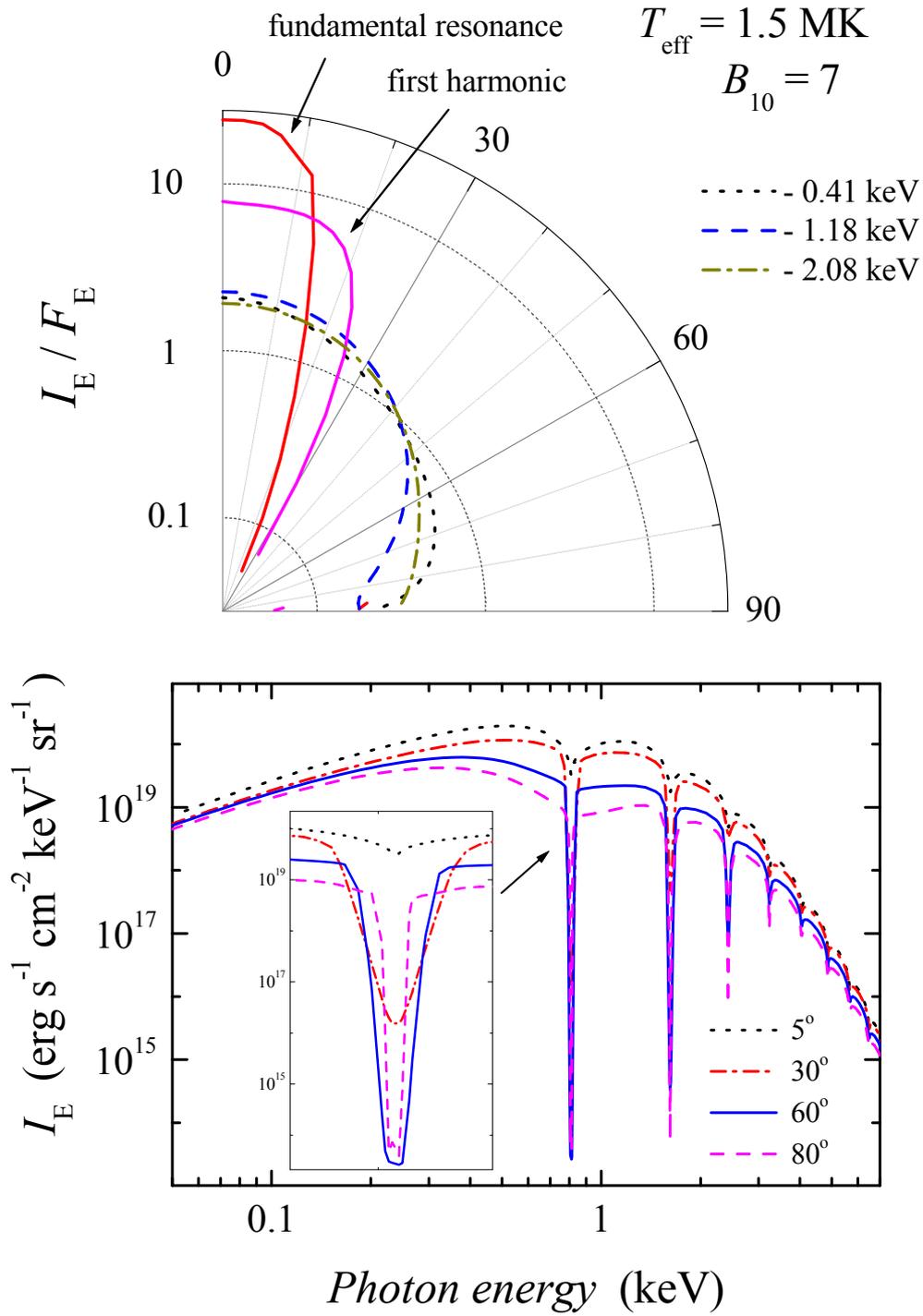


Figure 3: *Top panel:* Angular distribution of the emergent specific intensity in the fundamental resonance and the first harmonic, and for three continuum photon energies (indicated in the plot) for a NS atmosphere with $B = 7 \times 10^{10}$ G and $T_{\text{eff}} = 1.5$ MK. *Bottom panel:* Spectra of the emergent specific intensity for the same model at different angles to the surface normal (indicated in the plot).

References

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