Absorption Features in Spectra of Magnetized Neutron Stars

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Abstract. The X-ray spectra of some magnetized isolated neutron stars (NSs) show absorption features with equivalent widths (EWs) of 50 – 200 eV, whose nature is not yet well known.

To explain the prominent absorption features in the soft X-ray spectra of the highly magnetized ($B \sim 10^{14}$ G) X-ray dim isolated NSs (XDINSs), we theoretically investigate different NS local surface models, including naked condensed iron surfaces and partially ionized hydrogen model atmospheres, with semi-infinite and thin atmospheres above the condensed surface. We also developed a code for computing light curves and integral emergent spectra of magnetized neutron stars with various temperature and magnetic field distributions over the NS surface. We compare the general properties of the computed and observed light curves and integral spectra for XDINS RBS 1223 and conclude that the observations can be explained by a thin hydrogen atmosphere above the condensed iron surface, while the presence of a strong toroidal magnetic field component on the XDINS surface is unlikely.

We suggest that the harmonically spaced absorption features in the soft X-ray spectrum of the central compact object (CCO) 1E 1207.4–5209 (hereafter 1E 1207) correspond to peaks in the energy dependence of the free-free opacity in a quantizing magnetic field, known as quantum oscillations. To explore observable properties of these quantum oscillations, we calculate models of hydrogen NS atmospheres with $B \sim 10^{10}$–10^{11} G (i.e., electron cyclotron energy $E_{c,e} \sim 0.1$–1 keV) and $T_{\rm eff} = 1$–3 MK. Such conditions are thought to be typical for 1E 1207. We show that observable features at the electron cyclotron harmonics with EWs ≈ 100 – 200 eV can arise due to these quantum oscillations.

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ABSORPTION FEATURE IN THE SPECTRUM OF RBS 1223

XDINSs are a new class of pulsing X-ray sources with soft ($T_{\rm eff} \sim 10^6$ K) thermal-like spectra (see [1] for a review). Here we consider the most extreme member of the XDINSs – RBS 1223, which is pulsing with an amplitude of 18% [2] and shows the most prominent absorption feature with an equivalent width (EW) of ≈ 200 eV at ≈ 0.3 keV [3]. We investigate what kind of radiating surface can qualitatively explain the ob-

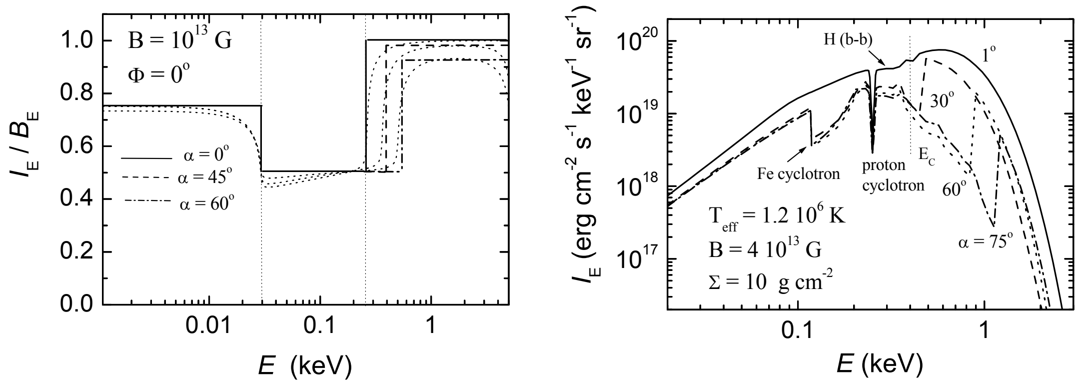

FIGURE 1. *Left:* Approximation of the dimensionless emissivity as a function of photon energy E for the case of a condensed iron surface at $B = 10^{13}$ G. The magnetic field is normal to the surface. *Right:* Emergent specific intensity spectra of a model atmosphere above a condensed iron surface.

served properties of this XDINS. For this aim, three local models are considered: naked condensed surfaces, semi-infinite magnetized model atmospheres, and thin magnetized model atmospheres above condensed surfaces.

Spectra of naked condensed iron surfaces [4] are represented using a simple analytical approximation (see Fig. 1, left panel). In the free-ion approximation, a broad absorption feature exists in the spectrum. It lies between the ion cyclotron energy $E_{\rm c,Fe} \approx 0.32\ (B/10^{14} G)$ keV, and some boundary energy $E_{\rm C}$, which weakly depends on the magnetic field and strongly depends on the angle α between the magnetic field and the photon propagation direction ($E_{\rm C} \approx$ 0.55 keV at $B \approx 10^{14}$ G).

Some examples of magnetized semi-infinite partially ionized hydrogen model atmospheres were computed by us in [5]. Here we computed thin (with surface densities $\Sigma \approx$ 1 – 10 g cm^{-2}) model atmospheres above condensed iron surfaces using their radiation properties as inner boundary conditions (Fig. 1, right panel). Because of the condensed surface emission properties, broad absorption features appear between $E_{\rm c,Fe}$ and $E_{\rm C}$, together with a strong edge in the angular distribution of the radiation at an energy between $E_{\rm C}$ and $4E_{\rm C}$ and corresponding edges in the specific intensity spectra. The absorption feature's EW may reach 300 – 400 eV in these models, whereas EWs are smaller than 100 eV for the absorption features in the spectra of the semi-infinite atmospheres. The emergent spectra of the semi-infinite and thin model atmospheres can be represented by diluted black-body spectra with one or two Gaussian absorption lines. The angular distribution of the radiation is represented by a simple step function between $E_{\rm C}$ and $4E_{\rm C}$ and is assumed to be isotropic for other photon energies.

To calculate the XDINS spectra and light curves, we use the model of a slowly rotating spherical isolated neutron star with a given compactness M/R, with account of the gravitational redshift and light bending. The distributions of the local color temperatures and magnetic field strengths over the stellar surface

$$T^4 = T_{\rm p}^4 \frac{\cos^2\theta}{\cos^2\theta + a\sin^2\theta} + T_{\rm min}^4, \quad B = B_{\rm p}\sqrt{\cos^2\theta + a\sin^2\theta} \qquad (1)$$

were taken from [6]. Here θ is the magnetic colatitude, $T_{\rm p}$ and $B_{\rm p}$ are the temperature

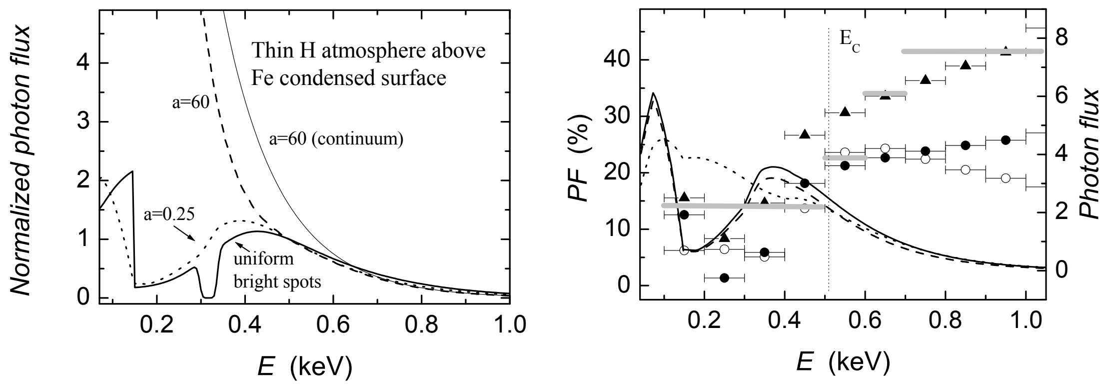

FIGURE 2. *Left:* Phase averaged photon spectra of the neutron star models. The local spectra are isotropic blackbodies with absorption features as in the spectra of the thin hydrogen model atmosphere above the condensed iron surface. *Right:* Energy dependence of pulsed fractions (symbols and left vertical axis) together with averaged photon spectra (lines and right vertical axis) for the neutron star models with a=0.25. Open circles and dotted curve - a naked condensed iron surface. Filled circles and solid curve - a thin atmosphere above condensed iron surface spectra with corresponding angular distribution. Triangles and dashed curve - the same local spectra, but with slightly different pole temperatures: $T_{\rm p,1}$ = 0.15 keV, $T_{\rm p,2}$ = 0.14 keV. The observed RBS 1223 pulsed fractions are shown by thick gray horizontal lines.

and the magnetic field strength at the poles, and the parameter a characterizes the geometry of the magnetic field: $a = 0.25$ corresponds to the pure dipole field, and $a \gg 1$ corresponds to a strong toroidal component (in this case $a^2 \approx B_{\rm tor}/B_{\rm p}$).

We consider a neutron star model with $kT_{\rm p} = 0.15$ keV, $B_{\rm p} = 6 \times 10^{13}$ G, and $z = 0.2$. Three temperature and magnetic field distributions are used: $a = 0.25$, $a = 60$ and two uniform bright spots with angular radii $\theta_{\rm sp} = 5^\circ$ and the dipole magnetic field. Local spectra of the three models of NS radiating surfaces are presented by analytical functions (see above). The central energies of the local absorption features depend on the local magnetic field.

We demonstrated that the EWs of the absorption features in the integral NS spectra are similar to the local EWs on the neutron star surfaces. Therefore, the EW of the absorption line in the spectrum of RBS 1223 (about 200 eV) can only be explained by a thin atmosphere above the condensed iron surface. The same local model with a smooth temperature distribution over the neutron star surface ($a = 0.25$) and slightly different pole temperatures can provide the pulsed fraction observed in RBS 1223 (see Fig. 2). A strong toroidal magnetic field component on the XDINS surfaces ($a \gg 1$) seems unlikely because such models exhibit a too wide, smoothed absorption feature. See details in [7].

ABSORPTION FEATURES IN THE SPECTRUM OF 1E 1207

The absorption features in the spectrum of 1E 1207, centered at about 0.7 and 1.4 keV, were discovered in [8]. We demonstrate that these lines can arise due to quantum resonances in the free-free absorption of photons in a magnetic field at energies of electron cyclotron line and its harmonics [9].

We present computations of fully ionized hydrogen atmospheres of NSs for magnetic

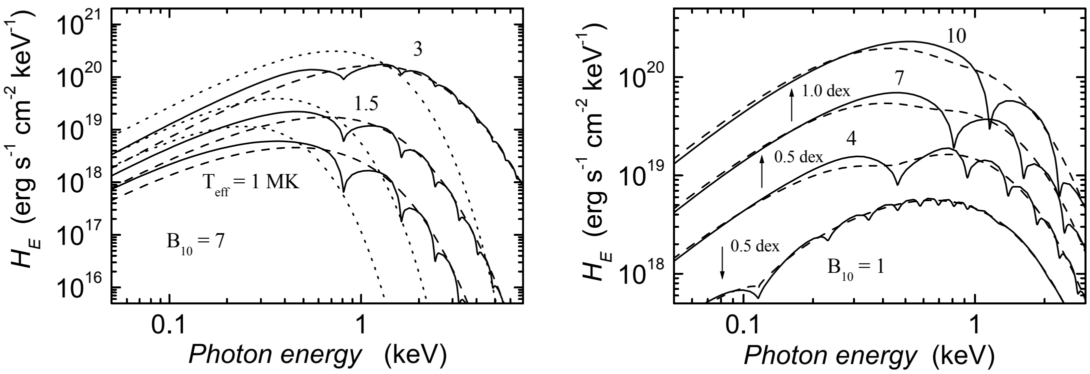

FIGURE 3. *Left:* Emergent spectra for NS atmospheres with magnetic field $B = 7 \times 10^{10}$ G (solid curves) and $B = 0$ (dashed curves) for three effective temperatures. The dotted curves are blackbody spectra for the same temperatures. *Right:* Emergent spectra for magnetic NS atmospheres with $T_{\rm eff} = 1.5$ MK and four different magnetic fields, calculated with magnetic and non-magnetic Gaunt factors.

fields $B \sim 10^{10}$–10^{11} G and the effective temperatures 1 – 3 MK (see Fig. 3). In these models the electron cyclotron energy is within the observed range of energies.

The electron quantum oscillations are best observable at moderately large values of the quantization parameter, $0.5 \leq b_{\rm eff} = E_{\rm c,e}/kT_{\rm eff} \leq 20$, when the quantization is significant but the features are not too far in the Wien tail of the spectrum. The equivalent widths of the absorption features reach ~ 100–200 eV in the examples considered; they grow with increasing $b_{\rm eff}$ and are lower for higher harmonics. Therefore, the observed features can be interpreted as caused by the quantum oscillations. See details in [10].

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REFERENCES

1. F. Haberl,*Astroph. and Space Sci.*, **308**, 181-190 (2007).
2. A. D Schwope, V. Hambaryan, F. Haberl, et al. *Astron. and Astrophys.*, **441**, 597-604 (2005).
3. A. D Schwope, V. Hambaryan, F. Haberl, and C. Motch *Astroph. and Space Sci.*, **308**, 619-623 (2007).
4. M. van Adelsberg, D. Lai, A. Y. Potekhin, and P. Arras *Astrophys. Journal* **628**, 902-913 (2005).
5. V. Suleimanov, A. Y. Potekhin, and K. Werner,*Astron. and Astrophys.* **500**, 891-899 (2009).
6. J. F. Pérez-Azorín, J. A. Pons, J. A., Miralles, and G. Miniutti *Astron. and Astrophys.*, **459**, 175-185 (2006).
7. V. Suleimanov, V. Hambaryan, A. Y. Potekhin, M. van Adelsberg, R. Neuhäuser, and K. Werner,*Astron. and Astrophys.*, in press,*(arXiv:1006.3292)* (2010).
8. D., Sanwal, G. G. Pavlov, V. E. Zavlin, and M. A. Teter, *Astrophys. Journal* **574**, L61-L64 (2002).
9. G. G. Pavlov, and A. N. Panov *Sov. Phys. JETP*, **44**, 300-306 (1976)
10. V. Suleimanov, G. G. Pavlov, and K. Werner,*Astrophys. Journal* **714**, 630-635 (2010).