Strongly Magnetized Atmospheres and Radiating Surfaces of Neutron Stars

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The theory of thermal emission from the surface layers of magnetized neutron stars is reviewed, including radiative transfer in partially ionized atmospheres with magnetic fields $B \sim 10^{10}$–10^{15} G and radiation from condensed surfaces at $B \gtrsim 10^{12}$ G. Applications of the theory to observations of thermally emitting isolated neutron stars with strong magnetic fields are summarized.

1 Introduction

A detailed study of the thermal spectra of neutron stars can yield precious information about properties of plasmas at extreme conditions in their atmospheres and interiors, about the neutron star masses M, radii R, temperatures T, and magnetic fields $\boldsymbol{B}$, and eventually help to constrain the equation of state (EOS) of the ultradense matter in the neutron star cores. In recent years, the number and quality of measured thermal spectra of neutron stars increased dramatically thanks to the data collected by the X-ray observatories *Chandra* and *XMM-Newton.* Some of the spectra can be understood with models of non-magnetic atmospheres (e.g., [1] and references therein). However, thermal spectra of many isolated neutron stars (INSs) are significantly affected by strong magnetic fields. The theory of these effects is reviewed in the present paper. Section 2 describes the theory of partially ionized neutron star atmospheres with strong magnetic fields, Sect. 3 considers the model of a condensed radiating surface and hybrid models of a condensed surface covered by a thin atmosphere, Sect. 4 describes synthetic energy and polarization spectra, and Sect. 5 presents examples of applications of the theory to observations.

2 Theory of strongly magnetized atmospheres

We call an atmosphere *strongly magnetized*, if a magnetic field strongly (non-perturbatively) affects opacities and radiative transfer of thermal photons. This occurs if the electron cyclotron energy $\hbar\omega_{\rm c} \equiv \hbar eB/m_{\rm e}c \approx 11.577\,(B/10^{12}$ G) keV is greater than either the photon energies $\hbar\omega$ or the atomic binding energies, or both. Here, ω is the photon angular frequency, $m_{\rm e}$ and $-e$ are the electron

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mass and charge, and c is the speed of light. These conditions imply (see [2] for discussion) $B \gtrsim 10^{10}\, T_6$ G, where $T_6 \equiv T/10^6$ K, and $B \gtrsim B_0$, where $B_0 = m_e^2\, c\, e^3/\hbar^3 \approx 2.35 \times 10^9$ G is the atomic unit of magnetic field. It is also convenient to define the relativistic magnetic-field parameter $b \equiv \hbar\omega_c/m_e c^2 = B/4.414 \times 10^{13}$ G. We call magnetic field *superstrong* if $b \gtrsim 1$. The superstrong fields are believed to exist at the surfaces of magnetars and high-B pulsars [3, 4].

At typical conditions in neutron star photospheres one can describe radiative transfer in terms of specific intensities of two normal polarization modes [5, 6], called extraordinary (X-mode) and ordinary (O-mode), which have different polarization vectors $\boldsymbol{e}_j$, depending on ω and on the angle θ_{kB} between the wave vector $\boldsymbol{k}$ and the magnetic field $\boldsymbol{B}$. The system of radiative transfer equations (RTE) for the two normal modes is presented in [7].

The polarization vectors of normal modes $\boldsymbol{e}_{\omega,j}$ are determined by the complex polarizability tensor $\boldsymbol{\chi}(\omega)$ and magnetic permeability tensor [5]. The anti-Hermitian part of $\boldsymbol{\chi}(\omega)$ is determined by the absorption opacities, and the Hermitian part can be obtained from it using the Kramers–Kronig relation [8, 9].

In strong magnetic fields, the effects called polarization and magnetization of vacuum can be important (see, e.g., [10]). At $B \lesssim 10^{16}$ G, they linearly add to $\boldsymbol{\chi}$ and can be parametrized by three numbers, called vacuum polarizability and magnetization coefficients, which were fitted by analytic functions of b in [9]. Convenient expressions of $\boldsymbol{e}_j$ through $\boldsymbol{\chi}(\omega)$ with account of the vacuum polarization were presented in [11].

Opacities for the X-mode are strongly reduced, if $\omega_c \gg \omega$. The opacities also depend on θ_{kB}. Nevertheless, at large optical depth radiation is almost isotropic: the magnitude of the diffusive radiative flux is much smaller than the mean intensity. In this case an approximate solution to the RTE is provided by the diffusion approximation [7], which serves as a starting point to an iterative method [12], allowing one to solve the RTE system accurately. To this end, one must know the dependencies of the temperature and densities of particles on the depth. These dependencies can be found from the equations of thermal, hydrostatic, and ionization equilibrium supplemented with the EOS. The plasma composition, EOS, and opacities are affected by the field, as reviewed in [2].

As first noticed in [13], atoms and ions with bound states should be much more abundant at $B \gg B_0$ than at $B \lesssim B_0$ in a neutron star atmosphere at the same temperature. This difference is caused by the increase of atomic binding energies and decrease of atomic sizes at $B \gg B_0$. Therefore, bound-bound and bound-free transitions are important in strong magnetic fields even for light-element atmospheres, which would be almost fully ionized at $B = 0$.

Many authors studied atoms with an infinitely heavy (fixed in space) nucleus in strong magnetic fields (see, e.g., [14], for review). This model, however, is only a crude approximation. If the ratio B/B_0 is not negligibly small compared to the nucleus-to-electron mass ratio, one should take into account quantum oscillations of an atomic nucleus, which depend on the quantum state. Moreover, the astrophysical simulations assume finite temperatures, hence thermal motion of particles. The theory of motion of a system of point charges q_i at points $\boldsymbol{r}_i$ in a constant magnetic field was reviewed in [15]. Instead of the canonical momentum $\boldsymbol{P}$, a relevant conserved quantity is pseudomomentum $\boldsymbol{K} = \boldsymbol{P} + (1/2c)\, \boldsymbol{B} \times \sum_i q_i \boldsymbol{r_i}$. The specific effects related to collective motion of a system of charged particles are especially important in neutron star atmospheres at $B \gg B_0$. In particular, so called *decentered states* may become populated, where an electron is localized mostly in a "magnetic well" aside from the Coulomb center. Binding energies and wave functions of the hydrogen atom moving across a strong magnetic field were calculated in [16, 17]. Bound-bound, bound-free, and free-free radiative transitions were studied in [17–21]. The absorption cross-sections have peaks at the multiples of both the electron and ion cyclotron frequencies for all polarizations α, but unlike the electron cyclotron harmonics, the ion harmonics, except the fundamental, are weak and can be neglected. The dependencies of energies and oscillator strengths on the transverse pseudomomentum $\boldsymbol{K}_\perp = \boldsymbol{K} - (\boldsymbol{B} \cdot \boldsymbol{K})\boldsymbol{B}/B^2$ cause a "magnetic broadening" of the spectral lines and ionization thresholds, which can be much larger than the usual Doppler and plasma broadenings.

The He^+ ion moving across a strong magnetic field was studied in [22, 23]. The basic differences from the case of a neutral atom are that the Cartesian components of the operator $\boldsymbol{K}_\perp$ do not commute and the values of K^2 are quantized [15]. Currently there is no detailed calculation of binding energies, oscillator strengths, and photoionization cross-sections for atoms and ions other than H and He^+, arbitrarily moving in a strong magnetic field. A practical method of calculation of the quantum-mechanical characteristics of multielectron atoms and ions, based on a combination of several perturbation theories with respect to different physical parameters, has been developed in [24].

Since the quantum-mechanical characteristics of an atom in a strong magnetic field depend on $K_\perp$, the atomic distribution over $K_\perp$ cannot be written in a closed form, and only the distribution over longitudinal momenta K_z remains Maxwellian. The first EOS calculations with account of these effects have been performed in [25] for hydrogen and in [26] for helium plasmas. To date, self-consistent calculations of the EOS and opacities, including both centered and decentered bound states (i.e., small and large $K_\perp$), have been realized only for neutron-star atmospheres composed of hydrogen [20, 27, 28]. For atoms and ions with several bound electrons (C, O, Ne), calculations have been performed in terms of a perturbation theory [29, 30].

3 Condensed surfaces and thin atmospheres

Ruderman [31] suggested that a strong magnetic field may cause a condensation of matter. Properties of the resulting condensed magnetic surfaces were studied in a number of papers (see [32] and references therein). Thermal radiation of the surface is determined by its emissivities in two normal modes, which are related to the reflectivities through the Kirchhoff law. They were calculated and fitted in [33] (see references therein for older approaches). Moreover, Motch et al. [34]

suggested that some neutron stars can possess a hydrogen atmosphere of a finite thickness above the solid iron surface. If the optical depth of such atmosphere is small for some wavelengths and large for others, the thermal spectrum differs from that of thick atmospheres. Such spectra were calculated in [35–37] using simplified boundary conditions for the radiative transfer equation at the bottom of the atmosphere. More accurate boundary conditions [33] take into account that any polarized wave, falling from the atmosphere on the surface, gives rise to reflected waves of both normal polarizations, whose intensities add to the respective intensities of the waves emitted by the condensed surface.

Local spectra of radiation emitted by thin hydrogen atmospheres over a condensed surface may reveal a narrow absorption line corresponding to the proton cyclotron resonance in the atmosphere, features related to atomic transitions broadened by the motion effects, and a kink corresponding to the ion cyclotron energy of the substrate ions. Some of these features may be absent, depending on the atmosphere thickness and magnetic field strength. At high energies, the spectrum is determined by the condensed-surface emission, which is softer than the spectrum of the thick hydrogen atmosphere.

One may also envisage an atmosphere having a helium layer beneath the hydrogen layer. The spectrum of such "sandwich atmosphere" can have two or three absorption lines in the range $E \sim (0.2\text{–}1)\,\text{keV}$ at $B \sim 10^{14}$ G [36].

4 Synthetic energy and polarization spectra

The strong gravity of a neutron star induces a significant redshift of the local photon frequency ω to $\omega_\infty = \omega/(1+z_g)$ in the remote observer's reference frame, where $z_g = (1 - 2GM/c^2R)^{-1/2} - 1$ is the gravitational redshift, and G the gravitational constant. Accordingly, a thermal spectrum with effective temperature T_{eff} transforms for the remote observer into a spectrum with a lower "observed" temperature $T_{\text{eff}}^\infty = T_{\text{eff}}/(1+z_g)$. Along with the radius R that is determined by the equatorial length $2\pi R$ in the local reference frame, one often considers an *apparent radius* for a remote observer, $R_\infty = R\,(1+z_g)$, so that the apparent photon luminosity L_{ph}^∞ is determined by the Stefan–Boltzmann law $L_{\text{ph}}^\infty = L_{\text{ph}}/(1+z_g)^2 = 4\pi\sigma_{\text{SB}}\,R_\infty^2\,(T_{\text{eff}}^\infty)^4$, where σ_{SB} is the Stefan–Boltzmann constant, and $L_{\text{ph}} = 4\pi\sigma_{\text{SB}}\,R^2 T_{\text{eff}}^4$ is the luminosity in the local reference frame.

The spectral flux that comes to an observer is distorted by the light bending in strong gravity. It can be calculated using equations presented in [38] provided that the emitted specific intensity distribution is known for the entire visible surface of the neutron star. The problem is complicated by nontrivial surface distributions of the magnetic field and effective temperature. A fiducial model for the magnetic field distribution is the relativistic dipole [39], but recent numerical simulations of the magnetothermal evolution produce more complicated distributions (see [40, 41] and references therein). The temperature distribution, consistent with the magnetic-field distribution, is found from calculations of heat transport in neutron star envelopes (see [42] for review).

Synthetic spectra of partially ionized hydrogen atmospheres were calculated in [43], including averaging over the stellar surface with realistic temperature and magnetic field distributions. The spectra depend on the magnetic axis orientation relative to the line of sight. As the star rotates, the latter dependence leads to a rotational phase dependence of the spectra. Model spectra of partially ionized, strongly magnetized neutron star atmospheres composed of hydrogen, carbon, oxygen, and neon with magnetic fields $B \sim 10^{10}$–10^{13} G are included in the open database *XSPEC* [44] under the names NSMAX [30, 43] and NSMAXG [30, 45, 46], with the latter allowing for varying surface gravity.

Thermal radiation emergent from neutron stars with strong magnetic fields is expected to be strongly polarized. Since the opacity is smaller for the X-mode, this mode escapes from deeper and hotter layers in the atmosphere, therefore the X-mode polarization prevails in the thermal radiation [47]. Polarization of the observed radiation depends on the distribution of magnetic field and temperature over the visible neutron star surface. As the star rotates, the polarization pattern shows periodic variations, so that measuring the polarization pulse profile allows one to constrain the orientation of the rotation axis and the field strength and geometry [48, 49]. Therefore, future X-ray polarization measurements are expected to resolve degeneracies that currently hamper the determination of magnetar physical parameters using thermal models [50, 51].

After a photon has left the surface of a neutron star with a strong magnetic field, it travels through the magnetosphere and experiences the influence of vacuum polarization, which induces a change in the wave electric field as photon propagates. If the magnetic field is sufficiently strong, then in the vicinity of the star a photon propagates adiabatically, so that its polarization instantaneously adapts to the variation of the magnetic field direction [52, 53]. Farther from the star the field decreases, and eventually photons leave the adiabatic region and maintain their polarization. The rays that leave the adiabatic region pass through only a small solid angle; consequently, polarizations of the rays originating in different regions will tend to align together. This effect can enhance the net observed polarization [54]. A comparison of polarizations assuming either gaseous atmospheres or condensed surfaces was analyzed in [55].

5 Theory versus observations

As argued above, models of strongly magnetized ($B \gg 10^9$ G) neutron-star atmospheres must take the bound species and their radiative transitions into account. Currently there are the following examples of application of models of *strongly magnetized and partially ionized* atmospheres to studies of thermal radiation of neutron stars with strong magnetic fields:

- RX J1856.5–3754, which is the closest and brightest of the class of X-ray INSs (XINSs, also known as the Magnificent Seven), whose X-ray spectra are apparently of purely thermal nature. Its measured spectrum was fitted in the entire range from X-rays to optical within observational error bars with the use of the model of a thin magnetized hydrogen atmosphere on top of a condensed iron surface [35] (see also a discussion in [46]).

– phase-resolved spectrum and light curve of XINS RX J1308.6+2127 (RBS1223) have been described in [56] by the model with a magnetized iron surface covered by a partially ionized hydrogen atmosphere;
– the X-ray spectrum of thermally emitting INS 1E 1207.4–5209 appears to have been explained by cyclotron absorption harmonics, corresponding to $B \approx 7 \times 10^{10}$ G [28, 57];
– the *XMM-Newton* spectrum of thermally emitting INS 2XMM J104608.7–594306 has been analyzed in [58] with the blackbody model and hydrogen atmosphere model NSMAXG;
– the spectrum of INS 1WGA J1952.2+2925 is equally well fitted either by the blackbody model with a temperature of $T \approx 2.5 \times 10^6$ K and an emitting area radius of ≈ 0.6 km or by the magnetized atmosphere model NSMAX with $T_{\rm eff} \sim 10^6$ K and emission from the entire neutron-star surface [59];
– rotation powered pulsars PSR J1119–6127, B0943+10, J0357+3205, and J0633+0632, whose thermal parts of spectra were analyzed in [60–63] using magnetized atmosphere model NSMAX.

A more detailed discussion of the interpretations of observations of the above-listed objects is given in [46].

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