Radiation of an X-ray pulsar with a strong magnetic field in the case of subcritical accretion: accounting for Compton scattering

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The work deals with the modeling of the radiation of subcritical pulsars with a strong magnetic field. A self-consistent radiation hydrodynamical simulation of the accreting plasma flow to the poles of a neutron star was carried out. The case of subcritical luminosities was considered, the recoil effect arising from the elastic collision of photons with falling matter was taken into account. The scattering cross section containing the main cyclotron resonance was used. Birefringence was taken into account in the cold plasma approximation. Under such assumptions, the spectra and polarization of the accretion column radiation were obtained.

Keywords: X-ray pulsars, accretion, radiation transfer.

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Neutron stars (NS) — are compact relativistic objects with masses of about 1−2 solar masses ($M_\odot$) and radii of 10−15 km. They possess strong magnetic fields, the magnitude of which can reach 10^{11} T. If the NS is part of a binary system, plasma can flow onto it from the side of the companion star. This phenomenon is called accretion. Starting from a certain distance, due to the strong magnetic pressure, the accreting plasma can no longer flow across the magnetic field lines, but moves along them towards the magnetic poles of the neutron star. Directly above the poles, a region of plasma is formed, shaped like an expanding bottleneck — the so-called accretion column. When the infalling material reaches the surface of the NS, the stored kinetic energy in it is illuminated in the X-rays range. The higher the accretion rate, the greater the luminosity. Inasmuch as the axis of rotation of the NS does not coincide with the magnetic axis, the radiation coming out of the polar regions of the NS is observed in the form of pulsations. Such NSs are called X-rays pulsars (see, e.g., [1]).

Due to the photon pressure, the radiation itself affects the dynamics of the incident plasma. When a certain threshold rate of accretion is reached, matter can be completely inhibited by radiation. In this case, a radiation-dominated shock wave is expected [2]. Such accretion is called supercritical, and at accretion rates below the threshold — subcritical.

The present work is devoted to finding the characteristics of the radiation coming out of the accretion column of a neutron star during subcritical accretion. Inasmuch as the radiation pressure has a significant impact on the dynamics of the incident plasma, which generates this radiation, a coordinated calculation of the accretion column structure is also necessary to solve the problem. We neglect the curvature of the magnetic field and treat the column as a rectangular cylinder. In subcritical accretion, this approximation is justified by the low height of the column compared to the radius of curvature of the magnetic field. Mathematically, the system is described by the equations of radiative hydrodynamics together with the equations of polarized radiation transport [3].

Magnetized plasma — is a birefringent medium in which X-rays propagate in the form of normal modes called ordinary (O-mode) and extraordinary (X-mode) waves. These two waves are elliptically polarized, with the semimajor axis of the electric vector O-mode ellipse lying in the plane of the magnetic field and the direction of motion of the photon, and the semimajor axis of the X-mode ellipse — perpendicular to it.

The system of equations of hydrodynamics and radiation transfer is solved by operator splitting scheme. The time step is divided into two substeps, one of which solves a purely hydrodynamic system with taking into account the force of gravity using the Virginia Hydrodynamics 1 (VH-1) hydrodynamic code. The resulting hydrodynamic solution sets the initial data at the second substep, where the radiation transfer and energy-momentum exchange between photons and plasma are calculated. For this purpose, the Monte Carlo method is implemented. The output is the characteristics of the radiation emitted by the column and the change in energy-momentum for each computational cell in the accretion column. Based on this, the final dynamic characteristics of the plasma are recalculated for the full time step.

The main process of interaction between radiation and matter in an accretion column is Compton scattering. The processes of true absorption and emission of the medium are neglected in the present work.

The magnetic field strongly influences the scattering cross-section. In calculating amplitudes for linear polarization photons, we use non-relativistic expressions from the paper [4] containing the basic cyclotron resonance. Birefringence in the medium is calculated in the cold plasma

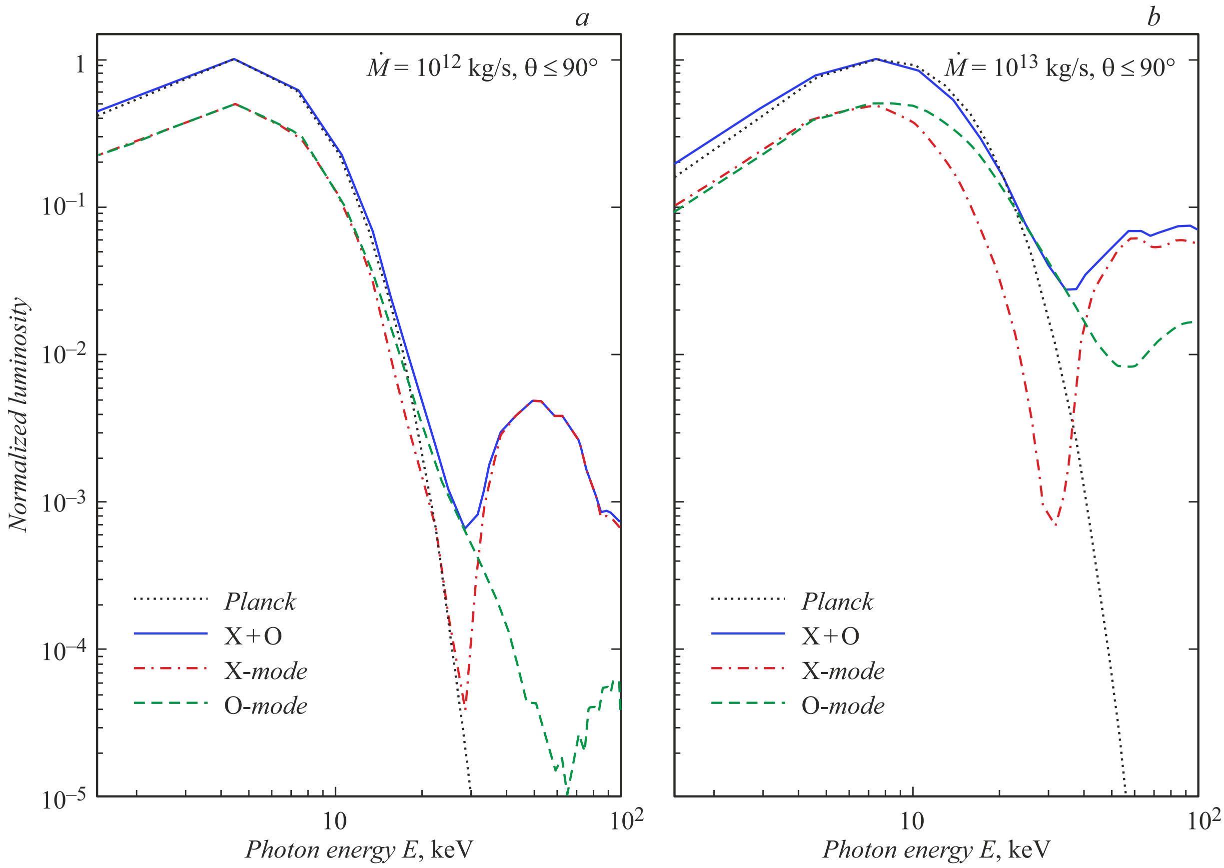

Figure 1. The luminosity of the column summed at the angles $\theta < 90^\circ$ as a function of the photon energy in the X-mode (red line (in the online version)), O-mode (green (in the online version)), the sum of the modes (blue (in the online version)) and the initial blackbody spectrum (black); *a* — accretion rate $\dot{M} = 10^{12}$ kg/s; *b* — $\dot{M} = 10^{13}$ kg/s. Normalization is performed to the maximum of the total spectrum.

approximation [5]. The transition from amplitudes for linear modes to amplitudes of elliptic polarizations is performed according to the method described in the article [6]. To save counting time, we pre-generate cross-section tables that depend on the direction of the photon's propagation, its energy and polarization. At the same time, tables are created for the cumulative functions of the distribution of the probability of a photon being scattered in a particular direction. When calculating the radiation transfer, linear interpolation is performed from these tables.

The parameters of the model are the radius R and the mass M of NS, the radius r_c of the accretion column, the accretion rate $\dot{M}$, and the cyclotron resonance energy E_{cyc}, proportional to the magnetic induction B. In the examples of calculation results below, some of these parameters are fixed: $M = 1.4\,M_\odot$, $R = 12$ km, $r_c = 1$ km, $E_{cyc} = 6.4 \cdot 10^{-15}$ J (40 keV).

Fig. 1 shows the luminosities of the accretion column summarized at the angles $\theta < 90^\circ$ in different modes (the angle θ is measured from the outer normal to the surface of the star). Such angles were chosen because the radiation on them goes directly in the direction of the observer, without crossing the NS surface. The spectra show a dip corresponding to the cyclotron feature. In this field, the O-mode is the main contributor to the radiation of the column. At higher photon energies, the X mode begins to predominate.

Knowing the intensities of the normal modes, it is possible to calculate the degree of polarization of the radiation. In the case of cold plasma, the degree of linear and circular polarization is calculated using the formulas

$$P_L = (I_2 - I_1)|q|/((I_2 - I_1)(1 + q^2)^{1/2})$$

and

$$P_C = (I_1 - I_2)\mathrm{sign}(q)/((I_2 - I_1)(1 + q^2)^{1/2}),$$

therefore, where $q = E_{cyc}\sin^2\theta/(2E\cos\theta)$ and E — is the energy of the photon, I_1 — intensity in the X-mode, I_2 — in the O-mode. The calculated degrees of polarization are shown in Fig. 2. In resonance, the radiation is strongly polarized, and at lower energies, the degree of polarization is much lower. For example, at radiation energies < 10 keV, the linear polarization can be several percent, which is consistent with the latest IXPE data on the polarization of X-rays pulsar radiation [7]. The degree of polarization near the resonance and at high energies depends significantly

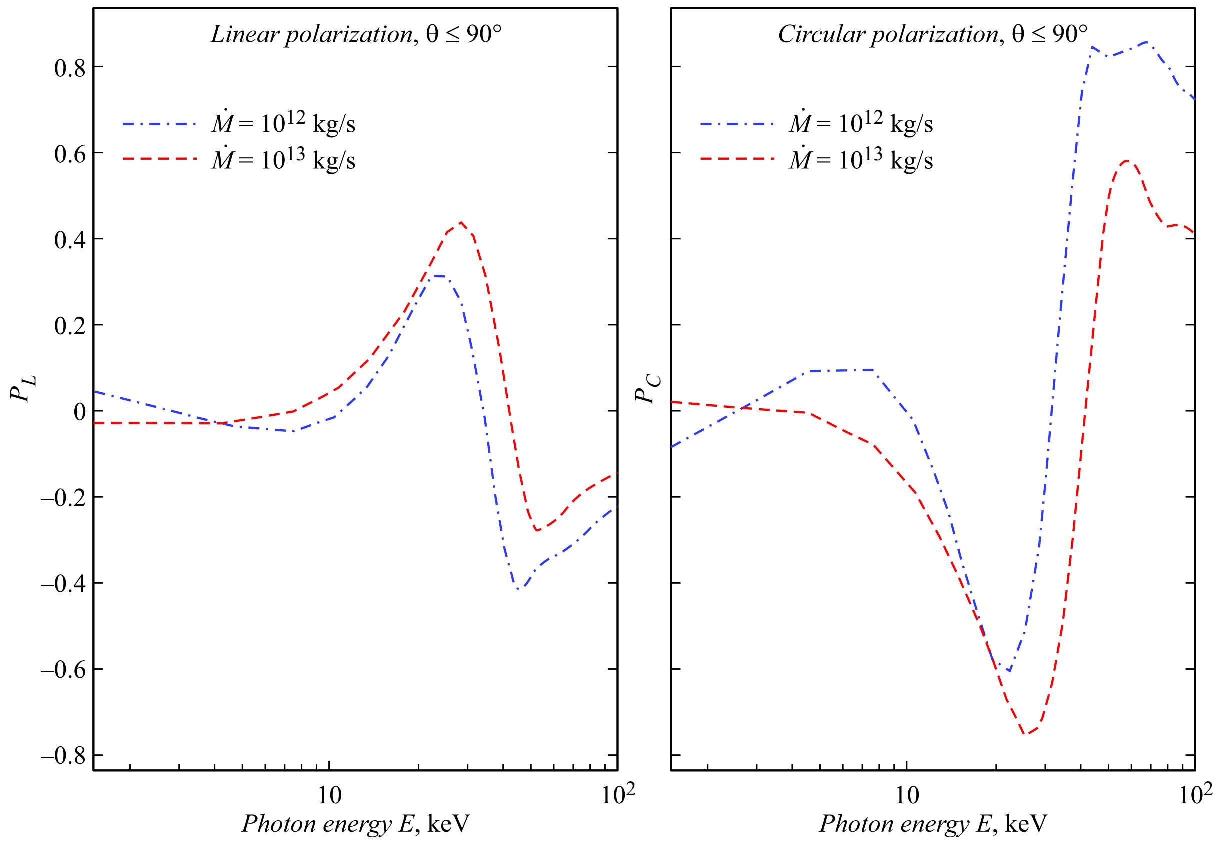

Figure 2. On the left — degree of linear polarization, right — circular polarization as a function of photon energy. Blue line (online) — $\dot{M} = 10^{12}$ kg/s, red line (online) — $\dot{M} = 10^{13}$ kg/s. The radiation is summed at the angles $\theta < 90°$.

on the accretion rate. If this result is confirmed in more stringent calculations, the degree of polarization can be used as an additional parameter to determine the accretion rate near the surface of the NS.

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Conflict of interest

The authors declare that they have no conflict of interest.

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