ON X-RAY PULSAR RADIATION MECHANISMS

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In this report we shall discuss the origin of radiation from the neutron star component of X-ray binary systems whose spectra contain cyclotron lines (Her X-1 and 4U0115+63). A relevant model of the polar region of a neutron star is presented in Figure 1. According to this model the observed X-rays (continuum + cyclotron lines) are generated in the dense plasma atmosphere of a star (in its hot spot heated by accreting matter). The problem of heating the neutron star atmosphere due to accretion has been earlier investigated by Zeldovich and Shakura (1969). Cyclotron lines are formed similarly to the Fraunhofer spectrum of ordinary stars and are absorption lines. For objects such as Her X-1 and 4U0115+63 the cyclotron emission and absorption in the extended accreting column with an inhomogeneous magnetic field should be unessential. Otherwise the accreting column will produce an X-ray continuum devoid of any line type features.

A possible formation of "Fraunhofer cyclotron lines" in the spectrum of Her X-1 was noted by Trümper et al. (1978) as well as the alternative version of emission cyclotron lines. The latter assumption had been made by Gnedin and Sunyaev (1974) and Basko and Sunyaev (1975) before these cyclotron lines were detected. For a more detailed version of this report see Zheleznyakov (1980).

Thus suppose that the X-ray pulsar component is formed in the polar hot spot of a rotating neutron star. In a spot the magnetic field is found by the cyclotron line frequencies: $B_o \cong 4 \cdot 10^{12}$ Gauss for Her X-1 and $B_o \cong 2 \cdot 10^{12}$ Gauss for 4U0115+63. Then assume that at altitudes corresponding to the X-ray source the star's atmosphere is an isothermal hydrogen plasma with temperature $T \cong 10^8$ K. This value accounts well for the observed form of the X-ray continuum spectrum. It characterizes the velocity dispersion of particles along the magnetic field $\vec{B}_o$. The particle density in the atmosphere is distributed according to the barometric formula

$$N = N_o \exp(-h/H) \qquad (1)$$

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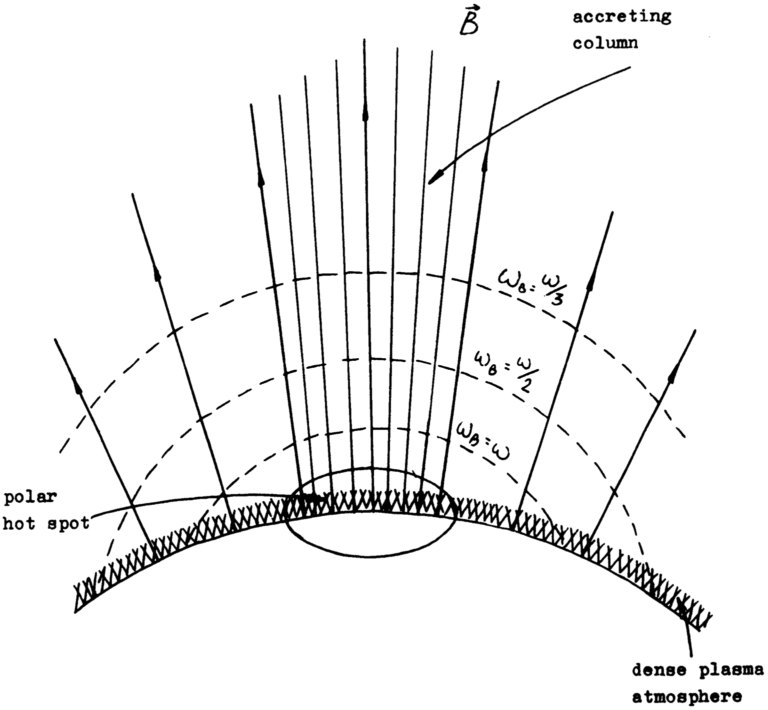

Figure 1: Model of neutron star polar region

where the scale height $H = 2\kappa T/m_p g \cong 10^2$ cm (κ is the Boltzmann constant, g the acceleration of gravity and m_p the proton mass). It is easy to show that the action of the dynamic pressure of the accreting gas on the particle density distribution (in those layers of the atmosphere where cyclotron lines and continuum in the hard X-ray spectrum are formed) is unessential for the binary systems considered (refer to Zeldovich and Shakura (1969)). However, the influence of the electric field $\vec{E}_0$ around a rotating neutron star on the form of (1) and the value of H needs careful investigation.

In our model of the atmosphere the inequality $\hbar\omega_B \gg \kappa T$ is always satisfied. In equilibrium conditions almost all the electrons are on the ground Landau level n = 1. Its population $N_1 \cong N$, where N is from (1). On a neutron star the thermodynamic equilibrium is violated since the radiation intensity is, in principle, different from that of a blackbody. It is the radiation that determines the populations of Landau levels $n > 1$ since the number of collisional transitions between Landau levels is small compared to that accompanied by cyclotron emission and absorption. The population of levels $n > 1$ increases with increasing radiation intensity. On a neutron star, however, the intensity does not exceed the equilibrium values corresponding to the temperature

T. Therefore the equality $N_1 \cong N = N_0 \exp(-h/H)$ is a good approximation.

The resonant transitions between Landau levels are unessential for the formation of the continuum spectrum in the Wien limit $\hbar\omega >> \kappa T$. The radiation intensity is described by three processes: spontaneous bremsstrahlung, bremsstrahlung absorption and Thomson scattering of electrons on the ground Landau level. The radiation intensity height profile $I_\omega(\theta,h)$ is described by the transfer equation

$$\cos\theta \frac{dI_\omega}{dh} = \mu_b B_\omega - (\mu_b + \mu_t) I_\omega + \frac{\mu_t}{2} \int_0^\pi I_\omega(\theta',h) \sin\theta' d\theta' \qquad (2)$$

Here θ is the angle in the atmosphere between the vertical and the ray direction. The first term to the right characterizes the spontaneous bremsstrahlung of equilibrium plasma (over longitudinal velocities); μ_b is the bremsstrahlung absorption coefficient, B_ω the blackbody intensity. The second term to the right describes the attenuation of $I_\omega(\theta,h)$ due to bremsstrahlung absorption and Thomson scattering; μ_t is the extinction coefficient for the latter process. Finally, the third term defines a contribution to $I_\omega(\theta,h)$ due to the radiation scattering from angles $\theta' \neq \theta$. The form of this term corresponds to the trivial case of isotropic scattering with the frequency retained.

The solution of Eq. (2) by the Schwarzshield-Shuster method permits us to assert that the intensity of radiation escaping the atmosphere

$$I = \int_0^{\pi/2} I_\omega \sin\theta \, d\theta$$

is equal to

$$I \cong B_\omega \left(\frac{2}{3}\right)^{2/3} \frac{\Gamma(2/3)}{\Gamma(4/3)} M^{1/3} \qquad (3)$$

where Γ is the gamma function, and

$$M = \mu_b / 2H\mu_t^2 . \qquad (4)$$

The correct expressions for μ_b and μ_t in a quantized plasma with $\hbar\omega_B >> \kappa T$ are, as far as we know, presently unavailable in literature. We have therefore to use instead of μ_b and μ_t the expressions for isotropic plasmas:

$$\mu_b = FN^2 ; \quad \mu_t = \sigma_t N ;$$

$$F = \frac{1}{6\sqrt{2}\,\pi} \cdot \frac{(4\pi)^3 e^6}{\omega^2 c (mh\omega)^{3/2}} ; \qquad \sigma_t = \frac{8\pi}{3}\left(\frac{e^2}{mc^2}\right)^2 \qquad (5)$$

The parameter M does not depend on N and for $T \cong 10^8$ K, $\omega \cong 7\ 10^{19}\ \mathrm{cm}^{-1}$ ($\hbar\omega \cong 40$ keV) the value of $M \sim 10^{-6}$ i.e. the ratio $I/B_\omega \sim 10^{-2}$.

Thus the continuum radiation at frequencies $\hbar\omega > \kappa T$ is depressed by about a factor of two orders compared to the blackbody radiation at the same temperature. This fact is essential for estimates of the stream density of accreting plasma which provides the effective heating of a hot spot and for estimates of the distance to X-ray binary systems by their observed continuum spectrum.

The specific flux of the pulsating component of radiation on the Earth averaged over the rotation (in view of (3)) is given by

$$\bar{P} = I \frac{r_s^2}{R^2} = 3\ 10^{-32} \frac{\omega^{11/6}\, r_s^2}{H^{1/3}\, R^2} \exp\left(-\frac{\hbar\omega}{\kappa T}\right) \tag{6}$$

By comparing theoretical and observed spectra we obtain the ratio r_s/R — i.e. of the radius of the hot spot to the distance to the pulsar. For the data obtained by Trümper et al. (1978) for Her X-1 this ratio is $3\ 10^{-16}$; and for 4U0115+63 $r_s/R \cong 3\ 10^{-17}$ according to Wheaton et al. (1979). These values of r_s/R are useful in estimates of the distances to the sources if r_s is known. We can estimate the value of r_s from the recorded depth of cyclotron absorption lines which depends on the magnetic field dispersion over the hot spot. Evidently, for Her X-1 $r_s \leqq 0.5\, r_* \cong 5\ 10^5$ cm, so that the distance $R \lesssim 1$ kpc. The line in 4U0115+63 which is not so deep corresponds to a greater spot: $r_s \lesssim r_* \cong 10^6$ cm and a distance $R \lesssim 10$ kpc (here r_* is the radius of the neutron star). Note that other papers give different distances to Her X-1 (about 4 - 7 kpc).

It is clear that the continuum depression takes place for the whole surface of a neutron star. This effect should be taken into account both in estimates of the cooling rate of neutron stars due to X-ray emission and in discussions of the possible detection of X-rays from the surface of neutron stars which are radio pulsars. The latter problem was discussed by Helfand et al. (1980) who proceeded from the ordinary assumption of blackbody radiation from the stellar surface.

The following processes are vital to the study of radiation transfer in the first cyclotron line: (1) bremsstrahlung and bremsstrahlung absorption at the ground level, (2) transitions from the ground Landau level to the second level with the radiation quantum being absorbed, and reverse spontaneous transitions. Other levels are unessential due to their small populations ($\hbar\omega_B >> \kappa T$). The induced processes are also unimportant in the Wien limit ($\hbar\omega >> \kappa T$). Owing to these facts and rather a wide radiation spectrum ($\Delta\omega >> w$ where w is the probability of spontaneous transition per time unit from the level $n = 2$) the cyclotron absorption with the transition $1 \rightarrow 2$ and spontaneous emission with the transition $2 \rightarrow 1$ can be treated as resonant scattering. For the study of the radiation transfer at frequency $\omega \cong \omega_{B_o} = eB_o/mc$ we again use an equation such as (2)

$$\cos\theta \frac{dI_\omega}{dh} = \mu_b B_\omega - (\mu_b + \mu_c) I_\omega + \frac{\mu_c}{2} \int_0^\pi I_\omega(\theta',h) \sin\theta' d\theta' \tag{7}$$

Here the term $-\mu_c I_\omega$ allows for the cyclotron absorption at the electron transition 1→2. The last term describes the resonant cyclotron scattering whose extinction coefficient coincides with the cyclotron absorption coefficient μ_c in the Wien limit (provided the collisional transitions between Landau levels are again unessential). With μ_t being substituted for μ_c, Eq. (7) coincides in form with Eq. (2). Thus it has a solution in the form of (3)-(4) with the same substitution

$$I \cong B_\omega \left(\frac{2}{3}\right)^{2/3} \frac{\Gamma(2/3)}{\Gamma(4/3)} M_c^{1/3} \tag{8}$$

where

$$M_c = \mu_b / 2 H \mu_c^2 \tag{9}$$

In its trivial form (neglecting the dependence on angle θ and the character of mode polarization) the cyclotron absorption coefficient is given by

$$\mu_c = \frac{2\pi^{3/2} e^2 N}{m v_T \omega_B} \exp\left[- \frac{(\omega - \omega_B)^2 c^2}{\omega^2 v_T^2} \right] \tag{10}$$

(see Melrose and Zheleznyakov, 1980, and Zheleznyakov, 1981, for more detail).

Since $\mu_c >> \mu_t$ for pulsars, the radiation intensity in the line is lower than that in continuum, i.e. the line should be observed in absorption. The intensity ratio in the line centre and in the adjacent continuum is

$$\delta = (\mu_t/\mu_c)^{2/3} = 2\ 10^{-19}\ \omega_{B_0}^{4/3}\ T^{1/3} . \tag{11}$$

For $T \sim 10^8$ K and $\omega_{B_0} \sim 7\ 10^{19}$ sec^{-1} the depth $\delta \sim 10^{-3}$. The dispersion of the magnetic field ΔB_0 over the hot spot may, in principle, increase δ. The value of δ given above is possible only for $\Delta B_0/B_0 << v_T/c \cong 0.1$, i.e. for strong Doppler line broadening. For Her X-1 $\delta \cong 10^{-1}$, which corresponds to $\Delta B_0/B_0 \sim v_T/c$. In a dipolar magnetic field $\Delta B_0/B_0 \cong 0.1$ is satisfied for a radiative spot of radius $r_s \cong 0.5\ r_*$. In the source 4U0115+63 the cyclotron line is highly diffused: $\delta \cong 0.6$. Therefore $\Delta B_0/B_0$ is greater than v_T/c and the radius of the hot spot is comparable to that of the star: $r_s \cong r_*$. It is possible, however, that higher resolution measurements will decrease δ compared to the given values. Thus the proposed size of r_s should be treated only as an upper limit.

The statement that the cyclotron lines are absorption features originates from the assumption that cyclotron radiation and absorption are the main cause for electron transitions between Landau levels. This assumption seems to be realistic in a neutron star atmosphere when the particle collisions are relatively rare. However, we should not completely exclude some additional sources of excitation of upper Landau levels which might be more effective than cyclotron transitions due to electromagnetic radiation. Such causes (for example, the emission and absorption of cyclotron plasma waves at frequency $\omega \cong \omega_{B_o}$) can, in principle, provide the formation of emission lines. The nature and the role of these waves is still to be investigated. However, in a classical plasma ($\hbar\omega_B \ll \kappa T$) these waves are unessential as the corresponding cyclotron transitions are less probable than those accompanied by electromagnetic radiation.

Finally, let us consider the part played by the accreting column in the formation of X-rays. Since the extended column is located in the inhomogeneous magnetic field of a neutron star, the cyclotron scattering of accreting plasma occurs in gyroresonant layers $\omega_B \cong \omega/s$ whose position depends on the radiation frequency ω (s is the cyclotron harmonic number). The thickness of these layers is then given by

$$\Delta h \cong 2\sqrt{2}\, L_B \frac{v_T}{c} |\cos\alpha| . \qquad (12)$$

Here α is the angle between the magnetic field $\vec{B}$ and the line of sight, L_B is the characteristic scale of the magnetic field. In the dipolar field of a star such a scale is equal to $(r_*/3)\cdot(s\omega_{B_o}/\omega)^{1/3}$. For $\cos\alpha \cong 1$, $\omega \cong s\omega_{B_o}$, $v_T/c \sim 0.1$, the thickness $\Delta h \sim 10^5$ cm. It is essential that the optical depth of the accreting column is not resonant (contrary to the case of a homogeneous magnetic field in a hot spot). Variation of frequency ω leads to a significant change in the localization of the effectively absorbing and emitting layer rather than in its optical depth $\tau_g \sim \mu_c \Delta h$.

When passing through a gyroresonant layer the hot spot radiation is depressed by resonant scattering by a factor $(1+\tau_g)^{-1}$. Thus the relevant spectrum will not be distorted or depressed if $\tau_g \ll 1$. As shown by these estimates the latter condition will be satisfied if the electron density of the accreting plasma $N_a \ll 10^{15}$ electrons cm^{-3}. For greater N_a the radiation intensity is highly attenuated (for $N_a \sim 10^{20}$ electrons cm^{-3} by a factor of 5 orders). If there is still more effective accretion, the X-ray radiation from a spot will become exponentially small on passing through the accreting column. Therefore bremsstrahlung and Thomson scattering of the accreting plasma above "thick" ($\sqrt{2\mu_b\mu_c}\cdot\Delta h \gg 1$) gyroresonant layers can be vital to the X-rays. Let us stress that in any case the accreting plasma is unable to provide either emission or absorption cyclotron lines. These originate solely from a hot spot in the polar atmosphere of a neutron star and are detectable only at moderate accretion $N_a \ll 10^{20}$ cm^{-3} as absorption lines.

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