LINE RADIATION FROM ACCRETING MAGNETIZED NEUTRON STARS

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ABSTRACT. A new non-thermal model on cyclotron line radiation from accreting magnetized neutron stars have been reviewed. Above the magnetic polar cap of accreting neutron stars, the maser instability may be excited by a part of non-thermal electrons, and the radiation with the frequency near electron cyclotron frequency and its second harmonic may be emitted as well. According to this model,the intensity and energy of line radiation will vary with pulsation phase of X-ray pulsars. These phenomen have been observed from Her X-1.

1. INTRODUCTION

The most direct measurement evidence for intense magnetic field of neutrc stars is the discovery of a rather sharp hard X-ray spectral feature from X-ray pulsar source Her X-1 since 1976 (Trümper et al, 1978). A lot of balloon borne experiments (Sheepmaker et al, 1981; Polcaro et al,1982; Voges et al,1983; Prantzos et al,1984) as well as satellite observations (Maurer et al,1979;Evans et al,1980; Gruber et al,1980) on Her X-1 hard X-ray spectrum have been analysed. An excess around 55 kev (or 40 kev corresponding absorption line) is interpreted as a cyclotron line, corresponding to a magnetic field of about $5x10^{12}$ Gauss (Trümper et al, 1978). A second excess at about 110 kev also reported by Trümper (1978) has not been confirmed yet. Recently, some new observational results from Her X-1 hard X-ray spectral analysis have been reported: a) An analysis of phase-dependent spectra shows a significant variation of the emission line centroid of the cyclotron feature during the main pulse (Gruber et al,1980; Voges et al,1982); b) There exists a correlation between the pulsar's hard X-ray luminosity and the intensity, energy of line feature (Prantzos and Durouchoux, 1984; Durouchoux, 1987). Another object that shows clear evidence for cyclotron lines is 4U 0115+63 (Wheaton et al,1979; White et al,1983).

On the other hand, a straightforward explanation of the cyclotron feature observed in the spectra of some binary X-ray pulsars is a very complicated task, because of the effects of the intense magnetic field in accretion column, and the coupling of the plasma flow of the accreted

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matter to the radiative transfer process (Mészáros,1983). No self-consistant exists up to now, but two approximation models have been developed during the past few years. One suggestion is the emission feature to be produced by electron quantum transition between Landau levels in the action of strong magnetic field (Basko,1975;Qu,1980); the other is caused by cyclotron resonsnces absorption of radiation transfer in the accretion column (Venttura et al,1979; Mészáros et al,1980; Yahel,1980; Nagel,1981; Arons,1987). However, the velocity distribution of electron considered in both models is thermal equilibrium.

In fact, above the magnetic polar cap of neutron stars, the velocity distribution of a part of electrons may be a non-thermal distribution. The possibility of non-thermal eletron is caused by rapid electron rotation around the strong magnetic field (hollow beam distribution), or by reflected electrons at magnetic mirror point (loss-cone distribution), or under the action of rotary electric field. For simplicity, we consider the magnetic mirror effect only. As the strength of magnetic field in the accretion column varies inversely with the cube of distance from neutron star, it form a magnetic mirror; a part of relativistic electrons with large pitch angle will be reflected at magnetic mirror point, and form a non-thermal distribution. In these case, the maser instability can be excited by these non-thermal electrons, and the radiation with the frequency near the cyclotron frequency can be emitted as well. In the case of X-ray pulsars, the accretion matter from companion flow uninterruptedly through accretion disk to the magnetic polar cap, and then a part of electrons with large pitch angle will be pumped continuousely to upper accretion column. The line radiation with cyclotron frequency are emitted with the excited maser instability. These lines have been observed from Her X-1 and some X-ray pulsars.

2. BASIC THEORY OF MASER INSTABILITY FOR LINE RADIATION

We assume the electron density of background plasma $n_o \gg n_s$, where n_s is the non-thermal electron density produced from magnetic mirror effect, and growth rate of instability $\omega_i \ll$ resonance frequency of instability ω_r, thus the growth rate of maser instability might be expressed as (Wu and Lee, 1979; Melrose et al, 1980; Freund et al,1983)

$$\left(\frac{\omega_i \, n_o}{\Omega_e \, n_s} \right)_j = \frac{2\pi^2}{G} \left(\frac{\omega_{pe}}{\Omega_e} \right) \left(\frac{\Omega_e}{\omega_r} \right) \sum_{m=j}^{\infty} \int_{-\infty}^{\infty} du_{\parallel} \int_0^{\infty} du_{\perp} \frac{u_{\perp}}{\gamma} \frac{m\Omega_e}{k_{\perp}} \left(m\Omega_e \frac{\partial}{\partial u_{\perp}} + k_{\parallel} u_{\perp} \frac{\partial}{\partial u_{\parallel}} \right) F(u_{\parallel}, u_{\perp}) \Psi_m(u_{\perp}) \, \delta(\gamma \omega_r - m\Omega_e - k_{\parallel} u_{\parallel}) \tag{1}$$

where $\gamma = (1 - v^2/c^2)^{-\frac{1}{2}} = (1 + u^2/c^2)^{\frac{1}{2}}$; $u_{\perp} = \gamma v_{\perp}$, $u_{\parallel} = \gamma v_{\parallel}$;
ω_{pe} is the electron plasma frequency; electron cyclotron frequency. G and Ψ_m are expressed in the same formulae as that in our previous paper (Wang and Mao, 1986); ω_r is obtained from cold plasma approximation for backgorund plasma. The loss-cone velocity distribution with intense gravitational potential has been adopted as the non-thermal electron velocity distribution function $F(u_{\parallel}, u_{\perp})$

$$F(u_\parallel, u_\perp) = \begin{cases} F_> = A\exp(-u^2/\alpha^2) \; ; \; u_\perp^2 \geqq \dfrac{u_\parallel^2 + \Phi}{d} \\ F_< = A\exp(-u^2/\alpha^2)\exp\left(\dfrac{u_\perp^2 - (u_\parallel^2 + \Phi)/d}{\beta}\right) \; ; \; u_\perp^2 < \dfrac{u_\parallel^2 + \Phi}{d} \end{cases} \qquad (2)$$

where $d = \frac{B_M}{B} - 1$, $\Phi = \frac{2(U - U_1)}{M}$, U_1 and B_M are gravitational potential and magnetic field at magnetic mirror point, respectively. A is normalization constant. We obtain

$$\left(\frac{\omega_i n_o}{\Omega_e n_s}\right)_j = \frac{4\pi^2}{G}\left(\frac{c}{\alpha}\right)^2\left(\frac{\omega_{pe}}{\Omega_e}\right)^2\left(\frac{\Omega_e}{\omega_r}\right)^2 \sum_{m=j}^{\infty}\Big\{\Big(\int_{u_m(-)}^{u_\parallel(A_m^-)} du_\parallel + \int_{u_\parallel(A_m^+)}^{u_m(+)} du_\parallel\Big) m\Big[m\left(\frac{\alpha^2}{\beta^2} - 1\right)\frac{\Omega_e}{k\sin\vartheta} - \left(1 + \frac{\alpha^2}{\alpha\beta^2}\right)\frac{\cos\vartheta}{\sin\vartheta}u_\parallel\Big] u(A_s) F_< \Psi_m - \int_{u_\parallel(A_m^-)}^{u_\parallel(A_m^+)} du_\parallel \cdot m\left(\frac{m\,\Omega_e}{k\sin\vartheta} + \frac{\cos\vartheta}{\sin\vartheta}u_\parallel(A_s)F_> \Psi_m\right)\Big\} ; \qquad \Delta > 0 \qquad (3.a)$$

$$\left(\frac{\omega_i n_o}{\Omega_e n_s}\right)_j = \frac{4\pi}{G}\left(\frac{c}{\alpha}\right)^2\left(\frac{\omega_{pe}}{\Omega_e}\right)^2\left(\frac{\Omega_e}{\omega_r}\right)\sum_{m=j}^{\infty}\int_{u_m(-)}^{u_m(+)} du_\parallel \Big[m\left(\frac{\alpha^2}{\beta^2} - 1\right)\frac{\Omega_e}{k\sin\vartheta} - \left(1 + \frac{\alpha^2}{\beta^2}\right)\frac{\cos\vartheta}{\sin\vartheta}u_\parallel\Big] u_\perp(A_s) F_< \Psi_m \qquad \Delta \leqq 0 \qquad (3.b)$$

where $\Delta \equiv \left(1 + \frac{1}{d}\right)\left(\frac{m\,\Omega_e}{\omega_r}\right)^2 - \left(1 + \frac{\Phi}{dc^2}\right)\left(1 + \frac{1}{d} - m^2\cos^2\vartheta\right)$

The relation between resonance ellipse in (1) and Δ has been discussed in detail (Mao and Wang, 1986). In order to compare with line radiation from Her X-1, following parameters have been used in the calculation, $M = 1\,M_\odot$, $r_M = 10^6$ cm, $c/\alpha = 1.7$, $c/\beta = 11$, $d = 0.728$, $B = 4.5\times10^{12}$ Gauss and magnetic mirror point $r = 1.2\,r_M$.

3. DISCUSSION AND SUMMARY

a) The growth rate of extraordinary mode (X mode) $\gg$ the growth rate of ordinary mode (o mode). This means that line radiation is produced from X mode maser instability. The polarization of line radiation from X mode is large.

b) The growth rates increase with the electron density (Fig. 1).

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Therefore, the line radiation from maser instability would be coherent, comparing with the incoherent radiation from other models.

c) In the region of $\omega_{pe}/\Omega_e \approx 0.01 - 0.1$, $\omega_i(j=2)/\omega_i(j=1) \simeq 0.05$ (Fig.1). Thus, second harmonic line (~ 110 kev) is quite weak from maser instability, if $n_s \ll n_o$ and $n_o < 10^{27}/cm^3$ are satisfied.

d) The growth rates depend intensely on the angle relative to magnetic field, as shown in Fig.2. This means that the emission line from maser instability can be observed only in a limited angle region, or the intensity of emission line will depend on the pulsation phase. The energy of emission line depends on the angle also (Wang and Mao, 1986). These results are consistent with observations by Voges et al (1983) qualitatively.

e) The resonance condition in the maser instability is ellipse (δ function in eq.(1)). Therefore, it is not only the electron velosity with $u_\perp \geqq u_{\perp c}$ can contribute to line radaition, but $u_\perp \leqq u_{\perp c}$ can also contribute to this line ($u_{\perp c}$ is a critical perpendicular velocity for single electron emitting cyclotron radiation). The electron number contributed to resonance emission line will increase vastly as compared with single electron process.

f) The ratio of quantum synchrotron radiation power $p^{(q)}$ and classical synchrotron radiation power $p^{(c)}$ for single electron may be expressed as follows (Sokolov, 1968)

$$\frac{p^{(q)}}{p^{(c)}} = 1 - \frac{55}{16}\frac{B\gamma}{B_c}\gamma + 48\left(\frac{B\gamma}{B_c}\right)^2 + \cdots\cdots ; \quad \text{for } B\gamma \ll B_c$$

where $B_c \simeq 4.4 \times 10^{13}$ Gauss, in

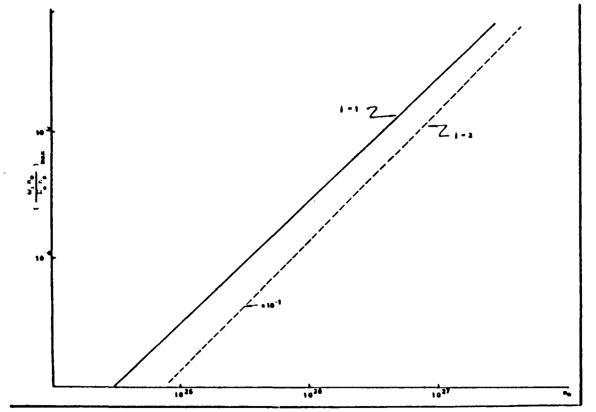

Fig.1 The maximum growth rate of X mode vs the electron desity n_o

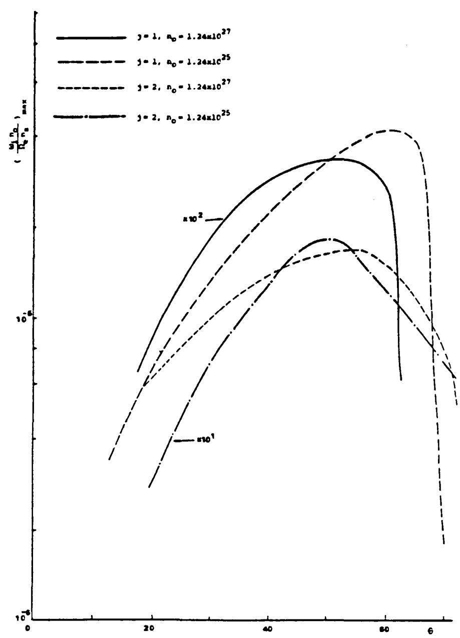

Fig.2 Maximum growth rate as a function of angle respect to magnetic field

the case of Her X-1, $p^{(q)}/p^{(c)} \simeq 1.0$. This result shows distinctly that classical synchrotron radiation process is same important as quantum Landau levels transition process in the X-ray pulsar Her X-1.

g) In order to investigate the relaxation time of non-thermal electron distribution, two effects should be considered. The first one is that the relaxation time of synchrotron radaition of single electron (include classical and quantum) may be expressed as below

$$\tau_{rel}^{(R)} \simeq \frac{3}{4}\frac{c}{r_o \Omega_e^2 \gamma} \simeq 0.16\text{x}10^{-16} \text{ sec}$$

However, the synchrotron radiation of single electron is limited to influence of the electrons with normal velocity $u_\perp > u_{\perp c}$. The second one is that the relaxation time of electron collision has been studied by Zhong and Hu (1986) in detail. They have found that the relaxation time of electron collision will be extended by Larmer motion of electron around the intense magnetic field. In the case of $B = 10^{12}$ Gauss, kT = 10 kev, $n_o = 10^{26}/\text{cm}^3$; $\tau_{ee}^{(c)} \simeq 0.73\text{x}10^{-15}$ sec. Therefore, the maser instability might be excited, if the relaxation time of non-thermal electron, τ_M , $\tau_M \approx \frac{1}{\omega_i} \leqq \tau_{ee}^{(c)}$ and/or $n_s/n_o \geqq 0.01$ are satisfied.

consequently, the maser instability (even if classical theory is considered only) should play an important role in the line emission from accreting magnetized neutron stars.

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DISCUSSION

D. Eichler: The optical depths of the accretion columns of neutron stars are many orders of magnitude larger than the plasma in the earth's magnetosphere. Would the mass emission be absorbed at the nth harmonic ($n > 2$) on the surfaces where B is $1/n$ of its value at the maser sight?

D. Wang: In the Her X-1 case, we used the parameter $W_{pe}/n_e \cong 0.01 \to 0.1$. If these values are quite small in the maser instability and in this parameter region the growth rate of the 2nd harmonic resonance is much lower than the first harmonic $(\omega_i, j=2)/(\omega_i, j=1) \cong 0.05$. Thus, I think the absorption at the nth harmonic is negligible.