The cyclotron lines in neutron star atmospheres with super-strong magnetic fields

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We numerically calculate the radiative transfer in neutron star atmospheres threaded by a uniform superstrong magnetic field ($\sim 10^9$ Tesla), where not only cyclotron resonant scattering but also photon splitting occurs. Here, the multiangle radiative transfer equations are solved for cyclotron resonant scattering, which depends strongly on the angle of photon propagation with respect to the magnetic field line. The structure of the cyclotron lines are investigated at the continuum formed by the photon splitting in the atmospheres injected the flux given by δ-function.

We find that the cyclotron absorption line may not be detected at the magnetic field of about 4.41×10^9 Tesla, if the atmosphere is the same optical depth as that of GRB at which the cyclotron absorption line around 20 keV is confirmed.

Introduction

Recently, neutron star atmospheres with extremely strong magnetic field of the order of the hundreds teragauss attract attention. First, the 1979 March 5 burst (GRB 790305) occurred within supernova (SN) remnant N49 in the Large Magellanic Cloud suggests that soft gamma repeaters (SGRs) could have a surface dipole field of the order of $B \simeq 10^{10}$ Tesla[1] Second, Paczynski[2] and Duncan & Thompson[1] pointed out that for sufficiently large magnetic fields the observed luminosities of SGRs may be sub-Eddington, using the magnetically reduced opacity. The required fields are given by $B > \frac{\omega m_e c}{e}(\frac{2L}{L_0})^{1/2}$ where $L_0 \approx 2 \times 10^{38} ergs^{-1}$ is the zero-field Eddington limit. The luminosities of some SGRs (SGR 1806-20 or SGR 0525-66) require $B > 10^{10} \sim 10^{12}$ Tesla. Such strong fields permit the process of magnetic photon splitting $\gamma \rightarrow \gamma\gamma$ to act effectively below the threshold of single photon pair production $\gamma \rightarrow e^+e^-$, which is about 1 MeV. The radiative transfer problems in such strong magnetic fields were solved by Baring.[3] SGRs are events that have episodes of short ($\sim$1 s), soft ($\sim$30 keV), intense ($\sim$100 Crab), gamma-ray bursts (GRBs).[4] The key character is that SGR spectra have similarities between bursts from the same source.

Cyclotron lines have been detected in the spectra of accreting pulsars and GRBs. It is also possible to detect these lines in the spectra of SGRs, which are phenomena similar to GRBs. A large number of numerical calculations[5] regarding the cyclotron lines of pulsars and GRBs have been performed using the Monte Carlo method or the Feautrier method, but the spectra for neutron star atmospheres with superstrong magnetic field ($\sim 10^9$ Tesla) taking into account cyclotron resonant scattering have not yet been calculated.

We calculate the radiative transfer in neutron stars with superstrong magnetic field ($\approx 10^9$ Tesla) including cyclotron resonant scattering and photon splitting. Since these are strongly dependent on the angle of photon propagation with respect to the magnetic field line, we solve the radiative transfer problem using multiangles. The polarization effects are ignored for simplicity. We also ignored Compton scattering of the continuum component, since photon splitting effects will be dominant there. In neutron star atmospheres with superstrong magnetic fields ($\approx 10^9$ Tesla), we discuss the features of continuum in the spectra. We also investigate the angle-dependence on the spectrum, since photon splitting depends severely on the photon propagation angle to the magnetic field line direction. In particular, we study the deformation of the continuum formed by photon splitting due to cyclotron resonant scattering. However, the polarization effects on cyclotron resonant scattering and photon splitting are considered to be significant. We will calculate the energy spectra including the polarization effect in the future.

Transfer equation

When performing the calculations, a static, plane-parallel, isothermal atmosphere was assumed. The magnetic field direction was taken to be perpendicular to the surface of the plane-parallel atmosphere. We also ignored the polarization effects. Using the Feautrier method[6] the radiative transfer equation can be written as

$$\mu^2 \frac{\partial^2 u(z,\mu,x)}{\partial \tau(z,\mu,x)^2} = u(z,\mu,x) - S(z,\mu,x), \quad (1)$$

where $u(z,\mu,x)$ is the average of the intensity of the incoming and outgoing photons. Here, z is the height of the slab, E is the radiation energy, and μ is the cosine of the angle θ between the direction of the magnetic field and the line of sight to the viewer. The optical depth $[\tau(z,\mu,x)]$, that is, the mean free path of a photon for scattering and absorption is defined as $d\tau(z,\mu,x) = -\kappa(\mu,x)\rho dz$. Also, x is the deviation from the cyclotron energy in units of the Doppler width of the line $x = \frac{E-E_L}{E_L\sqrt{2kT/m_e c^2}}$ and E_L is the energy of the cyclotron lines, $E_L = \frac{\hbar e B}{m} = 11.6 \frac{B}{10^8 Tesla}$ keV.

We took into account of cyclotron resonant scattering and photon splitting as scattering effects. We used the redistribution function and the cross section in cyclotron resonant

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scattering derived at Wasserman and Salpeter.[7] The method for solving the cyclotron resonant scattering is similar to that of Meszaros and Nagel.[5] The optical depth of photon splitting τ_{sp}[3] is given numerically by

$$\tau_{sp} = 7.43 \times 10^5 \left(\frac{B}{B_c}\right)^6 \left(\frac{\hbar\omega}{m_e c^2}\right)^5 (1-\mu^2)^3. \tag{2}$$

In an extremely strong magnetic field ($B \sim 4.414\times10^9$ Tesla), photons with energies of $\hbar\omega \geq 511$ keV split before escaping from the emission region, although this is strongly dependent on θ. The produced photons emerge at an angle θ to the field since splitting is a collinear process in the nondispersive limit.

The source function is, therefore, given by

$$S(z,\mu,x) = \frac{\kappa_e}{\kappa_{total}} \int dx' d\mu' R(x,\mu;x',\mu') u(z,\mu',x') + \frac{\kappa_{sp}}{\kappa_{total}} \int_x^\infty dx' \tau_{sp}(x',x) u(z,\mu,x').$$

Here, $R(x,\mu;x',\mu')$ and $\tau_{sp}(\epsilon,\omega)$ represent the redistribution function of cyclotron resonant scattering and photon splitting, respectively.

The inner boundary condition is incident radiation from inside, and the outer one assumes no incoming radiation from outside.

Assuming no radiation from above at $z = z_{max}$, then

$$\mu\frac{\partial u(z,\mu,x)}{\partial\tau(z,\mu,x)} = u(z_{max},\mu,x) \quad \text{at} \quad z = z_{max}. \tag{3}$$

The radiation is assumed to be the incident intensity $I(x) = I_0\delta(E - 2m_e c^2)$ from below at $z = 0$, then

$$\mu\frac{\partial u(z,\mu,x)}{\partial\tau(z,\mu,x)} = I(x) - u(0,\mu,x) \quad \text{at} \quad z = 0. \tag{4}$$

Results and discussion

We calculated the emergent spectra through the atmosphere threaded by super-strong magnetic field using a set of 25 frequencies and 2 angles. The density and temperature are assumed to be 10^{-4} kg/m^3 and 50 keV, respectively. The depth of the atmosphere is R = 10^2 m. According to Baring,[3] the spectrum of a quasi-monoenergetic injection around 1 MeV is transformed into quasi-thermal spectra at much lower energies by photon splitting $\gamma \rightarrow \gamma\gamma$. We investigated the structures of cyclotron resonant scattering in the spectra formed by the photon splitting.

The cyclotron line around 50 keV is formed at lower side than peak energy in the magnetic field $B \sim 4.3\times10^8$ Tesla in Fig. 1. The cross section of resonant scattering is so large that the clear line appears at both two angles.

Figure 2 shows that the cyclotron absorption line is clear around 100 keV in the direction perpendicular to the magnetic field line at the density of 10^{-4} kg/m^3. The line however become unclear in the direction parallel to the field line even at the density at which clear absorption lines exit around 50 keV in both two angles.

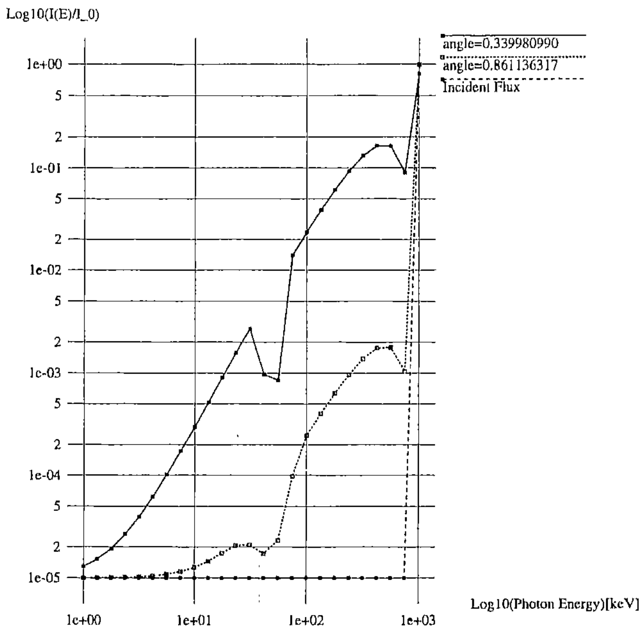

Fig. 1. The energy spectra at the atmosphere with the magnetic field of the cyclotron energy 50 keV. The clear line around 50 keV appears at both two angles.

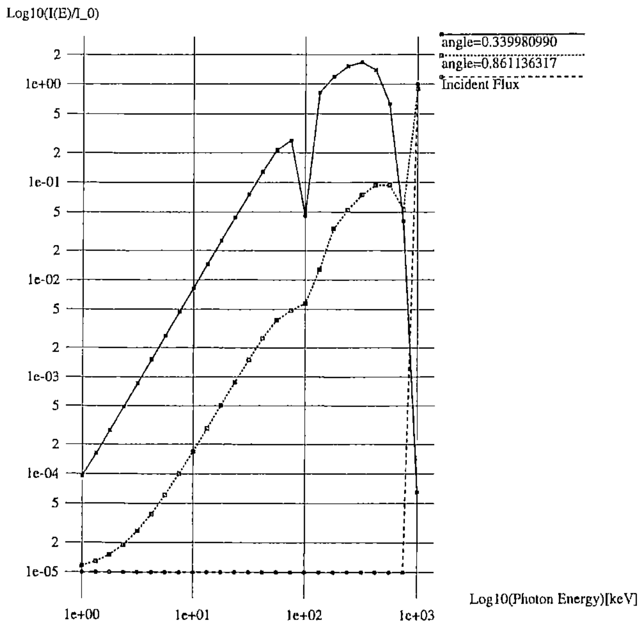

Fig. 2. Same as Fig. 1, but the cyclotron energy is 100 keV.

From Fig. 3, we see that the cyclotron absorption line is not clear at the density at which clear absorption lines exit around 50 keV. This is because the cross section of the cyclotron resonant scattering is proportional to $\frac{1}{B}$. Thus, the cyclotron absorption line around 200 keV may not be detected, assuming to be the atmosphere of the optical depth detected around 20 keV in the energy spectra of GRB.

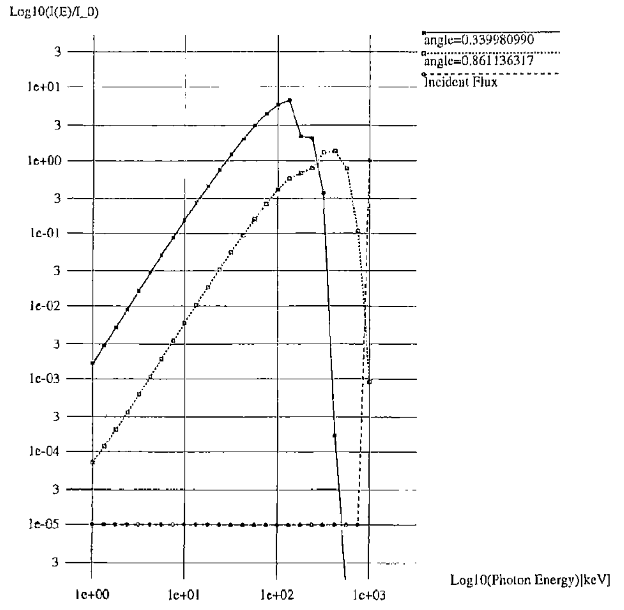

Fig. 3. Same as Fig. 1, but the cyclotron energy is 200 keV.

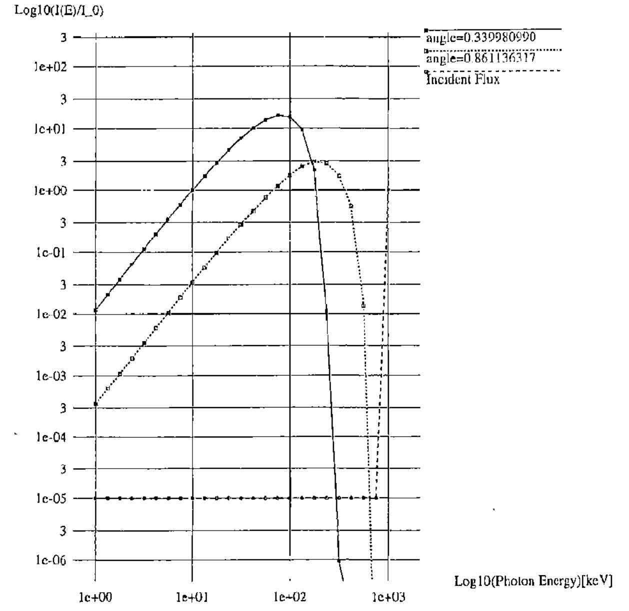

Fig. 4. Same as Fig. 1, but the cyclotron energy is 300 keV.

The cyclotron absorption line don't appear at the magnetic field of the cyclotron energy 300 keV in Fig. 4. This is because the cross section of cyclotron resonance is proportional to the inverse of the strength of the magnetic field B. Figure 4 shows that there is no absorption line even in the density $\rho = 10^{-4}$ kg/m^3.

In conclusion, we find that the structure of the cyclotron resonant line is influenced by the strength of the magnetic field. The structure of clear line doesn't appear around 300 keV at the atmosphere of the density at which clear absorption lines around 50 keV in both two angles. If the atmosphere is the same optical depth as that of GRB which the cyclotron absorption line around 20 keV is confirmed, the cyclotron line will not be detected at the atmophere threaded by the magnetic field strength of about B_c. In present paper, the second harmonics is neglected. This effect must be include at the lower strength of magnetic field than about 10^9 Tesla. It is also important to consider the polarization effect.

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