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A Review on Modeling of Cyclotron Lines in Accreting Neutron Stars

Abstract

Neutron stars are stellar compact objects which posses very high magnetic and gravitational fields. These stars are also found in binary systems in which one star is neutron star and other is normal companion star. Neutron star in binary system accretes material from companion star. When this material falls on neutron star, X-ray radiation is produced. The accreting material falling on the neutron star surface is decelerated by several mechanism and produce X-ray radiation. This X-ray spectra show some absorption and emission features called cyclotron lines or Cyclotron Resonance Scattering Features (CRSFs). CRSFs provide important information about the accretion physics of neutron stars. The physics of formation of Cyclotron lines in spectra of accreting neutron stars will be discussed in the present paper.

Keywords: Neutron Stars, X-Ray Pulsars, Magneto-Compton Scattering, Landau Levels, Cyclotron Lines

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Introduction

Neutron star is a collapsed compact object which is formed during the supernova of a massive star. Neutron star have radius of nearly 10 kilometers and mass in rage 1.4-2.16 solar masses. Neutron stars posses very strong magnetic ($10^8$to 10^{15} gauss) and gravitational fields ($\sim 10^{11}g$). Neutron stars are found in isolation and also in binary star systems. The neutron star in binary system accretes material from companion star and produces X-ray radiation (White, Swank & Holt 1983, Nagase 1989, Bildsten et al. 1997). Such binary star systems are called X-ray binary systems. Depending upon the mass of the companion star these binary systems are classified into three categories (i) Low Mass X-ray Binaries (LMXBs) (ii) Intermediate Mass X-ray Binaries (IMXBs) (iii) High Mass X-ray Binaries (HMXBs). In X-ray radiation of accreting neutron stars some absorption and emission features are present. These features are called cyclotron lines or Cyclotron Resonance Scattering Features (CRSFs). These features are generated due to Compton scattering in very high magnetic fields. To know how matter is detached from companion star? how it reaches neutron star surface? how X-ray radiation is generated? The reader is referred to Kumar (2016).

Review of Literature

Cyclotron lines are found in X-ray spectra of many accreting neutron stars (Doroshenko et. al. (2017), Shtykovsky et. al. (2018)). The modeling of cyclotron lines through radiative transfer equation was done by (Bonazzola_et al. 1979). The results were further improved by Alexander, Meszaros and Bussard_(1989) by incorporating the non-linear stimulated scattering terms in the radiative transfer equations. Alexander and Meszaros (1991) then improved the physics by using relativistic cross-sections, cyclotron absorption and one photon emission. All of these works assumed uniform magnetic field and plasma parameters in the emission region. Later Nishimura (2015) studied the effect of the spatial dependence of these quantities and got more accurate results.

Aim of the paper

In this paper following aspects of physics of cyclotron line formation will be presented.

1. What are cyclotron lines?
2. How they are generated?
3. What are features of cyclotron lines?
4. What is the role of cyclotron lines in understanding of accretion physics of neutron stars?

X-Ray Radiation from Neutron Star

The typical emission region of X-ray spectra showing cyclotron lines is thought to be located at or near the magnetic polar cap of accreting X-ray pulsars. As a result the plasma is then guided by the magnetic field to fall on the magnetic poles of the neutron star. Close to the neutron star surface the inflowing plasma passes through a standing shock and decelerates to finally settle down at the base, forming a dense "accretion mound". The setting flow above the mound is referred to as an "accretion column" (Basko and Sunyaev (1976)). Accretion physics of neutron star in X-ray binary system is described in Kumar (2016).

The spectrum of the escaping radiation consists of X-ray continuum photons containing blackbody, Bremsstrahlung and Compton components, upon which are superposed the cyclotron lines. The blackbody emission originates in deeper region of the mound where local thermodynamic equilibrium is established. The photons of cyclotron and Bremsstrahlung radiation are generated in optically thin upper layers of the mound. When the photons are generated in the mound they propagate in the accretion column, soft photons are converted into hard X-ray photons by inverse Compton scattering. Cyclotron lines are produced when the continuum photons are resonantly scattered, absorbed and re-emitted as they pass through the optically thin layers of the mound and the accretion column.

Cyclotron Lines

Cyclotron lines are absorption and emission features in X-ray spectra of X-ray pulsars. These features are generated due to absorption, emission and resonant scattering between electron and photon in high magnetic fields regions near neutron star surface.

High Magnetic Fields and Onset of Quantum Effects

The stellar magnetic fields of X-ray pulsars are strong e.g. $4.5 \times 10^{12} G$ for Her-X1, $3.4 \times 10^{12} G$ for Cen X-3 (Coburn et al. 2002). At fields of this magnitude higher relativistic quantum effects begin to contribute. Quantum effects become important when the Larmor radius $r_L = \gamma m v_\perp / eB$ approaches the De Broglie wavelength $\lambda_D = 1/(\gamma m v_\perp)$ ie. for

$B \geq m^2 \gamma^2 \beta_\perp^2 / e = \gamma^2 \beta_\perp^2 B_c$ ……………………..…….(1)

with

$B_c = m^2/e = 44.1 \times 10^{12}$ G ………..……..(2)

Where m is the mass and e is the charge of the electron.

Here all quantities are given in the natural units ($\hbar = c = 1$). The magnetic field B_c is called the critical magnetic field. As the magnetic field B approaches B_c, the cyclotron energy of the electron approaches the rest mass energy

$\omega_B = eB/m = m(B/B_c)$ ………………..(3)

Landau levels and resonant energy

The solution of Dirac equation in high magnetic fields results in quantization of linear momentum perpendicular to the magnetic fields ($p_{\perp n} = \sqrt{(2nm^2(B/B_c))}$). These discrete quantum levels (n) are called Landau levels. Parallel component p of the momentum remains a continuous variable. The total energy can be written as the sum of energy in parallel motion and transverse motion

1. $E_n = \sqrt{(m^2 + p^2 + p_{\perp n}^2)}$ ………………..(4)
   The electron-photon interaction becomes resonant as the photon energy (ω_i) approaches a resonant energy $\omega_n^{res} = E_n - E_0$ with
2. $\omega_n^{res}(\mu_i') = (m(\sqrt{((1 + 2n(B/B_c)\sin^2\theta_i'))} - 1)))/(\sin^2\theta_i)$ ………………..…(5)
   Where prime denotes values in a frame with zero parallel momentum of the electron. Here θ_i' is the angle between the direction of photon propagation and the magnetic field and $\mu_i' = \cos\theta_i'$.

Features of Cyclotron Lines

The central energy of the cyclotron lines are given by $\omega_1^{res}, \omega_2^{res}, \omega_3^{res}$... from Eq. 5 and has slightly anharmonic ratios for different values of Landau levels $n = 1, 2, 3...$. Some features of cyclotron lines are described here

1. Resonance energies ($\omega_n^{res}(\mu_i')$ from Eq. 5) depend on magnetic field strength and the angle of propagation of photon.
2. The cyclotron line energy can be used to provide a direct estimate of the field strength in the emission region, usually located close to the neutron star surface.
3. The angle dependence of the resonance energies as well as the optical depth introduces a strong anisotropy in photon propagation and the emitted spectra from neutron star mound and column.

Cyclotron Lines in Observations

The cyclotron lines are generally found in hard X-rays (10-100 keV). In the spectra of nearly 20 X-ray pulsars cyclotron lines have been confirmed (Santangelo et al. (2000), Coburn (2002), Staubert (2003), Heindl et al. (2004)).

1. The observed cyclotron lines are found in general to be broad, and the fundamental usually has a shape more complex than a single Gaussian.
2. The ratios of the of line center energies, when multiple features are seen, are not harmonic in some sources e.g. Vela-X1 (Kreykenbohm et al. (1999, 2002)) etc.
3. In many sources (with a few exceptions like V0332+53) line parameters are found to vary significantly as a function of the spin phase of the neutron star.
4. In some sources the line energy of the fundamental shows a dependence on the source luminosity. e.g. V0332+53 (Tsygankov et al. (2010)), 4U0115+63 (Tsygankov et al. (2007)), A0535+26 (Klochkov et al. 2011), Her-X1 (Staubert et al. 2007), GX-304-1 (Klochkov et al. 2012). These observations shows that the behavior of the cyclotron line features vary qualitatively from source to source.

Modeling Via Radiative Transfer 5 Equation

There are two important methods of modeling of cyclotron lines in X-ray pulsars 1) Solving the radiative transfer equation 2) Monte Carlo simulations. In this paper the first method is discussed. In this method the radiative transfer is performed via solving the radiative transfer equation (Eq.6). This equation can be solved with two boundary conditions on I(intensity) 1) Inner boundary condition 2) outer boundary condition. One inside the column column and one at the surface of accretion column. The inner boundary condition is usually provided by assuming that the radiation field is in thermodynamic equilibrium ($I = B(T)$). The radiative transfer equation for static case ($\partial/\partial t = 0$) and ignoring the stimulated scattering terms (nonlinear terms for I^2) is given as

$$\mathbf{\Omega}\cdot\nabla I = -\kappa(I - S) \qquad \text{…………………(6)}$$

Where $\mathbf{\Omega}$ is the direction of photon propagation, $\kappa = \alpha + \sigma - q$ is the total opacity with continuum absorption (α), resonant scattering (σ) and stimulated emission (q). S is the source function. In the above equation all the quantities I, κ and S are functions of position, energy and angles (r, ω, θ, φ). While solving Eq.6, the thermodynamic state of the plasma is assumed a priori. The effect of strong magnetic field is hidden in different opacities for absorption, emission and scattering.

To Solve the radiative transfer equation (Eq.6) one needs to define the source term S. The source function S should contain the terms for: 1) the production of continuum photons, 2) the generation of photons due to emission by electrons in excited Landau levels, and 3) the resonance scattering. The corresponding opacities terms in source function are 1) continuum absorption 2) cyclotron absorption 3) scattering opacities. However, in very early works the cyclotron absorption and cyclotron emission terms were not included in the source term, only the magneto-Compton scattering and free-free absorption and emission were considered. The source function in such cases (neglecting the cyclotron absorption and cyclotron emission) may be written as

$$\kappa S = \alpha' B_\omega + \int d\omega' \int d\Omega' \langle (d^2\sigma_{sc})/(d\omega d\Omega)(\omega, \theta, \varphi \leftarrow \omega, \theta, \varphi) \rangle_{fe(p)} \times (\omega)/(\omega') I(\omega, \theta, \varphi) \qquad \text{…………………….(7)}$$

Where in Eq.7 the term containing α is for free-free emission, absorption and second term is for magneto-Compton scattering. Later this method is improved by taking more care on angular re-distribution of photons and by including cyclotron absorption and cyclotron emission.

Conclusions

Cyclotron lines are absorption and emission features observed in X-ray spectrum of accreting neutron stars. In very high magnetic fields region, near the neutron star surface, the perpendicular component (perpendicular to local magnetic fields) of linear momentum of the electron becomes quantized. These quantized levels are called Landau levels. Cyclotron lines are formed due to absorption and emission of photons during transition between Landau levels and due to resonant scattering of photons with electrons. Cyclotron lines are modeled via two methods 1) Solving radiative transfer equation 2) Monte-Carlo simulations. The first method is described in this paper. Cyclotron lines give estimation of magnetic fields of accreting neutron stars. They also give information of accretion physics of neutron stars.

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