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Changes in Cyclotron line energy with luminosity in Accreting X-ray pulsars

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Abstract. I model changes in cyclotron line energy with luminosity, considering the effect of polar cap dimensions and changes in beam pattern as well as shock height. Cyclotron lines are calculated by a superposition of a large number of cyclotron lines formed in different heights of an accretion column. Cyclotron line energy has been observed to change with luminosity in a number of accreting X-ray pulsars. In X0115+63 and V0332+53, the fundamental cyclotron line energy has been observed to decrease with increasing luminosity. This phenomenon has been interpreted as a change in shock height with luminosity. However, the rate of the change seems to be very different, in which the line energy in V0332+53 seems to vary slowly with luminosity compared with that in X0115+63. I found that the changes in the cyclotron line energies with luminosity can be explained by changes in beam pattern and the size of a polar cap rather than a shock height.

Keywords. cyclotron line, neutron star,magnetic field

1. Introduction

Cyclotron lines have been observed in the spectra of a number of X-ray accreting pulsars. We can investigate geometry, electron temperature and density of a line-forming region as well as the strength of the magnetic field(B-field) of a line-forming region above the surface of neutron star(NS) via the cyclotron lines. Negative correlation between the centroid energy of the cyclotron line and luminosity has been observed in V0332+53(Tysgankov *et al.* 2010) and X0115+63(Nakajima *et al.* 2006). In this work, I consider the affect of changes in beam patterns with luminosity on cyclotron line energy.

2. Line-forming region

The magnetic field is assumed to be a dipole field. The temperature is also approximated by $kT \sim \hbar\omega_{cyc}$ /4. The distribution of the flux of radiation escaping through the walls of the accretion column, $F(x)$, is given by $F(x) \propto [7 - (\frac{7}{2} + \epsilon_c)\mu]\epsilon_c\mu$, where $\mu(x) = (\frac{14}{7+2\epsilon_c})[1 - (\frac{14}{7-2\epsilon_c})^{-x/x_{shock}}]$ and $\epsilon_c = 0.5$(Becker 1998). Here, x denotes a distance from a shock region in units of a shock height. The resonant energy in the lab frame is given by $E_n = \frac{1}{\gamma(1-\beta\mu)}\frac{2nb}{1+\sqrt{1+2nb(1-\mu^r)}}$. The top of the line-forming region is assumed to be a distance of polar cap diameter from the altitude of emission region which is located on the surface of thermal mound, z_{th}, becaues $\sigma_{\|} = \sigma_{\perp}$ at the fundamental cyclotron energy E_{cyc} in which $\sigma_{\|}$ and $\sigma_{\perp}$ are the energy- and mode-averaged scattering cross section for photons propagating parallel and perpendicular to B-field. The polar cap radius is assumed to increase with luminosity via the equation below(Becker and Wolff 2007): $r_0 \lesssim 6.5 \times 10^4(\frac{B}{10^{12}\text{G}})^{-2/7}(\frac{R_{NS}}{10\text{km}})^{9/14}(\frac{M_{NS}}{M_\odot})^{1/14}(\frac{L_{37}}{1.3})^{1/7}\text{cm}^2$.

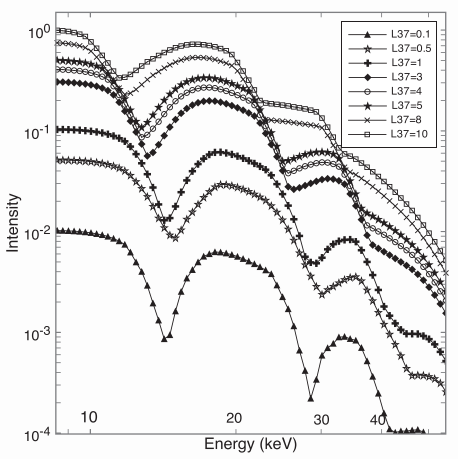

Figure 1. Spectra from bottom to top are for luminosity $L_{37} = 0.1, 0.5, 1, 3, 4, 5, 8, 10$ for X0115+63. The bottom of B-field strength is assumed to be 17 keV. Downward photon propagation is assumed for $L_{37} \lesssim 3$, while upward photon propagation is assumed for $L_{37} > 5$.

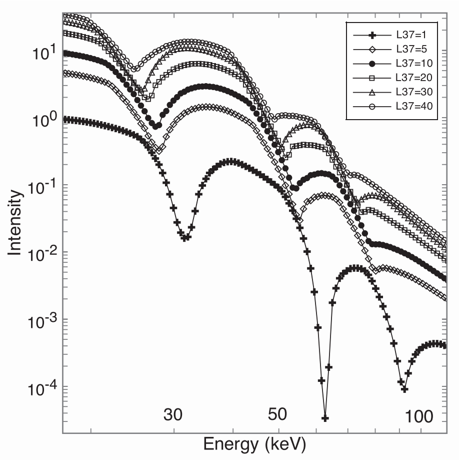

Figure 2. Spectra from bottom to top are for luminosity $L_{37} = 1, 5, 10, 20, 30, 40$ for V0332+53. The bottom of B-field strength is assumed to be 36 keV. Downward photon propagation is assumed for luminosity $\lesssim 5$.

3. Results

X0115+63: The top of the line-forming region is expected to go away from the shock region with increasing luminosity so that upward photon propagation would dominate over downward photon propagation in the line-forming region. Thus, E_{cyc} significantly changes during $\sim 3.0 \times 10^{37}$ erg s^{-1} to $\sim 5.0 \times 10^{37}$ erg s^{-1} via a change in beam pattern from downward to upward in the line-forming region. Downward photon propagation is assumed to dominate for $L_{37} \lesssim 4$. On the other hand, upward photon propagation is assumed to dominate for $L_{37} \gtrsim 5$. As a result, higher cyclotron line energy for $L_{37} \lesssim 4$ can be reproduced in agreement with the observation. Furthermore, E_{cyc} also continues to change via Doppler effect as a result of a change in the direction of emission pattern around $L_{37} \sim 5$.

V0332+53: The top of the line-forming region increases by $\sim 1.5 \times 10^{4}$ cm per $\Delta L \sim 1.0 \times 10^{38}$ erg s^{-1} via an increase in polar cap dimensions. The width of the observed line tends to be constant for luminosities higher than $\sim 5.0 \times 10^{37}$ erg s^{-1} probably because of no considerable change in beam pattern as a result of no affect of shock region, unlike X0115+63. This is because the line-forming region is sufficient far from the shock region so that beam pattern would not change considerably with luminosity. In addition, the observed equivalent width decreases with increasing luminosity, which is consistent with the numerical results that the line becomes shallower with increasing luminosity as a result of the superposition of a larger number of the lines. For lower luminosity $L_{37} \lesssim 5$, a larger variation on E_{cyc} with luminosity can occur at lower luminosity due to a transition from upward to downward photon propagation.

References

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