Superposition of cyclotron lines in accreting X-ray pulsars

Osamu Nishimura

Department of Electronics and Computer Science,
Nagano National College of Technology, 716 Tokuma, Nagano 381–8550
E-mail: nishi@ei.nagano-nct.ac.jp

Abstract

We model cyclotron lines by calculating a superposition of the spectra of a number of the cyclotron lines emerging from different heights of line-forming regions with non-uniform density, temperature and magnetic field strength in each region. We found that a shallower and broader fundamental line associated with a deeper second harmonic line as observed in Vela X−1 and A0535+26 can be produced via the superposition of a large number of the cyclotron lines. Our simplified model succeeds in reproducing an asymmetric line profile, an anharmonic line ratio.

Key words: stars:atmospheres — stars:magnetic fields — stars:neutron

1. Calculation of cyclotron lines

The cyclotron line is modeled by superposing a number of the lines calculated in each slab with a different height with a Feautrier code with 120 frequencies. The original cyclotron line emerging from each slab is calculated for scattering in the two-stream formalism. An initial power-law photon density, $U_i(E) \propto \omega^{-1}$, is injected into each slab. We include excitation up to three harmonics in Landau levels and photon spawning followed by decay of these levels in cyclotron resonant scattering. In this work, we examine the effect of a superposition of a number of the cyclotron lines emerging from different heights of a line-forming region with a gradient in magnetic field, temperature, density on the property of the resulting lines. We consider a cylindrical, plane-parallel geometry for the line-forming region(Nishimura 2009). Moreover, the magnetic field, temperature, density vary in each region with height. We consider an extended atmosphere, which is thick to cyclotron resonant scattering and thin to the continuum scattering, as a line-forming region and calculate a superposition of the cyclotron lines emerging from a number of different heights of the line-forming region.

2. Results

We first calculate cyclotron lines with one angle $\mu \equiv cos\theta = 0.57$, which corresponds to angle-averaged spectra, and the cyclotron energy at the bottom of the line-forming region, $\hbar\omega$=30 keV. Figure 1 shows the superposing cyclotron lines for the numbers of the superposing lines $n_s = 1, 4, 8, 14, 18$ which can correspond to the polar cap radius $R \sim 5 \times 10^3, 3 \times 10^4, 6 \times 10^4, 1 \times 10^5$ and 1.3×10^5 cm, respectively, because broader polar cap is able to yield a larger number of the superposing lines in our model. The fundamental line becomes broader and shallower with increasing number of the superposing lines, whereas the second harmonic line becomes deeper and deeper. The fundamental line is formed via resonant scattering so that its peak energy tends to be formed around the surface of the wall in spite of lower density. This is because a number of photons scattered around the surface of the column transfer to different energy and refill the parts of other absorption feature formed in lower part of the line-forming region. Thus, the peak energy of the fundamental absorption line tends to indicate the B-field strength near the sides of the line-forming region(e.g. accretion column). The resulting fundamental line formed by the superposition of a number of the lines with different peak energies tends to be broader and shallower. On the other hand, each original second harmonic lines possess nearly the same peak energy. This is because they are formed via almost pure absorption process by Raman scattering, such that the peak energy corresponds to the magnetic field strength near the bottom of the line-forming region where the density is highest in our model. Consequently, the resulting second harmonic line tends to be deeper with increasing number of the superposing lines as opposed to the fundamental. Moreover, the peak energies of the higher harmonic lines almost remain constant in spite of increasing number of the superposing lines, while the peak energy of the fundamental line changes noticeably toward lower energy. As a result, the ratio of the peak energy of the second harmonic absorption line to the fundamental tends to be larger than the harmonic ratio 2. Furthermore, Meszaros and Nagel(1985) roughly predicted the FWHM of the line $\Delta\omega_{FWHM} \sim \omega_c(8ln(2)\frac{kT}{mc^2})^{1/2}|cos\theta|$. In our calculations, however, the width of the superposing fundamental line can be comparable to or larger than that of the second harmonic as a result of the superposition of a large number of the lines in contradiction to theoretically Doppler broadening. This is because the second harmonic line width does not increase as much as that of the fundamental line, since the peak energies of the original higher harmonic lines form in nearly the same location. In addition, the line profile becomes asymmetric, which is shallower toward lower energies, when the superposition of a large number of the lines occurs. This is because the maximum overlapping area of each original absorption feature is located around higher energies.

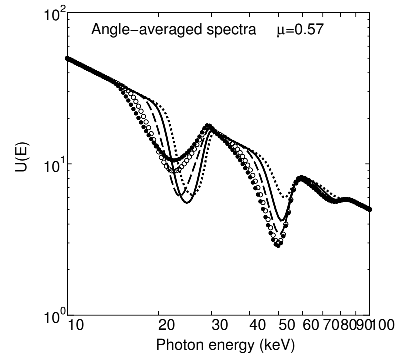

Fig. 1. Superposing cyclotron lines in the line-forming region with decreasing B-field for the numbers of the superposing lines n_s=1(dotted line), 4(solid line), 8(dashed line), 14(open circles) and 18(filled circles). The viewing angle is taken to be $\mu = 0.57$. The electron number density is taken to be in the range of $N_{e,21} \sim 0.4 - 3.5$ electrons cm^{-2} where $N_e \equiv N_{e,21} \times 10^{21}$.

Next, we consider a polar cap radius $R_p \sim$ 1km for an emission region. Figure 2 shows the angle-dependent spectra at four angles $\mu = 0.18, 0.52, 0.79$ and 0.96. The superposition of a smaller number of the lines at larger viewing angle with respect to the magnetic field can operate in such a small area. Thus, the peak energies of narrow lines at $\mu = 0.18$ at the fundamental tend to indicate higher energies and its depth remains deeper. On the other hand, those of broader lines at the fundamental tend to indicate lower energies as a consequence of the superposition of a large number of the lines. The line depth is however deeper for smaller viewing angle. This is because thermal Doppler width becomes broader at smaller angle. The overlapping area of the original lines is therefore larger for smaller angle so that the line remains deeper. The second harmonic lines however tend to be deeper, since the peak energy of each line is nearly constant due to almost pure absorption in the line-forming region with the density gradient. Consequently, the ratio of the second harmonic line energy to the fundamental tends to be more than 2 for smaller viewing angles whereas it remains to be nearly 2 for larger viewing angles as a result of the superposition of a small number of the lines. The second harmonic line, however, tends to be even shallower for smaller angle, since the scattering profiles of higher harmonics have a $\sin^{2(n-1)}\theta$ factor. Moreover, the line width of the fundamental can be comparable to or larger than that of the second harmonic for smaller viewing angles, while the line width of the second harmonic is nearly twice times that of the fundamental for larger viewing angles, as expected by theoretically Doppler broadening.

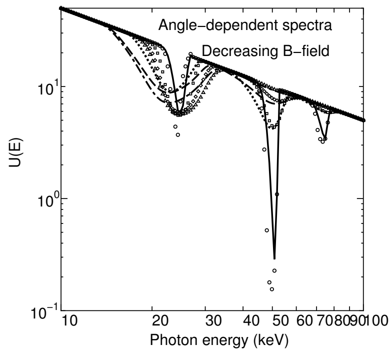

Fig. 2. Superposing angle-dependent spectra at four viewing angles $\mu = 0.18$(solid line),0.52(dotted line),0.79(dashed line) and 0.96(dot-dashed line). For comparison, original angle-dependent spectra emerging from the height $z = 3.0 \times 10^4$ cm at four viewing angles $\mu = 0.18$(open circles),0.52(open squares),0.79(open diamonds) and 0.96(open triangles). Here, the polar cap radius is assumed to be 1km and $h_{shock} = 2.1 \times 10^5$ cm. The electron number density is in the range of $N_{e,21} = 0.27 - 2.2$ electrons cm^{-2}.

References

Meszaros, P. & Nagel, W. 1985, ApJ., 298, 147
Nishimura, O. 2009 ApJ., submitted