Understanding Cyclotron Lines in the Spectra of Accreting Neutron Stars

P. Kretschmar[1], G. Schönherr[2], J. Wilms[3], O. Nishimura[4], I. Kreykenbohm[3], R. Staubert[5], D. Klochkov[5], A. Santangelo[5], I. Caballero[5,9], C. Ferrigno[5,10], K. Pottschmidt[6,11],R. Rothschild[7], E. Rivers[7], S. Suchy[7], V. McBride[8]

[1] ESA – European Space Astronomy Centre, 28691 Villanueva de la Cañada, Madrid, Spain
[2] Astrophysikalisches Institut Potsdam, 14482 Potsdam, Germany
[3] Dr. Karl Remeis-Sternwarte & ECAP, FAU Erlangen-Nuremberg, 96049 Bamberg, Germany
[4] Nagano National College of Technology, Nagano 381-8550, Japan
[5] Institut für Astronomie und Astrophysik, Univ. of Tübingen, 72076 Tübingen, Germany
[6] CRESST, University of Maryland Baltimore County, 1000 Hilltop Circle, Baltimore, MD 21250, USA
[7] Center for Astrophysics and Space Science, UCSD, La Jolla, CA, USA
[8] School of Physics and Astronomy, Southampton University, Hampshire SO17 1BJ, United Kingdom
[9] CEA Saclay, DSM/IRFU/SAp – UMR AIM (7158) CNRS/CEA/Univ. P. Diderot – F-91191 Gif sur Yvette France
[10] ISDC Data Centre for Astrophysics, 1290 Versoix, Switzerland
[11] NASA Goddard Space Flight Center, Code 661, Greenbelt, MD 20771, USA
E-mail(PK): Peter.Kretschmar@esa.int

Abstract

Cyclotron lines are formed through transitions of electrons between discrete Landau levels in the accretion columns of accreting neutron stars with strong ($B \sim 10^{12}$ G) magnetic fields. We summarize recent results on the formation of the spectral continuum of such systems, describe recent advances in the modeling of the lines based on a modification of the commonly used Monte Carlo approach, and discuss new results on the dependence of the measured cyclotron line energy from the luminosity of transient neutron star systems.

Key words: X-rays: binaries — stars: neutron — magnetic fields — line: formation

1. Accreting X-ray pulsars and Cyclotron Lines

Accreting X-ray pulsars are highly magnetized neutron stars in a binary system, accreting matter from their companion star. The mass transfer can take place via Roche-Lobe overflow, strong stellar winds for giant stars or the Be mechanism. Typical accretion rates are $\dot{M} \sim 10^{-9\ldots-11}\,M_\odot\,\mathrm{yr}^{-1}$.

The accreted plasma couples to the B-field at the Alfvén radius. For typical parameters ($M \sim 1.44\,M_\odot$, $B \sim 10^{12}$ G) this radius is of the order of a few 1000 km. The plasma is then funneled along the B field lines onto the magnetic poles forming accretion columns and reaching a free-fall velocity of $v \sim 0.7\,c$.

The X-ray spectra of accreting X-ray pulsars can usually be described by a power law continuum modified by an exponential cutoff which is due to Compton scattering. Normally there is also a strong Fe Kα line.

Becker & Wolff (2005a, 2005b, 2007) describe this basic spectral shape for high luminosity systems by bulk and thermal comptonization in a radiative shock of source terms including bremsstrahlung, cyclotron and blackbody emission. Ferrigno et al. (2009) have incorporated this model into XSPEC and applied it to observations of 4U 0115+63.

Due to the strong B field, electron energies perpendicular to the field are quantized (Landau levels):

$$E_n = m_\mathrm{e} c^2 \frac{\sqrt{1 + 2n(B/B_\mathrm{crit})\sin^2\theta} - 1}{\sin^2\theta} \tag{1}$$

where n is the major quantum number and

$$B_\mathrm{crit} = \frac{{m_\mathrm{e}}^2 c^3}{\mathrm{e}\hbar} \sim 4.4 \times 10^{13}\,\mathrm{G} \tag{2}$$

For $B \ll B_\mathrm{crit}$, the distance between Landau levels can be written as ("$12 - B_{12}$-rule"):

$$E_\mathrm{cyc} = \frac{\hbar e}{m_\mathrm{e} c} B = 11.6\,\mathrm{keV} \left(\frac{B}{10^{12}\,\mathrm{G}} \right) \tag{3}$$

Resonant scattering of photons with electrons at these energies leads to Cyclotron Resonance Scattering Features (CSRF) or "cyclotron lines" at:

$$E_n = n\,E_\mathrm{cyc} = (1+z)\,E_{n,\mathrm{obs}} \tag{4}$$

where $1 + z \sim 1.25 \ldots 1.4$ is the gravitational redshift.

The hot plasma leads to thermal broadening of the lines with narrow lines perpendicular to the B-field and broad lines for motion along the B-field. The expected line width is $\Delta E_{\mathrm{FWHM}}/E_{\mathrm{cyc}} \sim \sqrt{kT_{\mathrm{e}}}|\cos\theta|$ (Trümper et al. 1978).

2. Observations

Cyclotron lines have by now been observed in ~15 sources. The number of detection slowly increases with new and improved data from recent observatories. Still, a majority of X-ray pulsars remains without such features being detected.

Accretion in (high mass) X-ray binaries can be strongly variable on long timescales. Thus, observations can cover a large range in luminosity (and thus presumably $\dot{M}$).

Several cyclotron line sources have been shown to have the energy of the fundamental cyclotron line change with luminosity. In V 0332+53 a clear decrease of the line energy with increasing luminosity has been observed (Mowlavi et al. 2006; Tsygankov et al. 2006). Similarly, for 4U 0115+63 (Mihara et al. 2004; Nakajima et al. 2006). In contrast, Staubert et al. (2007) found a positive correlation between luminosity and cyclotron line energy in Her X-1. Other sources, such as A 0535+26 (Caballero et al. 2007), Cep X-4, or 4U 1538-52 *do not show any significant line energy variation* with L.

Staubert et al. (2007) explain these different results by the different interaction of the ram pressure in the accretion stream and radiation pressure in sub- and super-Eddington luminosity regimes.

3. Modeling Cyclotron Lines

While analyzing observations, cyclotron lines are usually simply approximated by Gaussian or Lorentzian absorption line shapes. For more detailed models, two approaches have been used in the recent literature.

Nishimura (2008, 2005) uses a Feautrier radiative transfer code to model emission from complex line forming regions consisting of multiple individual domains with varying parameters, e.g., magnetic field strength; see also Nishimura's contribution in these proceedings.

Schönherr et al. (2007) use a Monte-Carlo method, based on the work by Araya& Harding (2000), to implement a Green's functions approach, calculating the response of the column to monoenergetic photons. This model has been experimentally incorporated into XSPEC for direct data fitting.

The CRSF shape depends on the non-resonant optical depth and angle. The resonance depth is $\sim 10^5 \cdot \tau_{\mathrm{T}}$!

4. Simulations versus Data

Both the radiative transfer and the Monte-Carlo method can qualitatively reproduce various of the observed features in cyclotron line spectra, i.e., the complex, asymmetric shape of the fundamental line in several sources; anharmonic line ratios and the existence of very shallow fundamental lines "filled up" from contributions by higher harmonics. But detailed quantitative results require still further improvements.

Direct fits of cyclotron line spectra of V 0332+53 with the Monte-Carlo model of Schönherr et al. (2007) are promising and allow to constrain the emission geometry, but also show some of the limitations like stronger predicted line wings than found in the data.

Efforts are ongoing to incorporate more detailed physics, e.g., B-field or temperature gradients into the models and to make these models available for spectral fitting.

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