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Cyclotron features in X-ray spectra of accreting pulsars

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Abstract

The hard X-ray spectra of small subset of accreting pulsars show absorption-like line features in the range 10–100 keV. These lines, referred to as cyclotron lines or cyclotron resonance scattering features, are due to photons scattered out of the line of sight by electrons trapped in the 10^{12} G pulsar polar cap magnetic field. In this paper we present a review of observations, from the discovery of a cyclotron line in Hercules X-1 to recent results with *RXTE* and *INTEGRAL*.

Keywords: X-rays; X-ray binaries; X-ray spectroscopy; Cyclotron lines; Neutron stars; Pulsars; Accretion

1. Introduction

Accretion powered X-ray pulsars are spinning, highly magnetized ($B \gtrsim 10^{12}$ G) neutron stars, accreting matter from the wind of a companion star or through Roche-lobe overflow. Most of these systems are transient in nature, usually (but certainly not always) with an OBe companion. Accreting pulsars have typical luminosities in the range 10^{34}–10^{37} ergs cm^{-2} s^{-1}, with the low end for persistent sources and the upper during transient outbursts.

Regardless of what type of accretion occurs, wind or Roche-lobe overflow, as material spirals in towards the highly magnetized neutron star an accretion disk is expected to form. Due to the magnetic field of the neutron star, the disk will be truncated by the magnetic pressure far from the surface of the neutron star (Ghosh and Lamb, 1979). At this point the accreting material will become entrained on the field lines and channeled towards the neutron star magnetic poles, forming two "hot-spots" on the surface. If the magnetic field axis and spin axis are misaligned, then much like a terrestrial lighthouse pulsations will be seen at the neutron star rotation frequency.

The matter channeled onto the magnetic poles of an accreting pulsar is stopped either by a shock front above the neutron star surface, or through collisions with electrons and protons in the neutron star atmosphere. The exact accretion structure geometry depends largely on the accretion rate, plasma properties, and the geometry of the accretion columns. Idealized, this leads to two principal modes of radiation. This first is a "fan beam" from the column beneath the shock front, and with emission perpendicular to the magnetic field. The second is a "pencil beam" from a thin slab at the magnetic pole, and with emission parallel to the magnetic field (see e.g., Harding, 1994). The details of the emerging pulse profiles in these two idealized cases are very different, although the realities of summing emission from two poles and including light bending

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makes the situation far less simple. Still though, pulse shapes and their dependence on energy are an excellent diagnostic tool for the determination of the emission geometry and indirectly for the physics of the accretion flow (e.g., Bulik et al., 1995).

Cyclotron resonance scattering features, CRSFs or "cyclotron lines," are line-like spectral features resulting from photons being resonantly scattered by electrons out of the observers line of sight. The electron energies are quantized into Landau levels, so the energy of the cyclotron line is a direct measure of the magnetic field strength in the scattering region.

The non-relativistic cyclotron energy is given by the formula

$$E_n = n\frac{\hbar eB}{m_e} = 11.6\frac{B}{10^{12}\ \mathrm{G}},$$

where B is the magnetic field strength and $n = 1, 2, \ldots$ is the number of the harmonic. Note that since n starts counting at one, we usually refer to the $n = 1$ line as the fundamental while the $n = 2$ is the second harmonic.

Since the emission is coming from near the surface of a compact object, the observed cyclotron line energy is redshifted from the actual energy. This factor is given by $E_n^{\mathrm{obs}} = E_n(1+z)^{-1}$, where z is the redshift. For a canonical neutron star with a mass $M = 1.4\ \mathrm{M}_\odot$ and radius $R = 10$ km $(1+z)^{-1} \simeq 0.76$.

The energy of the fundamental is a little different when relativistic effects are taken into account. The relativistic cyclotron line energy is given by

$$E_n = nm_e c^2 \frac{[1 + 2n(B/B_{\mathrm{QED}})\sin^2(\theta)]^{1/2} - 1}{\sin^2(\theta)},$$

where θ is the angle of the incident photon with respect to the magnetic field, and $B_{\mathrm{QED}} = m_e^2 c^3/(\hbar e) \simeq 44$ TG is a magnetic scale factor. This dependence on θ can lead to non-harmonic line spacing.

When the full relativistic cyclotron scattering cross sections are taken into account, photons propagating perpendicular to the B-field have a narrower cross section than those photons propagating perpendicular to the B-field (Fig. 1). Also, since the electron motions are quantized perpendicular to the magnetic field but allowed to stream along the field lines, doppler broadening effects are important (Araya and Harding, 1999). These two effects lead to a non-uniform angular redistribution of scattered photons, the result of which is non-symmetric, non-Gaussian line profiles that are highly dependant on magnetic field strength, electron temperature, emission geometry, and viewing angle (Araya and Harding, 2000). See Fig. 2 for examples of how complex line shapes can emerge at the fundamental line energy.

Even with the relatively low spectral resolving power of scintillation detectors, fitting cyclotron lines can be quiet challenging. We currently have only phenomenological models for the broad-band continuum, and poor continuum fits can require lines that are little more than artifacts induced by the model. Therefore, when reporting a new cyclotron line it is important to verify that the line fits are relatively insensitive to the details of the continuum fit.

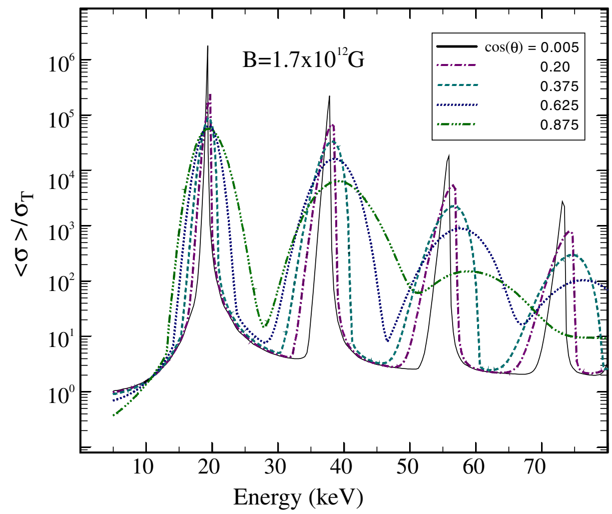

Fig. 1. Cross sections, as a function of photon propagation angle, for photon scattering in a $B = 1.7 \times 10^{12}$ G magnetic field. The large widths at low angles are primarily due to doppler broadening, and the angular dependence in the cross sections leads to a non-uniform angular redistribution of photons and complex line shapes. From Araya and Harding (1999).

The continuum of accreting X-ray pulsars are roughly described as a power-law with index Γ below a characteristic "cutoff" energy ($E_{\mathrm{cut}} \sim 10$–20 keV). Above the cutoff energy, the power-law falls exponentially with a characteristic folding energy ($E_{\mathrm{fold}} \sim 5$–20 keV). Mathematically, this is realized in three common forms (see Coburn et al., 2002, for a more complete description):

$$\mathrm{PLCUT}(E) = AE^{-\Gamma} \times \begin{cases} 1 & (E \leqslant E_{\mathrm{cut}}), \\ e^{-(E-E_{\mathrm{cut}})/E_{\mathrm{fold}}} & (E > E_{\mathrm{cut}}), \end{cases}$$

$$\mathrm{FDCO}(E) = AE^{-\Gamma}\frac{1}{1 + e^{(E-E_{\mathrm{cut}})/E_{\mathrm{fold}}}},$$

$$\mathrm{NPEX}(E) = A(E^{-\Gamma_1} + BE^{+\Gamma_2})e^{-E/E_{\mathrm{fold}}}.$$

All of these equations have the same general form. However, one will tend to fit a particular pulsar better than others. The "Cutoff Power-law" (PLCUT) has the advantage that it is fairly simple. However, the discontinuity in the derivative at the cutoff energy can and does lead to a line-like artifact in the residuals. Therefore a second, smoothing function is usually applied to remove this. The "Fermi-Dirac Cutoff" (FDCO) is used because of its shape, but otherwise has no physical significance and is not related to the Fermi-Dirac distribution of quantum mechanics. The "Negative/Positive Exponential" (NPEX) uses a pair of power-laws, one with a *positive* index, along with an exponential to mimic the shape of pulsar continua. See Mihara (1995) for a possible physical interpretation of this model.