CYCLOTRON LINE STUDIES IN MAGNETIZED X-RAY PULSARS

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ABSTRACT

Cyclotron resonance scattering features (CRSFs), also referred to simply as "cyclotron lines", are detected as absorption lines in high-energy spectra of magnetized accreting neutron stars. They form in the presence of a strong magnetic field due to resonant scattering processes with electrons which are quantized in discrete Landau energy levels perpendicular to the B-field. Providing the only direct estimate of the magnetic field strength of an accreting neutron star, cyclotron lines are of fundamental importance to understanding the physics of magnetized X-ray pulsars. Their line profiles reflect the geometrical and physical properties of the accretion column near the magnetic poles of the neutron star, and therefore constitute a diagnostic tool for accessing the physics of accretion. Todays' high-energy telescopes allow for a resolution of those line shapes. Continuing an earlier approach by P. Kretschmar (Kretschmar et al., 2004), and making a renewed effort of simulating cyclotron lines with a revised Monte Carlo code based on the work of R. Araya (Araya & Harding, 1999), we fit our theoretical models to recent observational data.

Key words: CRSFs; neutron stars; γ-rays; X-rays.

1. INTRODUCTION

Considerable progress has been achieved in the field of instrumental high energy astronomy since the first detection of a cyclotron line in a Her X-1 spectrum with Balloon-HEXE in 1979. Spectra with a remarkable energy resolution of the cyclotron line shapes are obtained by instruments from e.g. the *INTEGRAL* and *RXTE* satellites. However, a theoretically established XSPEC model for analysis of these data is lacking. Instead it is still common procedure to fit CRSFs with simple but unsatisfactory Lorentzian or Gaussian shapes. In the following, we discuss new results leading towards more realistic modeling of cyclotron lines and better future exploitation of their diagnostic potential.

2. LINE FORMATION

Cyclotron lines have been observed in spectra of many magnetized accreting neutron stars as absorption features in the 10 to 100 keV energy regime. Due to the high magnetic field, the kinetic energies of the plasma electrons in the accretion region are quantized perpendicular to the B-field in discrete so-called Landau levels. Photons with energies of $\sim n$ times the fundamental Landau energy undergo resonant scattering with the Landau electrons. They are trapped in the dense plasma of the accretion mound, being absorbed, quasi instantly re-emitted or spawned and absorbed again by the Landau electrons. Those photons may escape once their energy has changed sufficiently from the resonant Landau energies. Thus, they produce absorption features in the observed spectrum at the Landau line energies:

$$E_n = m_{\mathrm{e}}c^2 \frac{\sqrt{1+2nB/B_{\mathrm{crit}}\sin^2\theta}-1}{\sin^2\theta}\,\frac{1}{1+z}$$

where $(n = 0, 1, 2, \ldots)$, B/B_{crit} is the magnetic field strength in units of the QM critical field $B_{crit} = 4.4 \cdot 10^{13}$ G, θ is the angle between the photon and the magnetic field, $m_{\mathrm{e}}c^2$ is the electron rest energy and z denotes the gravitational redshift.

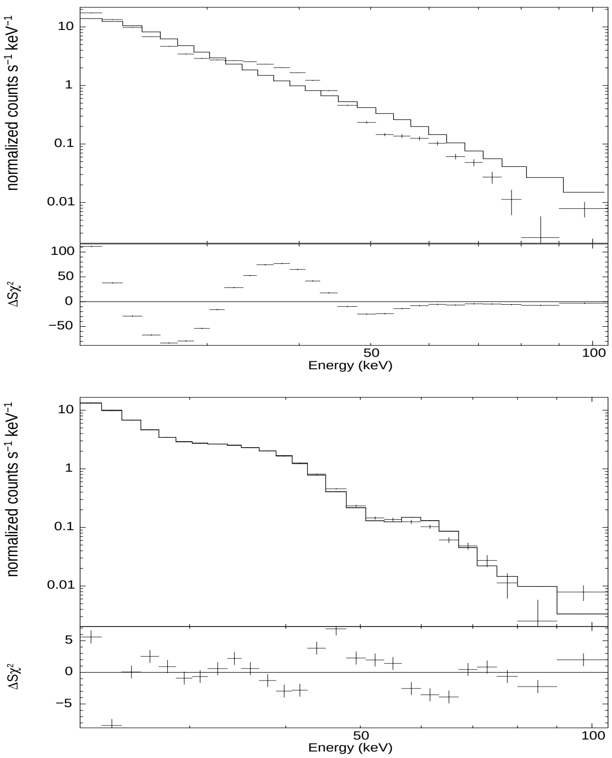

Figure 1. V0332+53 outburst spectrum fitted with a cutoffpl model (top) and the same continuum model multiplied by our new XSPEC table model for cyclotron line features (bottom).

3. MODELS

We model CRSFs using a revised version of a Monte Carlo code developed by Araya et al. (Araya & Harding, 1999, 2000) including relativistic scattering cross sections and photon spawning. Two extreme cases of plasma geometries in the accretion mound are considered: a slab of infinite extension corresponding to the so-called "pencil beam" scenario of strongly beamed radiation, and a cylinder of infinite length representing the "fan beam" picture of a wide radiation cone. Physical conditions are furthermore adjusted by the choice of electron parallel temperature $T_{\rm e}$, Maxwellian e^- momentum distribution and the energetic and angular distribution of the injected Monte Carlo photons. ($f(E) \sim$ high energy cutoff powerlaw, isotropic photon injection). Calculations are valid for the low-density / high-field ($B < B_{\rm crit}$) regime of internally irradiated plasmas.

4. RESULTS

A recent *INTEGRAL* observation of the outburst of *V0332+53* in Januar 2005 was chosen for a comparison of preliminary models to real source data. Multiplicative *XSPEC* table models have been constructed for both geometrical extremes from simulations on a parameter grid of varying B and $\cos\theta$. The continuum input spectrum parameters have been estimated from standard continuum and line fits of the observational data. Fig. 1 shows at the top the time-averaged *V0332+53* spectrum (Kreykenbohm et al., 2005) fitted with the *XSPEC cutoffpl* model. In the bottom plot the data is fitted with a *cutoffpl* multiplied by our cyclotron line model. The best fit is obtained for cylinder geometry, $B/(1+z) = 0.53$ and $\cos\theta = 0.6$ producing a reduced χ^2 of $\chi^2_{\rm red} = 12$. The fit quality is not yet satisfactory, however, this had to be expected due to the narrowness of model parameter space. The magnetic field strength obtained agrees nicely with the one from standard fits.

5. CONCLUSIONS AND OUTLOOK

Our revised Monte Carlo cyclotron models indicate that we can qualitatively explain CRSFs in real observed source data. Our approach differs from common fitting procedures in the following key points:

- All lines are fitted simultanously with one model, ensuring consistence of for instance line energy ratios with theory.
- A non-trivial line shape is modelled.
- Fits allow for the determination of physical parameters in addition to the magnetic field strength, such as plasma geometry and electron parallel temperature, giving insight into the physical conditions in the accretion column.

These points are not only desirable but have also become a necessity when considering high-quality data with complex line shapes as seen e.g. in the fundamental line of *V0332+53*, which could so far only be fitted by artificially overlaying several Gaussians in standard procedures (Kreykenbohm et al., 2005; Pottschmidt et al, 2005). This work is ongoing, aiming at a systematic testing of theoretical models on observed cyclotron line spectra and a dynamic fine-tuning of simulations and models in the near future. It serves as a proof of concept that modeling X-ray pulsar spectra with more realistic CRSFs will be possible once the computation of our Monte Carlo grids has finished.

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