Cyclotron lines in X-ray pulsars as a probe of relativistic plasmas in superstrong magnetic fields

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Abstract. The systematic search for the presence of cyclotron lines in the spectra of accreting X-ray pulsars is being carried on with the BeppoSAX satellite since the beginning of the mission. These highly successful observations allowed the detection of cyclotron lines in many of the accreting X-ray pulsars observed. Some correlations between the different measured parameters were found. We present these correlations and discuss them in the framework of the current theoretical scenario for the X–ray emission from these sources.

INTRODUCTION

Accreting magnetized neutron stars are an ideal cosmic laboratory for high energy relativistic physics. Cyclotron resonance features are the signature of the presence of a superstrong magnetic field, following the first discovery in Her X-1 (Trümper et al. [1]). These features are due to the discrete Landau energy levels for motion of free electrons perpendicular to the field in presence of a locally uniform superstrong magnetic field. A slight deviation from a pure harmonic relationship in the spacing of the different levels is expected due to relativistic effects ($\omega_n = \left((1 + 2nB/B_{crit}\sin^2\theta)^{1/2} - 1\right)/\sin^2\theta$, e.g. Araya and Harding [2]). Therefore the detection of these features in the emitted X–ray spectra is in principle a direct measure of the field intensity.

As the number of sensitive measurements in the hard X–ray interval (above $\sim 10$ keV) is continuously growing, a sample is available to search for possible correlations between the observed parameters. A detailed modeling is difficult and a parametrized shape of the continuum still is not available from theoretical models, but substantial advances in our understanding of the radiation transport in strongly magnetized atmospheres were done in the last decade (e.g. Alexander et al. [3], Alexander and Mészáros [4], Araya and
Harding [2], Isenberg et al. [5,6], Nelson et al. [7]). Some of these new results focused on the properties of the cyclotron resonance features observed in the spectra of accreting X–ray pulsars. In this report we discuss the current status of the measurements of cyclotron lines, with emphasis on the possible correlations between observable parameters.

THE DATA

The BeppoSAX satellite has observed all the bright persistent and three bright transient (recurrent) accreting X–ray pulsars. Apart from the case of X Persei (Di Salvo et al. [8]), a source with a luminosity substantially lower than the other sources in the sample, the spectra observed by BeppoSAX can be empirically described using the classical power–law–plus–cutoff spectral function by White et al. [9]. The sensitive broad band BeppoSAX observations also allowed the detailed characterization of low energy components below a few keV (like in Her X–1, Dal Fiume et al. [10], and in 4U1626–67, Orlandini et al. [11]) and the detection of absorption features in the hard X–ray range of the spectra, interpreted as cyclotron resonance features.

A summary of the properties of the broad band spectra and of the cyclotron lines as measured with BeppoSAX is reported in Dal Fiume et al. [12]. From these measurements we obtained evidence of a correlation between the centroid energy of the feature and its width. This correlation is presented and discussed elsewhere (Dal Fiume et al. [12,13]).

Transparency in the line

A straightforward parameter to be obtained from observations is the transparency in the line, defined as the ratio between the transmitted observed flux and the integrated flux from the continuum without the absorption feature. This ratio likely depends on the harmonic number of the feature we are observing (e.g. Wang et al. [14]) and on the physical parameters of the specific accretion column. From an observational point of view, this ratio is strongly affected by the modelization of the “continuum” shape, that is by the spectral shape used to describe the differential broad band photon number spectrum. In Figure 1 we report the observed transparencies obtained dividing the observed by the expected flux, both integrated in a $\pm 2\sigma$ interval around the line centroid (here $\sigma$ is the Gaussian width of the measured cyclotron feature). To further emphasize the uncertainty in this estimate, we added a 10% error to the data. The purely statistical uncertainties are substantially smaller. This measured transparency is related to a simple physical parameter, the opacity to photons with energy approximately equal to the cyclotron resonance energy. However the emerging integral flux and the shape of the line itself are non trivially related to the radiation transport in this energy interval, a rather difficult problem to be solved.

From the phenomenological point of view, one can observe that the measured transparencies cluster around 0.5–0.6, with the notable exception of Cen X–3.
FIGURE 1. Transparency in the observed cyclotron resonance features with BeppoSAX. The error bars are NOT statistical, but rather indicate the uncertainty in the determination of the shape and intensity of the expected continuum flux (with no line absorption).

**Magnetic field intensity and spectral hardness**

The influence of the magnetic field intensity on the broad band spectral shape is debated. Early attempts to estimate a possible dependence of electron temperature, and therefore of broad band spectral shape, on the magnetic field intensity were done by Harding et al [15]. Actually they conclude that “the equilibrium atmospheres have temperatures and optical depths that are very sensitive to the strength of the surface magnetic field”. If this is the case and if the broad band spectral hardness is related, as one could naively assume, to the temperature of the atmosphere, some correlation between this hardness and the cyclotron line energy should appear in data.

This seems to be the case shown in Figure 2. Here we report the ratio between photon fluxes in two “hard” bands (the flux in 20–100 keV divided by the flux in 7–15 keV) versus the cyclotron line centroid. The ratio between the two fluxes is affected by the choice of the continuum, as in Figure 1. We therefore also in this case added 10% error bars that indicate this uncertainty. The statistical errors are substantially smaller.
FIGURE 2. Ratio between the measured photon flux in two energy band versus the cyclotron line energy with BeppoSAX. The error bars are NOT statistical, but rather indicate the uncertainty in the determination of the shape and intensity of the measured photon flux.

The number of sources in this plot is still very limited and therefore one cannot exclude that this apparent correlation is merely due to the limited size of the sample. Nevertheless the apparent correlation is in the right direction, i.e. harder spectra are observed for higher field intensities.

We parenthetically add that no cyclotron resonance feature was observed in the pulse–phase averaged spectra of the two hardest sources of this class observed with BeppoSAX (GX1+4 Israel et al. [16] and GS1843+00 Piraino et al. [17]). If this correlation proves to be correct, this may suggest that cyclotron resonance features in these two sources should be searched at the upper limit of the BeppoSAX energy band or beyond.

Conclusions

In conclusion, even if no complete, parametric theoretical approach to model the observed spectra of accreting X-ray pulsars is still available, some quantitative measures of parameters of hot plasmas in superstrong magnetic fields are possible. Modeling the transparency in the cyclotron resonance feature is a complex problem. Fur-
ther information will be extracted from maps of this transparency as a function of pulse phase.
The correlation between spectral hardness and field intensity is in agreement with theoretical models. This correlation, if confirmed, can be used as a rough estimate of the magnetic field intensity from the measured spectral hardness.

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REFERENCES

1. Trümper, J. et al. 1978 Ap. J. Letters, 219, L105
2. Araya, R. A. and Harding, A. K. 1999 Ap. J, 517, 334
3. Alexander, S. G. et al. 1996 Ap. J., 459, 666
4. Alexander, S. G. and Mészáros, P. 1991 Ap. J., 373, 565
5. Isenberg, M. et al. 1998a, Ap. J., 493, 154
6. Isenberg, M. et al. 1998b, Ap. J., 505, 688
7. Nelson, R. W. et al. 1995 Ap. J. Letters, 438, L99
8. Di Salvo, T. 1998 Ap. J., 509, 897
9. White, N. E. et al. 1983 Ap. J., 270, 711
10. Dal Fiume, D. et al. 1998 Astron. Astrophys, 329, L41
11. Orlandini, M. et al. 1998 Ap. J. Letters, 500, L165
12. Dal Fiume, D. et al. 1999 Adv. Sp. Res., in press (astro-ph/9906086)
13. Dal Fiume, D. et al. 1998 Nucl. Physics B, 69, 145
14. Wang, J. C. L. et al. 1993 Ap. J.. 414, 815
15. Harding, A. K. et al. 1984 Ap. J., 278, 369
16. Israel, G. L. et al. 1998 Nucl. Phys. B, 69, 141
17. Piraino, S. et al. 2000 Astron. Astrophys., submitted