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PROCEEDINGS
SUPPLEMENTS

The broad band spectral properties of galactic X–ray binary pulsars

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BeppoSAX observed several galactic binary X–ray pulsars during the Science Verification Phase and in the first year of the regular program. The complex emission spectra of these sources are an ideal target for the *BeppoSAX* instrumentation, that can measure the emission spectra in an unprecedented broad energy band.
Using this capability of *BeppoSAX* a detailed observational work can be done on the galactic X-ray pulsars. In particular the 0.1–200 keV energy band allows the shape of the continuum emission to be tightly constrained. A better determination of the underlying continuum allows an easier detection of features superimposed onto it, both at low energy (Fe K and L, Ne lines) and at high energies (cyclotron features).
We report on the spectral properties of a sample of X–ray pulsars observed with *BeppoSAX* comparing the obtained results.
Some ideas of common properties are also discussed and compared with our present understanding of the emission mechanisms and processes.

1. Introduction

The instrumentation aboard *BeppoSAX* [1-5] is particularly well suited to study the X–ray emission from X–ray pulsars. This class of sources is composed by binary systems in which a magnetized rotating neutron star accretes matter from a less evolved mass–donor star. The mass–donor may be a OB supergiant star as in the case of Vela X–1, a Be main–sequence or near–main–sequence star as in the case of transient recurrent pulsars like A0535+26, a low mass star as in the case of 4U1626–67. The type of mass donor star strongly affects the temporal behaviour on the medium (days) to long (years) time scales. The transient behaviour is almost completely restricted to the subclass of X–ray pulsars that have Oe or Be counterparts.

BeppoSAX has observed some persistent pulsars and one transient pulsar during the first year of its operative life. We report results from the observations of some of these sources, emphasizing the commonalities and the differences. In particular we discuss the observational evidence on cyclotron line feature, comparing the observed results, also in terms of possible correlations, with the expected ones on the basis of the available theoretical models.

2. Observations

X–ray pulsars are a relevant section of the *BeppoSAX* Core Program [6] devoted to compact galactic sources. During the Science Verification Program (SVP) and the AO1 regular program a number of sources in this class were observed. In this paper we report the results on Her X–1 (SVP), Vela X–1 (SVP), 4U1626–67 (SVP), Cen X-3 (AO1) and GS1843+00 (AO1). The SVP observaton of Cen X–3 will not be discussed here. A log of the *BeppoSAX* observations is reported

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Table 1
BeppoSAX log of observations

Source Name	Observation Date	Live Time on Source (seconds)
Her X-1	1996/07/24-28 (SVP)	90000
Vela X-1	1996/07/14 (SVP)	21600
4U1626-67	1996/08/06 09-10 (SVP)	97000
Cen X-3	1997/02/27-28 (AO1)	20000
GS1843+00	1997/04/04 (AO1)	22000

in Table 1

Details of the single observations can be found elsewhere (Her X-1: [7]; Vela X-1: [8]; 4U1626-67: [9]; Cen X-3 [10,11]; GS1843+00 [12]).

All the observations we report were performed with all *BeppoSAX* telescopes, covering the energy band 0.1-200 keV. The observations were performed before the failure of the MECS 1 HV module occurred in May 1997, therefore all the three MECS telescopes are available. The live time in column three is calculated for the MECS telescopes. The LECS live time is $\sim$ 40% of that due to the fact that the instrument is operated only during satellite night time. The HPGSPC and PDS live time is $\sim$ 50% of that, due to the background measure with the rocking collimators.

In all the observations but for Vela X-1 the rocking instruments (HPGSPC and PDS) were using the default collimator laws: one rocking every 96s. In the Vela X-1 observation the dwell time was 50s. All data were transmitted using the default direct telemetry modes, apart from the observation of Her X-1, in which the HPGSPC data were transmitted using the full diagnostic mode.

Here we report and compare the results on the pulse-phase averaged spectra in 0.1-200 keV. In four of these five sources, we have evidence of the presence of a cyclotron line.

3. Results

The modeling of the broad-band spectra of X-ray pulsars is quite difficult. The Her X-1 spectrum is a prototype of this complexity [7]. It needs several different spectral components to be reasonably modeled: a low energy cutoff, a low energy black body – likely due to reprocessing of primary X-ray radiation at the magnetospheric boundary–, a Fe L line, a Fe K line, a power law, a high energy exponential cutoff and a cyclotron feature. A formal fit to the observed data has 15-19 free parameters. Only the *BeppoSAX* capability to observe the energy spectrum in more than four decades in energy allows the clear separation of the different components resulting in formal fits in which the correlations between parameters are reasonably low.

Currently there is no theoretical model that provides a parametrized model function to fit the observed spectra. Therefore the fit to the observed count rate spectra can be performed only using *ad hoc* analytical models. The first and more widely used model function to describe the broad band continuum is the power-law-plus-cutoff [13] that gives a quite reasonable empirical description of the shape of the energy spectra of X-ray pulsars.

$$\begin{array}{ll} E^{-\alpha} & E < E_{cutoff} \\ E^{-\alpha} \times \exp(-\frac{E - E_{cutoff}}{E_{folding}}) & E \geq E_{cutoff} \end{array} \qquad (1)$$

This model function has a discontinuity at $E=E_{cutoff}$.

Other widely used functions are the Fermi-Dirac CutOff (FDCO - [14])

$$E^{-\alpha} \frac{1}{1 + \exp(\frac{E - E_{cutoff}}{E_{folding}})} \qquad (2)$$

and the Mihara Negative and Positive power-law

Table 2
Cyclotron lines in the spectra of X–ray pulsars

Source Name	ECycl Feature keV[(a)]	FWHM Cycl. keV [(a)]
Cen X–3	28.5 ± 0.5	6.3±2.0
4U1626–67	36.5±1.0	7±2.8 [(b)]
Her X–1	42.1±0.3	14.7±0.9
Vela X–1	57.9±1.0	24.0±1.
A0535+26	*110.*[(c)]	*56*[(c)]

(a) Using a multiplicative Gaussian absorption function
(b) The FWHM is significantly larger using a Lorenzian function [9]
(c) Using a Lorenzian function [16]

plus EXponential (NPEX – [15])

$$(A_1 E^{-\alpha_1} + A_2 E^{+\alpha_2}) \times \exp(-\frac{E}{kT}) \qquad (3)$$

We tried all the model functions listed above for the sources in Table 2. All these model functions show the same practical problem: they do not adequately describe the shape and the bending of the cutoff, especially in the energy interval where the power law joins the exponential tail.

We also tried for all sources a "modified" power–law–plus–cutoff model, in which we used a broken power law:

$$\begin{array}{ll} E^{-\alpha_1} & E < E_{break} \\ E^{-\alpha_2} & E \geqq E_{break} \\ E^{-\alpha_2} \times \exp(-\frac{E - E_{cutoff}}{E_{folding}}) & E \geqq E_{cutoff} \end{array} \qquad (4)$$

This empirical function seems to provide the best performance in fitting the count rate spectra *on the average*, therefore it can be used to compare the results from the different sources.

In Table 2 we summarize the results of the broad band fits concerning the cyclotron line. The values reported in this table come from fits using the model functions in equation 4 to describe the broad band continuum. The results for A0535+26 are taken from Grove et al. [16]. In this table all measurements apart that of A0535+26 were done with *BeppoSAX* .

In GS1843+00, the source in our sample with the hardest spectrum [12], we do not detect any cyclotron feature in the pulse–phase averaged spectrum.

The results in this table suggest that there may be a correlation between the cyclotron feature centroid energy and its FWHM. This correlation is reported in Figure 1, where we also added the data on the cyclotron feature observed in A0535+26 by OSSE [16]. We stress that the FWHM parameter in the fit to the count rate spectra shows a possible dependence on the choice of the function modeling the broad band continuum, therefore this correlation must be taken with caution. We tried to limit this effect due to the choice of the continuum model function, using the same broad band continuum in all fits. The data follow a general linear trend (with slope $\alpha \simeq 1.7$) with some evident scatter.

We also caution that the line energy reported here may not be the energy of the fundamental cyclotron feature, but its first harmonic. This may be the case of Vela X–1 and A0535+26.

A summary of the cyclotron lines measured by *BeppoSAX* is shown in Figure 2. In this Figure we plot a "modified Crab ratio" as described in [7,8]. To obtain this ratio we

- divided the count rate spectrum by the measured Crab count rate spectrum
- multiplied the result by the slope of the Crab Nebula photon spectrum ($E^{-2.1}$)
- divided the result by the continuum model function used for the broad band fit

This procedure enhances the deviations from the broad band continuum and gives a way to *visually*

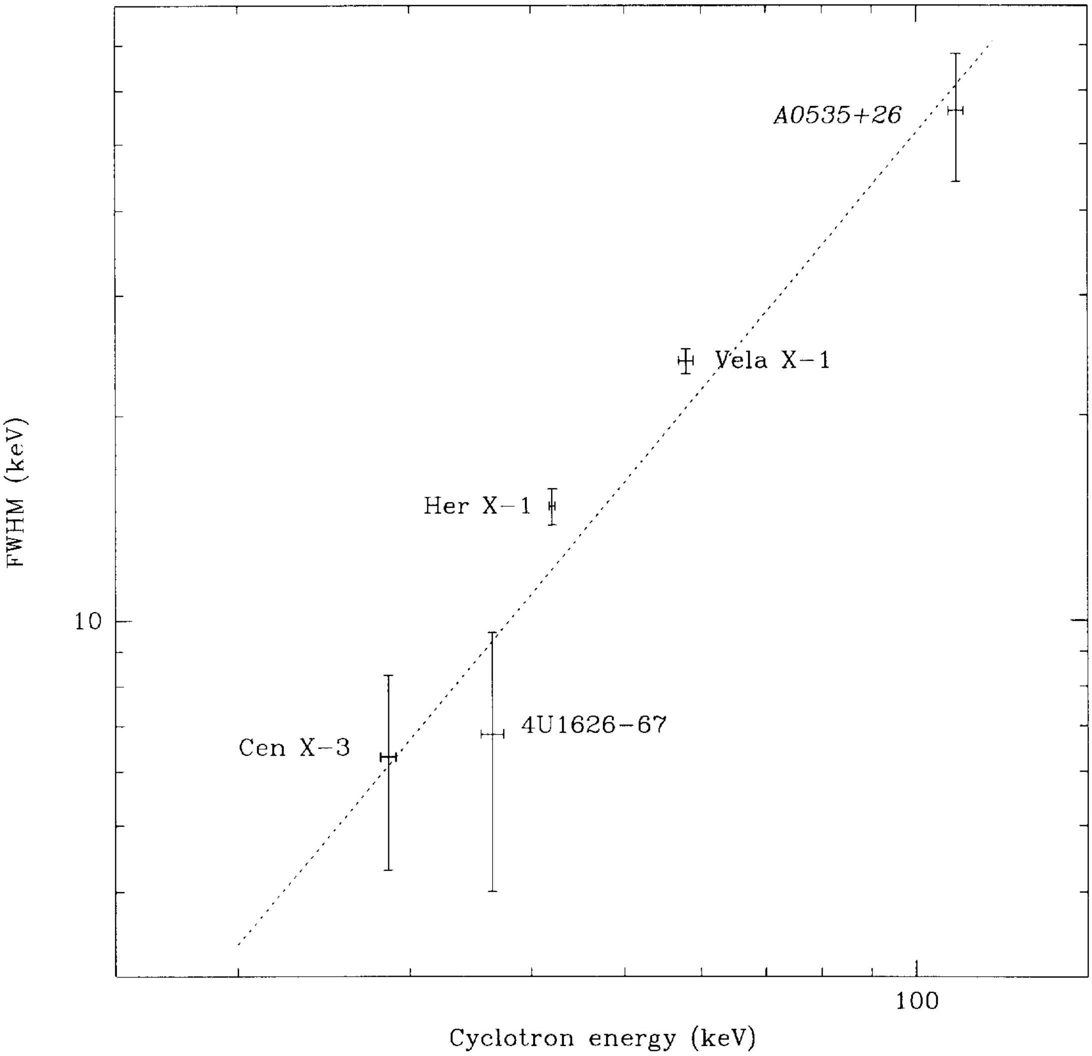

Figure 1. Cyclotron feature FWHM versus centroid energy. The dashed line shows a simple least square linear fit. Even with some scatter present in data (see text for a discussion), a correlation between these quantities seems present.

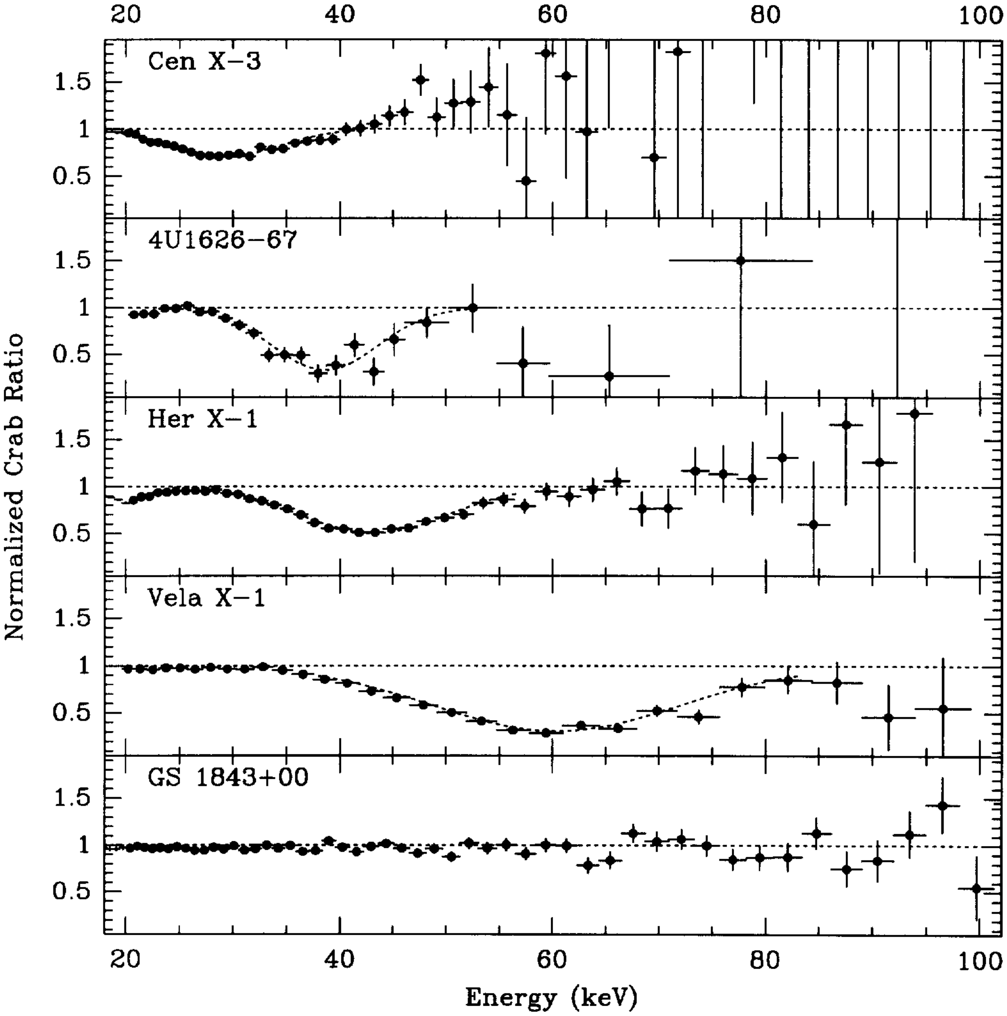

Figure 2. Ratios between the count rate spectrum of the different sources and the Crab count rate spectrum. The ratios are normalized to the shape of the broad band continuum (see text for details). The shape and position of the cyclotron features are well evident. The spectrum of GS1843+00 does not show any deviation from the shape of the broad band continuum

compare the different features observed in the different sources.

4. Discussion

The correlation showed in Figure 1 was "qualitatively" predicted by Mészáros and Nagel [20] (see also [17]). The model predicts a width of the cyclotron feature proportional to its energy and to the square root of the electron temperature of the atmosphere

$$\Delta\omega_B \simeq \omega_B \left(8 \times \ln(2) \times \frac{\mathrm{kT_e}}{\mathrm{m_e c^2}}\right)^{\frac{1}{2}} |\cos\theta| \qquad (5)$$

In this equation $\Delta\omega_B$ is the line width, ω_B is the cyclotron line frequency, T_e is the electron temperature and θ is the viewing angle with respect to the magnetic field axis. A better insight on the properties of the cyclotron lines can be obtained with pulse–phase resolved spectroscopy, as equation 5 suggests that there may be a dependence on the viewing angle of the observed line width (see also [19]).

However Araya and Harding (1996) [18] caution that, in the limit of a single scattering, the line width is not related to the electron temperature.

This ambiguity in the interpretation of these observational data points out the need of a more detailed and quantitative model for the line properties and for the broad band continuum emission of X–ray pulsars

REFERENCES

1. Boella, G., Butler, R. C., Perola, G. C., Piro, L., Scarsi, L., Bleeker, J. 1997a, A&A SS, 122, 299
2. Parmar, A. N., Martin, D. D. E., Bavdaz, M., Favata, F., Kuulkers, E., Vacanti, G., Lammers, U., Peacock, A., Taylor, B. G. 1997, A&A SS, 122, 309.
3. Boella, G., Chiappetti, L., Conti, G., Cusumano, G., Del Sordo, S., la Rosa, G., Maccarone, M. C., Mineo, T., Molendi, S., Re, S., Sacco, B., Tripiciano, M 1997b, A&A SS, 122, 327
4. Manzo, G., Giarrusso, S., Santangelo, A., Ciralli, F., Fazio, G., Piraino, S., Segreto, A. 1997, A&A SS, 122, 341
5. Frontera, F., Costa, E., Dal Fiume, D., Feroci, M., Nicastro, L., Orlandini, M., Palazzi, E., Zavattini, G. 1997, A&A SS, 122, 357
6. Perola G. C. et al., "*BeppoSAX* Core Program"
7. Dal Fiume D., Orlandini M., Frontera, F. et al., 1998, A&A, 329, L41.
8. Orlandini M. , D. Dal Fiume, Frontera, F. et al., 1998, A&A in press
9. Orlandini M., Dal Fiume D., Frontera, F. et al., 1998, Ap. J. letters (submitted)
10. Del Sordo, S. et al. these proceedings
11. Santangelo A. et al. in preparation
12. Piraino S., et al. these proceedings
13. White, N. E., Swank, J., Holt, S. S., 1983, Ap. J., 270,711
14. Tanaka, Y. in *"Radiation Hydrodynamics in Stars and Compact Objects"*, D. Mihalas and K. H. Winkler editors (Springer:Berlin) (1986)
15. Mihara T., PhD thesis, Riken, IPCR CR–76 (1995)
16. Grove, J. E., et al., 1995, Ap. J. Letters, 438, L25
17. Mészáros, P., *"Radiation from Magnetized Neutron Stars"* (Unyversity Press:Chicago) (1992)
18. Araya, R. A. and Harding, A. K. 1996, Ap. J. Letters, 463, L33
19. Santangelo, A., et al., these proceedings
20. Mészáros, P., Nagel, W. 1985, ApJ, 298, 147