



THE BROAD BAND SPECTRAL PROPERTIES OF BINARY X-RAY PULSARS

D. Dal Fiume¹, M. Orlandini¹, S. Del Sordo², F. Frontera^{1,3}, T. Oosterbroek⁴, E. Palazzi¹, A. N. Parmar⁴, S. Piraino², A. Santangelo² and A. Segreto²

¹*TeSRE, Consiglio Nazionale delle Ricerche, via Gobetti 101, I-40129 Bologna, Italy*

²*IFCAI, Consiglio Nazionale delle Ricerche, via La Malfa 153, I-90146 Palermo, Italy*

³*Dipartimento di Fisica, Università di Ferrara, via Paradiso 1, I-44100 Ferrara, Italy*

⁴*ESA-SSD, ESTEC, Keplerlaan 1, 2200 AG Noordwijk, The Netherlands*

ABSTRACT

The X-ray telescopes on board BeppoSAX are an optimal set of instruments to observe bright galactic binary pulsars. These sources emit very hard and quite complex X-ray spectra that can be accurately measured with BeppoSAX between 0.1 and 200 keV. A prototype of this complexity, the source Her X-1, shows at least seven different components in its spectrum. A broad band measure is therefore of paramount importance to have a thorough insight into the physics of the emitting region. Moreover the detection of cyclotron features, when present, allows a direct and highly significant measure of the magnetic field intensity in the emission region.

In this paper we briefly report the results obtained with BeppoSAX on this class of sources, with emphasis on the detection and on the measured properties of the cyclotron lines.

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1 INTRODUCTION

X-ray pulsars are studied since more than 25 years but still we are far from understanding the details of the mechanisms that produce the emission of their complex and variable spectra. The overall scenario was depicted with bright accuracy soon after their discovery (Davidson and Ostriker 1973). As the observational data became of better and better quality, it clearly emerged that the X-ray spectra emitted from these sources are quite complex. The spectra of almost all sources are characterized by a very hard power-law like emission in the 1–10 keV band (photon index α between 0 and -1) and by a high energy cutoff, approximately exponential, starting between 10 and 20 keV.

While the task of understanding and convincingly modeling the X-ray emission is exceedingly difficult, the final reward to a success in this field is rather appealing. The emitting neutron stars are by themselves relativistic objects. Moreover the magnetic field, needed to channel the accreting matter onto the surface hot spots from which we observe the pulsed emitted radiation, is relativistic. Therefore these systems are an ideal laboratory to test relativistic effects by observational means.

In this paper we report the observations of a small sample of bright X-ray pulsars, describing the observational results both on the broad band spectrum and on the cyclotron line features.

2 OBSERVATIONS AND RESULTS

During its first two years of operational life BeppoSAX observed all the bright persistent X-ray pulsars and one recurrent transient pulsar (GS 1843+00). The BeppoSAX observations of bright X-ray pulsars are listed in Table 1.

Table 1

Source name	Total elapsed time (ks)	Source name	Total elapsed time (ks)
SMC X-1	75	4U 1538-52(*)	234
X Persei	227	4U 1626-67(*)	172
LMC X-4	163	GX 1+4	148
Vela X-1(*)	625	Her X-1(*)	1036
Cen X-3(*)	97	GX 301-2	450
GS 1843+00	46	4U 1907+09(*)	230

(*): cyclotron features in the spectra

A straightforward observational goal is to obtain a possibly simple and unique model spectrum to fit data from different sources. Restricting ourselves to a purely heuristic, and thence phenomenological, approach, and using the more common spectral models (e.g. White et al. 1983, Mihara 1995), we are not able to obtain satisfactory fits covering the entire BeppoSAX energy band for all the observed sources using only one modelization.

In some cases, like Her X-1 and possibly 4U1626-67, additional components at energies ≤ 1 keV must be added. In other cases, like Vela X-1 and GX 301-2, a highly variable source intensity is coupled with huge variations in intrinsic opacity at low energies (≤ 2 keV) due to a highly varying amount of intervening matter along the line of sight. These additional spectral components are variable with time. In the case of GX 301-2 the observational results are further complicated by the substantial value of this variable absorption at low energies, with an equivalent hydrogen column $N_H \sim 10^{23} - 10^{24}$.

This difficulty may seem purely phenomenological, as intrinsic unabsorbed X-ray spectra emerging from the accreting zones onto the neutron star surface may quite reasonably differ due to differences in mass accretion rate, NS mass, NS magnetic field, eventually NS magnetic field geometry. However this ambiguity must be solved in order to have reliable direct measures of relevant physical quantities. In fact the other spectral components that seem quite frequent in the spectra of X-ray pulsars as measured by BeppoSAX are cyclotron features. These features appear substantially broad and cluster between 20 and 60 keV. Adding other previous measurements to the BeppoSAX ones, one can conclude that up to now the cyclotron line energies range between 10 and 100 keV, as the lower cyclotron resonance energy was measured at 11-12 keV in 4U 0115+63 (White et al. 1983; Nagase et al. 1991) and the higher was measured at 100-115 keV in A0535+26 (Grove et al. 1995). *As these features are broad, they are strongly coupled to the continuum shape and intensity and therefore the parameters that characterize each feature in each given source are slightly but clearly dependent on the choice of the continuum spectral model.*

This point must be kept in mind while looking at Table 2, where we report the results of broad band fits to the X-ray pulsars spectra using only BeppoSAX published data.

Apart from these cautionary remarks, as the differences between source spectra in the sample are a obvious difficulty in the use of a single model, some commonalities do emerge. In all the measured spectra we can easily identify some characteristic components, already suggested more than fifteen years ago by White et al (1983): a power law at energies below 10 keV; a cutoff between $\sim 6 - 7$ and $\sim 20 - 30$ keV; a high energy tail up to 100 keV (and more for the harder sources). While the details in the modeling of the single sources differ, these components are stably present in all the sources we are discussing in this report.

In Table 2 we summarize the results from BeppoSAX on these common components. We caution that this is a first order approach to source spectra modelization, as it is often necessary to further complicate these components in order to get reasonable values of χ^2 from the spectral fits.

The count rate broad band spectra of these sources are shown in Figure 1 (references as in Table 2).

Up to now, cyclotron lines are present in 6 out of the 12 bright X-ray pulsars observed by SAX, including 4U1538-52 that is not in this sample. The observations of GX 301-2 are being analyzed.

It is remarkable the fact that the two hardest sources in this small sample (GX 1+4 and GS 1843+00) do not show any feature at least up to 100-200 keV. The other sources in whose spectra cyclotron features were detected are the recurrent transient pulsars A0535+26 (Grove et al. 1995), 4U 0115+63 (White et al. 1983; Nagase et al. 1991), X0331+53 (Makishima et al. 1990), Cep X-4 (Mihara et al. 1991). These sources were quiescent during the first two years of BeppoSAX operational life.

Table 2

Source name	Power law spectral index	High en. cutoff (keV)	High en. folding (keV)	Cycl. line centroid (keV)	Cycl. line FWHM (keV)	Model ¹
Cen X-3	1.21±0.01	14.9 ± 0.2	12.1±0.9	27.9± 0.5	9.8± 1.9	(1)
4U 1626-67	0.86±0.01	19.6±0.5	10.6±0.7	37±1	7.05±2.35	(2)
4U 1907+09 ²	1.27±0.01	12.0±0.3	12.0±0.3	39.4±0.6	8.5±1.6	(2)
Her X-1	0.884±.003	24.2±0.2	14.8±0.4	42.1±0.3	14.9 ^{+1.25} _{-1.0}	(1)
Vela X-1 ²	(NPEX)	(NPEX)	(NPEX)	54.4 ^{+1.5} _{-0.2}	17 ⁺³ ₋₂	(3)
GX1+4 ³	1.0	25± 2	29± 1	no line	no line	(2)
GS 1843+00 ³	0.34± 0.04	5.95± 0.45	18.4± 0.6	no line	no line	(2)

¹ The models for the continuum used in the reference papers are: (1) broken power law plus high energy cutoff; (2) power law plus high energy cutoff; (3) NPEX (Mihara 1995)

² In these sources it is suspected the presence of cyclotron features both at the fundamental energy and at the first harmonic

³ No cyclotron line in the X-ray spectrum

⁴ References are: Cen X-3, Santangelo et al. 1998; 4U 1626-67, Orlandini et al. 1998a; 4U1907+09, Cusumano et al. 1998; Her X-1, Dal Fiume et al. 1998; Vela X-1, Orlandini et al. 1998b; GS 1843+00, Piraino et al. 1998, 1999; GX1+4, Israel et al. 1998

A major observational topic in these last years has become the measure of multiplicity in the cyclotron line features. In Table 2 we marked with an asterisk the two sources for which there is some evidence of the presence of two features that may tentatively be identified as the fundamental resonance and the first harmonic. In both cases the fundamental should be half the energy reported in Table 2.

From a purely observational point of view, still some ambiguity remains. In both cases the fundamental should be of quite low equivalent width, and it is located near or exactly at the high energy cutoff. This is a quite relevant complication from a purely technical point of view. In fact, while the deeper feature located at higher energy (~ 55 keV for Vela X-1 and ~ 39 keV for 4U1907+09) is superposed to a continuum with a well defined slope, that "after" the feature clearly recovers the shape shown "before", in the case of the possible feature at ~ 27 keV for Vela X-1 and at ~ 19 keV for 4U1907+09 the shape of the continuum is rapidly evolving with energy, and it is also reasonable that the exponential-like shape of the cutoff is only a purely phenomenological approach. This empirical model has also the disadvantage to have a jump in its first derivative at the cutoff energy.

In this sense a sensible attempt to model the shape of the broad band continuum of X-ray pulsars without the presence of a second order discontinuity of the power-law-plus-cutoff model of White et al. (1983) was attempted by Mihara (1995). His results convincingly show that some more smooth functionals, like

the NPEX model (negative plus positive power law plus exponential), give quite satisfactory fits to the X-ray pulsars in the GINGA bandpass. However the extension of the measures to a broader energy range with BeppoSAX shows that unfortunately this functional must be modified in order to get acceptable values of χ^2 from the fits.

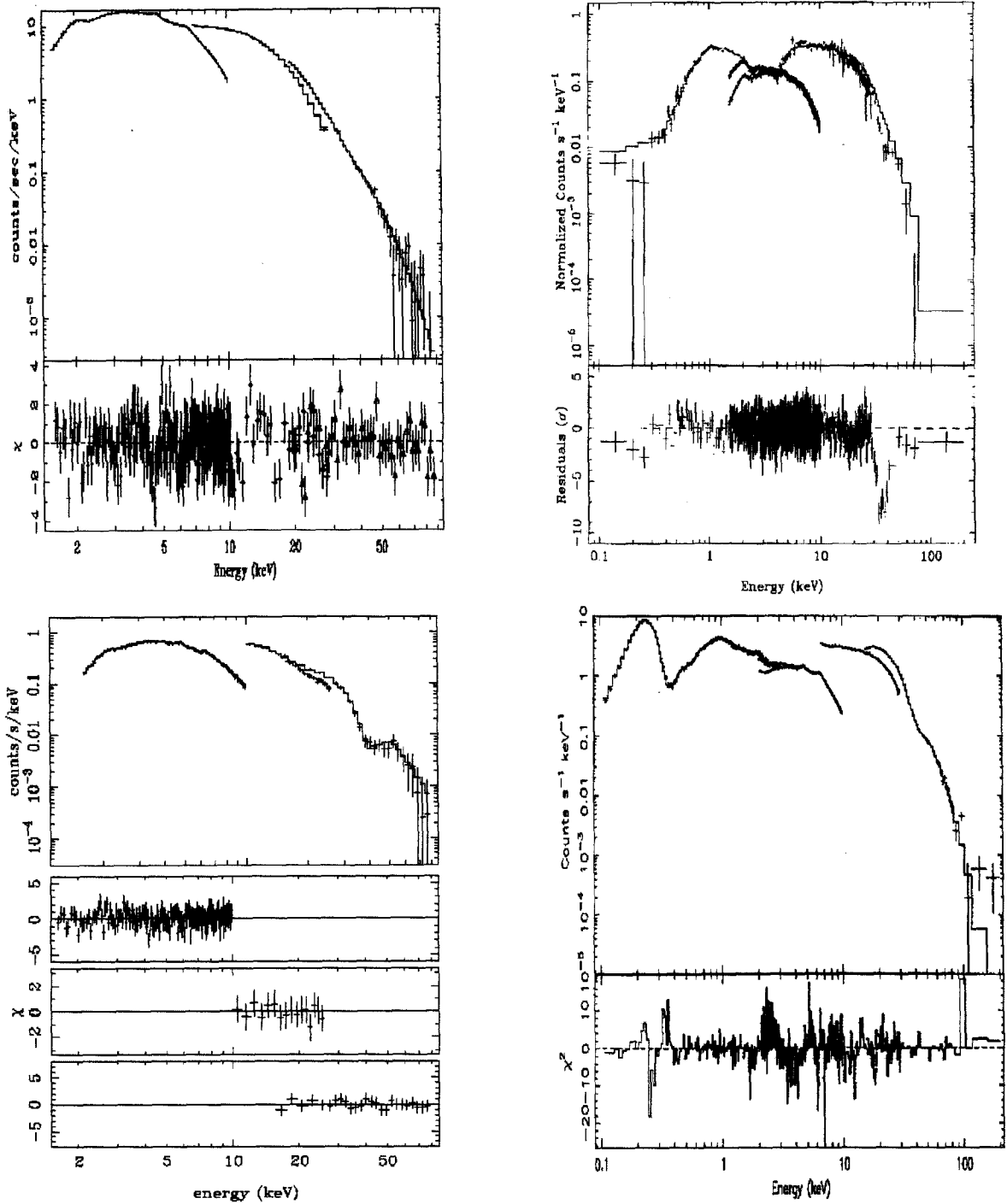


Figure 1a: BeppoSAX count rate spectra of Cen X-3, 4U 1626-67, Her X-1 and 4U1907+09 (clockwise from top left)

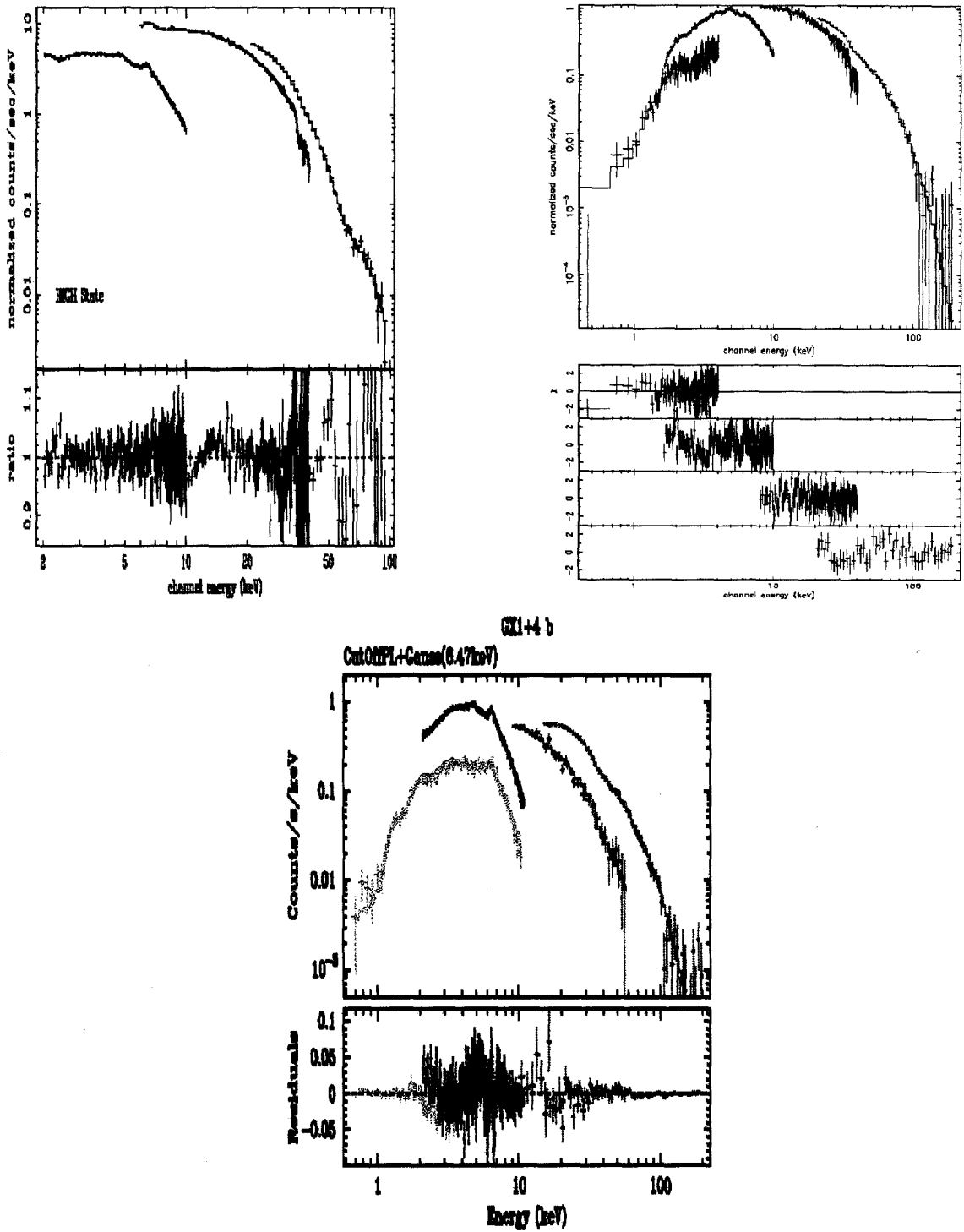


Figure 1b: BeppoSAX count rate spectra of Vela X-1 (top left), GS 1843+00 (top right) and GX1+4 (bottom)

A reliable method to enhance the presence of features in the X-ray spectra of cosmic sources is the so called "Crab ratio". This method was extensively used by Mihara (1995) in his survey of X-ray pulsars observed with GINGA. This ratio is simply the ratio between the source count rate spectrum and the count rate spectrum of the Crab Nebula. As this second spectrum is known, with great accuracy, to be free of features and to be modeled at first order with a power law in a very broad energy range, this ratio is quite well suited to enhance the presence of features in the spectrum (iron line, iron K edge, cyclotron features). Furthermore the ratio is in first approximation independent from the calibration of the instrument.

We added to this method a further step, that gives easily readable and comparable plots. After this ratio on count rate, we multiply by a $E^{-2.1}$ power law, that is the functional form of the Crab Nebula spectrum, and we divide by the functional describing the continuum shape of the source. The procedure is described in Figure 2, where we plot the result of each different step used to obtain the final result in the case of 4U1626-67.

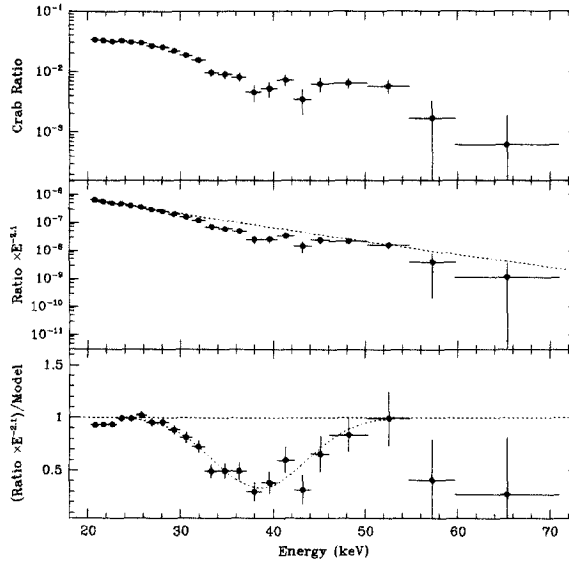


Figure 2: first panel: ratio between the count rate spectrum of the Crab Nebula and the count rate spectrum of 4U1626-67; second panel: the ratio multiplied by a function describing the Crab photon spectrum ($E^{-2.1}$); third panel: the normalized ratio obtained dividing the result plotted in the second panel by a function describing the continuum of 4U1626-67

In Figure 3 we plot the normalized ratios for the X-ray pulsars listed in Table 2.

The results plotted in Figure 3, apart from a normalization factor, come therefore from

$$C_{norm}(E_1, E_2) = \frac{E^{2.1}}{C_{Crab}(E_1, E_2)} \times \frac{C_{source}(E_1, E_2)}{Continuum(E)} \quad (1)$$

where C_{Crab} and C_{source} are the Crab nebula and the source count rate spectra respectively and $Continuum$ is the functional form of the continuum of *source* from the fit.

In this plot the cyclotron features listed in Table 2 are apparent. In 4U 1907+09 and Vela X-1 the possible fundamental at half the line energy is barely visible. It is also clearly evident the difference between the sources showing a cyclotron feature in their spectrum (the first five from top) and the other two (GX1+4 and GS1843+00) that do not show any feature, included for comparison.

Confining ourselves to a purely phenomenological point of view we therefore conclude that in absence of a reliable theoretical model all claims of presence of a double feature in the spectrum of a source should be substantiated by a clear detection also in its normalized Crab ratio. While this second method is less sensitive, it is rather robust, as it is in first approximation independent from instrument calibrations and, using only the non-normalized Crab ratio, even from any modelization of the source continuum.

A caution must be used while having a negative result, as this method is only qualitative. Given that the detectors are relatively dispersive and that the fundamental line is broad and with a small equivalent width, no definitive statement can be said in the case of apparent non-detection, unless some quantitative test is used.

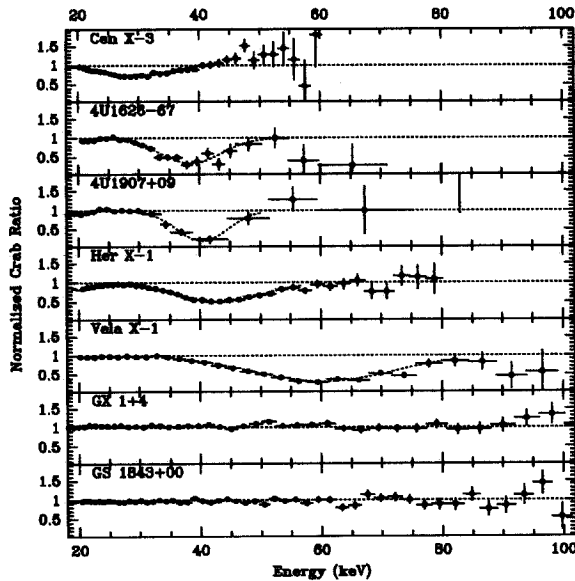


Figure 3: the normalized Crab ratio of seven X-ray pulsars as observed by BeppoSAX. See text for details

3 DISCUSSION

The detections of the cyclotron line features give direct estimates of the intensity of the magnetic field of the neutron stars at the emission zone, that should be near the neutron star surface, apart the case of extreme radiative shock.

The measured resonance energies of course must be corrected for the gravitational redshift due to relativistic gravitational field of the neutron star. The correction factor $\frac{1}{1+z}$ depends on the square root of $\frac{M}{R}$, where M is the mass of the neutron star and R is the radial distance from the centre of the neutron star of the emission zone. We can reasonably assume that $R \sim R_{NS}$, that is the emission zone is at the surface of the neutron star or negligibly above it, but this assumption may break if a radiative shock is present above the neutron star, dislocating the emission region at a non negligible distance from the NS surface.

The other possible uncertainty in this correction is the mass of the neutron star itself and its mass/radius ratio. A Monte Carlo method applied to orbital data (Rappaport and Joss 1983) shows that NS masses should be between 1 and 2 solar masses. If we assume a 50% possible scatter in the NS masses and if we assume a value of R using the more recent equation of states coupled with the constraints coming from the observation of kHz QPOs in LMXRBs (Miller, Lamb and Cook 1998), we have an additional $\pm 10\%$

scatter in the *corrected* resonance energy, to be added to the statistical uncertainty from the fit, that usually is of the order of 1–3%. The observed resonance energy E_{cyc}^∞ must be corrected using equation 2.

$$E_{cyc}^0 = E_{cyc}^\infty \times \left(1 - 0.295 \frac{M}{M_\odot} \frac{10km}{R} \right)^{-\frac{1}{2}} \quad (2)$$

A simple interpretation of the observed line broadening is that it is produced via thermal Doppler broadening (e.g. Mészáros 1992). In this case the FWHM of the feature can be a measure of the temperature of the emitting atmosphere using equation 3.

$$\Delta\omega_B \simeq \omega_B \left(8 \times \ln(2) \times \frac{kT_e}{m_e c^2} \right)^{\frac{1}{2}} |\cos \theta| \quad (3)$$

It is reasonable that different sources with different intrinsic luminosities have atmospheres with different temperatures (e.g. Harding *et al.* 1984). Moreover equation 3 depends on the average cosine of the aspect angle θ (the angle between the magnetic field axis and the line of sight). However the data in Table 2 show a correlation between the centroid energy and the width of the measured cyclotron features, even if with some scatter. This correlation is plotted in Figure 4, in which we added the data coming from the OSSE measurement of the cyclotron feature in A0535+26 during its 1994 outburst (Grove *et al.* 1995).

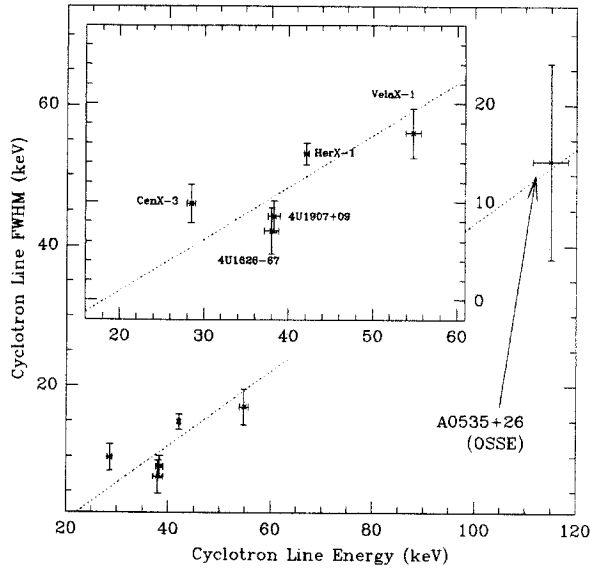


Figure 4: FWHM versus centroid energy for the cyclotron features measured with BeppoSAX. The point for A0535+26 comes from the OSSE measurement during the 1994 outburst (Grove *et al.* 1995)

Therefore, from this apparent correlation one can conclude that the spread in both mass/radius ratio (this is *not* the NS mass/radius ratio, as the emission zone may be relatively distant from the NS surface as discussed above) and in the temperature of the atmosphere is relatively small. The estimated temperatures of the atmospheres are reported in Table 3, using equation 3 as a first order approximation. The estimates of NS masses are also reported, when available (Rappaport and Joss, 1983).

Table 3

Source name	Centroid energy (keV)	FWHM (keV)	kT_e (keV)	NS mass ¹ (M_\odot)	B field at surface (10^{12} G)
Cen X-3	27.9± 0.5	9.8± 1.9	11.3±4.5	1.07 ^{+0.63} _{-0.57}	3
4U 1626-67	37±1	7.05±2.35	3.3±2.1		4.1
4U 1907+09	39.4±0.6	8.5±1.6	4.5±1.6		4.4
Her X-1	42.1±0.3	14.9 ^{+1.25} _{-1.0}	11.3±1.9	1.45 ^{+0.35} _{-0.40}	4.8
Vela X-1	54.4 ^{+1.5} _{-0.2}	17 ⁺³ ₋₂	8.9±2.9	1.85 ^{+0.35} _{-0.30}	7.0
A0535+26	115 ⁺³ ₋₄	52 ^{+13.8} ₋₁₄	18.5±10		13

¹ NS mass is assumed $1.4 M_\odot$ when an estimate is not available

From this table some spread in the estimated electron temperature is evident. This may be intrinsic, but we caution that we used a rough estimate to obtain these values. More reliable values will certainly come from a self-consistent model of X-ray pulsars atmosphere, when available for data fitting. These values are in fair agreement with the self-consistent calculations of Harding et al. (1984).

As previously noted, in at least two cases (4U 1907+09 and Vela X-1) the observational data may show, depending on the model used, a double cyclotron feature. The resonant photon energies are

$$\hbar\omega = \frac{\left[-m_e c^2 + (m_e^2 c^4 + 2m_e c^2 \hbar\omega_c n \sin^2 \theta)^{\frac{1}{2}} \right]}{\sin^2 \theta} \quad (4)$$

where $\hbar\omega_c$ is the fundamental resonance energy and n is the Landau principal quantum number. As can be seen, the levels are not exactly equispaced.

The possible presence of the first harmonic of the fundamental frequency was discussed e. g. by Mészáros and Alexander (1989) in the framework of Gamma Ray Bursts and by Araya and Harding (1995) for A0535+26. A naive approach, as suggested by Mészáros and Alexander, should bring to the conclusion that the line at the lower energy, the fundamental, should be deeper given that the cyclotron opacity decreases for increasing harmonics. Actually the observational scenario, even if with a non negligible ambiguity, suggest that in the case of two features, the first harmonic is much deeper than the fundamental, exactly the contrary than that said before.

A way around this problem may be the addition to the radiation transfer of two-photon scattering (Alexander and Mészáros, 1991; Mészáros, 1992). Due to this process, the photons are redistributed from the higher harmonics to the lower. A photon with energy $2\omega_c$ therefore may be splitted in two photons of energy ω_c . The addition of this process to the calculations gives much deeper first harmonic, and, parenthetically, also a second harmonic. Of course, in order that the photon splitting of this process be sufficiently effective to replenish the fundamental feature, enough photons at and above $2\omega_c$ must be present. This may be a problem with X-ray pulsar spectra.

In the case of the possible double lines in A0535+26 (Grove et al. 1995) Araya and Harding (1996) calculated X-ray spectra near the fundamental and the first harmonic for both a “low” (5.2×10^{12} G) and a “high” (10.7×10^{12} G) magnetic field. The difficulty to model both the low energy (55 keV) and the high energy (115 keV) features with their model brings the authors to the conclusion that the “high” field hypothesis must be preferred. This obviously implies that the 115 keV observed feature corresponds to the fundamental resonance energy of the magnetic field in A0535+26.

A different approach is suggested by Alexander et al. (1995). They suggest that the double features in the spectra of X-ray pulsars may be produced in separate parts of a shocked accretion column and

that one of the features is produced via Doppler shifting by the pre-shock plasma. In this case, the “blue” line is the fundamental and the “red” one is due to the interaction of the emitted radiation with the pre-shock infalling matter, that has relativistic velocity. In this case, the infalling electron “see” the photons emitted by the post-shock high density atmospheres as blue shifted. Therefore the resonant scattering does not occur anymore at the energy $\hbar\omega_c$, but at a lower energy, depending on the velocity of the infalling electrons.

In summary, this report shows that the BeppoSAX campaign on X-ray pulsars allowed to extend the observational results on cyclotron lines, giving a small but significant set of measures of fundamental physical quantities of accreting magnetized neutron stars.

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