4. Discussion

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

\[ \Delta \omega = \omega_0 \left( \frac{5 \times 10^4}{\text{cm}} \right) \left( \frac{T_e}{10^4 \text{K}} \right) \left( \frac{\text{cm}}{\text{m}} \right) \]

In this equation \( \Delta \omega \) is the width of the cyclotron line, \( \omega_0 \) is the electron temperature, and \( \theta \) 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, Agra and Harding (1990) [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 sources.

REFERENCES

6. Pereira, G. C. et al., "BeppoSAX Core Program"
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1. INTRODUCTION

Observations and studies of galactic X-ray sources and among them of accreting strongly magnetized neutron stars in binary systems is one of the main guidelines of the BeppoSAX scientific Core Program. In this framework a key role is played by Pulse Phase Resolved Spectroscopy. Indeed, BeppoSAX has this unique capability: to obtain, combining simultaneous observations of its Narrow Field Instruments (NFIs), spectra for different segments of the pulse phase, over an unprecedented broad energy band (from the fraction of keV up to 200 keV), with good energy resolution and statistics. This has a great impact in three areas: 1) phase dependence of the primary spectral component; 2) phase dependence of the fluorescence line, typically the iron line; 3) phase dependence of high energy features, typically Cyg X-3 and Centaurus A scattering features (CFs).

Aim of this paper is to show some recent results from BeppoSAX on two well known X-ray Binary Pulses, Cyg X-3 and Her X-1. As far as Cyg X-3, after discussing the evolution of pulsed profile with similar energy, we report some results on the phase dependence of the iron line spectrum. We will then, conclude with the study of the high energy BeppoSAX spectrum of BeppoSAX NFIs in the post-ergo high state of the source reporting the detection of an absorption-like feature that we interpret as a cyclotron feature. Some preliminary results on both phase-resolved spectra and pulse profile evolution with energy on two sources of this class, Cyg X-3 and Her X-1.

Widely used for its "quantitative" prediction by Montes and Nagel [20] (see also [17]). The model predicts a width of the cyclotron feature proportional to the square root of the electron temperature at the atmosphere.

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2. Cyg X-3

Cyg X-3 was the first binary pulsar to be discovered in the X-ray sky [1,2]. The system consists of a neutron star, which exhibits a pulse period of 4.8 s, orbiting a blue, rapidly rotating (O-type) companion, [3], every 2.25 days. Although a strong stellar wind emanates from the companion, due to the behaviour of its optical light curve, Cyg X-3 is thought to be powered by an accretion disk fed by BeppoSAX and the discovery of QPOs from the source,[4], further implies the presence of an accretion disk. The X-ray luminosity of the system has been found to vary from a high luminosity to a low luminosity state, by a factor of 5 on a timescale of months. This pulsar is a variable showing both the energy and the shape of the X-ray emission is highly variable. BeppoSAX, the Italian–Dutch Mission for X-ray Astronomy [6], observed Cyg X-3 with the...
Narrow Field Instruments (IFS, IFS, 10) twice. The first time the source was observed on August 15th, 1996 in the framework of Science Verification Phase Program. It was found, assuming a distance of 8 Kpc, at a luminosity level of 4.6 x 10^{36} erg s^{-1}. Data from this observation are not discussed here and will be the subject of a different paper [11]. The source was observed again by the NFIs on February 17th, 1997 in the framework of the AO1 program, covering the orbital phase from 0.0 (mid-eclipse) to 0.3. As can be seen in Fig. 1, where the light curves observed by the Medium Energy Concentration Spectroimeters (MEC) is shown, during this second observation part of the eclipse, the post-eclipse egress and the post-eclipse high luminosity state were monitored. Unfortunately, part of the eclipse, the LECS instrument was off. Assuming again a distance of 8 Kpc, the X-ray luminosity of the source was, during this second observation, at a level of 4.3 x 10^{36} erg s^{-1} (in the 2-10 keV band).

2.1. Pulse Profiles.

Pulse Profiles of Cen X-3 in six different energy bands relative to high post-eclipse state are shown in Fig. 2.

Pulse profiles clearly evolve with the energy. At lower energies, below 15 keV, it shows a "single main" peak with a sharp rise and a more gradual decline ending in a shoulder that is usually defined as the "subsidiary" peak. Three peculiar phase segments can be distinguished: the "single main" peak, the "subsidiary" peak (separated 180 degree from the main peak) and a third phase segment that we define as interpulse. At higher energies (above 15 keV), the subsidiary peak is almost suppressed and only the main single peak is observed. It is also interesting to note that in the 10-15 keV energy range a small shoulder on the trailing edge is clearly observed by the High Pressure Gas Scintillation Proportional Counter (HPGSPC).

The "single peak" structure is not unique. A rarely observed double peaked (not strongly asymmetric) profile has been reported in a few occasions[5]. Nagy et al. suggested a possible dependence of pulse profiles on luminosity as in the case of EXO 2030+375[10]. In that case the luminosity dependence of the pulse profile is explained with the change of emission from flat beam to pencil beam, due to a different structure of the accretion column. As we already said, during the Science Verification Phase BeppoSAX observed Cen X-3 while the source was in the post-eclipse orbital phase but at a very different luminosity level. Pulse profiles as a function of the energy are reported in Fig. 3. A complex, more complicated structure is clearly detected.

2.2. Pulse Phase Spectroscopy of the Iron Line.

The detection, in the Ginga data, of pulsed iron line emission from Cen X-3 was reported by Uay et al. in 1990[12]. The discovery of such a pulsation in such a weak source is, of course, a great impact in suggesting the existence of a two component model, one component the iron line emission mechanism and second must satisfy.

In order to search for pulse phase dependencies in the spectrum, we integrated the spectra in 20 pulse phase bins, each with a different integration time of about 15 s. Data were fitted with a single model, comprising a power law, a gaussian, shape iron line and the photoelectric absorption. Over the 2-10 keV range the power law provides a good modelling of the continuum and good fits (χ^2 < 1) are obtained at each phase bin. The relevant best fitting parameters, absorption column, phase index and intensity of the line are shown in Fig. 4 as functions of the pulse phase.

Errors on a single parameter are at 90% confidence level in χ^2 variation. Both the absorption column N_H and spectral index α vary with the phase, the "subsidiary peak" being the fast part of the pulse profile, while the "main" peak shows a harder spectrum. The vector-averages of iron line intensity vary less than 40% and however outside the 90% error bars. Moreover, the absorption column N_H and the iron line intensity are not in phase with each other. This result is different from what Ginga observed in 1992 and could be related to the difference in luminosity between the two observations.
of Fig. 5, a clear absorption feature centered at 28.5 keV emerges. Fitting the data with a simple Gaussian in absorption, we get $E_{\text{abs}} = 29.3 \text{keV}$, $\sigma_{\text{abs}} = 0.1$, for a $\chi^2 = 1.4$ (22).

To extract physical information, however, we searched for this feature, fitting the phase averaged spectrum of the post-eclipse high state with different theoretical models (Fig. 6). The only continuum model which came close to describing the observed spectrum was a broken powerlaw with an exponential turnover at high energies (see [18], for the functional form). Also the photoelectric absorption [19] and a combination from a gaussian shape line for cold iron were included in the continuum. Regardless of the continuum used some persistent feature was present in the residuals. This suggested us to include a cyclotron resonant scattering line in the model. We did introduce the absorption-like line in two different ways: 1) Coupled Lorentzians [14] for a Gaussian line in absorption [21], [17]. The relevant best fit parameters for the two cases are reported in Table 1. In both cases an absorption-like feature is found at $E_{\text{abs}} = 28$ keV, interpreting this feature as due to cyclotron resonant scattering the magnetic field strength at the surface of the neutron star can be calculated from the line centroid using $E_{\text{abs}} = 11.6(1+z) - (1+z)(2 - 12) \times 10^{-22}$ keV where $z$ is the gravitational redshift. In the case of Cas X-3 a magnetic field of about $2.4 \times 10^{12}$ Gauss is inferred. If we consider $z = 0$ the strength of magnetic field is about $2.5 \times 10^{12}$ Gauss. This value is in good agreement with what reported in [23] on the basis of hea frequency mass accretion model.

### Table 1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>No Line</th>
<th>Gaussian</th>
<th>Lorentizan</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{\text{H}}$</td>
<td>$10^{22}$ cm$^{-2}$</td>
<td>1.22(2) 0.02</td>
<td>1.22(2) 0.01</td>
</tr>
<tr>
<td>$\sigma_{\text{H}}$</td>
<td>3.2(2)</td>
<td>2.8(2) 0.10</td>
<td></td>
</tr>
<tr>
<td>$E_{\text{abs}}$</td>
<td>17(5) 0.3</td>
<td>17(5) 0.3</td>
<td></td>
</tr>
<tr>
<td>$E_{\text{cyc}}$</td>
<td>15.5(10) 0.5</td>
<td>15.5(10) 0.5</td>
<td></td>
</tr>
<tr>
<td>$E_{\text{abs}}$</td>
<td>28.5(0.5)</td>
<td>28.5(0.5)</td>
<td></td>
</tr>
</tbody>
</table>

**NOTE** — All quoted errors represent 90% confidence level for a single parameter.

3. HER X-1

The Low Mass eclipsing X-ray binary Her X-1 [22], is one of the most observed and studied X-ray pulsars in the sky. Inside a pulse period of 1.24 sec and an orbital period of 1.7 days, the source exhibits a 35-day X-ray intensity cycle which manifests itself at a 10-day minimum on states followed by a 5-day secondary short-0 state during which the intensity of the source is a factor of 3 fainter. The two on-states are separated by periods of relatively low flux. This modulation has been explained with a tilted precessing accretion disk that periodically obscures the line of sight toward the neutron star [35]. Her X-1 was the first pulsar from which a cyclotron, scattering feature was detected [26,27]. The feature has been, since then, extensively studied and discussed in terms of either an emission line at 45 keV or an absorption line at 35 keV. Variations of spectral parameters with the pulse light curve have also been observed (Costa et al., [21]) and results seem to make the absorption interpretation more likely. The NF is obtained. BeppoSAX observed Her X-1 on July 24th, 1996, during the Science Verification Phase, covering two full orbital cycles near the minimum of the main-on state.

3.1. Pulse Profiles

Pulse profiles from 0.2 to 100 keV have been already presented and discussed by Dai et al., and will be reported here. Major changes are present below 1 keV, where the transition from a broad sinusoidal shape to a more peaked structure can be interpreted as corresponding to the inner part of the accretion disk, and above 10 keV where the pulse profile is much less structured. The pulse profile, however, evolves with the energy in the entire BeppoSAX
Figure 7. Her X-1 pulse profile as observed by the MECS in the 2–10 keV energy range. The pulse light curve has been divided in 7 phase segments, numbered from left to right.

...indicating that there is a dependence on the phase of the spectrum.

3.2. Spectral Analysis

The broad band phase averaged spectrum of Her X-1 as observed by BeppoSAX [23,24], is quite complex. Three different components are evident in the continuum: 1) a low energy excess modelled as 0.1 keV blackbody; 2) a power law; 3) a higher energy exponential cut-off. Superimposed in the continuum, Fe K and L emission line at 6.6 and 6.9 keV respectively and a cyclotron absorption feature at 40 keV are detected.

In order to study the dependence of line parameters on pulse phase, the pulse light curve has been divided in 7 phase segments as shown in Fig. 7.

PDS Count rate spectra normalized with respect to the Crab spectra and multiplied by The Crab spectral functional form have been then, obtained for all the phase segments and are shown in Fig. 8.

Although results are quite preliminary a strong dependence on the pulse phase of the line parameters is clearly evident, the line being larger and more deeper around the peak of the pulse. A more detailed and quantitative analysis is, of course, on the way.

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Figure 8. In the Upper panels, the ratio of the PDS count rate spectra of Her X-1 and the Crab Nebula, multiplied by $E^{-1}$, are shown together with the best fitting exponential continuum, for all different phase segments. In the lower panels the same ratio divided by the continuum emphasizes the shape of the line. The line depth, width and centroid clearly depend on the pulse phase.