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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Adv. Space Res. Vol. 25, No. 3/4, pp. 409–412, 2000

Printed in Great Britain
0273-1177/00 \$20.00 + 0.00

PII: S0273-1177(99)00768-1

BEPPOSAX OBSERVATION OF 4U 1907+09: DETECTION OF A CYCLOTRON LINE AND ITS SECOND HARMONIC.

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ABSTRACT

We report the detection of a cyclotron absorption line and its second harmonic in the average spectrum of the high mass X-ray binary 4U1907+09 observed by the BeppoSAX satellite. The broad band spectral capability of BeppoSAX allowed a good determination of the continuum against which the two absorption features are evident at ~ 19 and ~ 39 keV. Correcting for the gravitational redshift of a ~ 1.4 $M_\odot$ neutron star, the inferred surface magnetic field strength is $B_{surf} = 2.1 \times 10^{12}$ G.

1 INTRODUCTION

4U1907–09 is an X-ray pulsar powered by wind accretion from a close blue supergiant companion star. The pulsar is characterized by a pulse period of 440.341 ± 0.006 s. The orbital period is 8.3753 ± 0.0001 d and the eccentricity is 0.28 ± 0.04 (in 't Zand *et al.* 1998). The energy spectrum of 4U1907+09 was observed with several X-ray missions (Ariel V, Tenma, EXOSAT, Ginga, XMPC and RXTE) covering, not simultaneously, the range 2–100 keV. It was fitted by an absorbed power law (N_H in the range $1.5 - 5.7 \times 10^{22}$ cm^{-2} and photon index in the range 0.83 - 1.52 - see Schartz *et al.* 1980, Marshall and Ricketts 1980, Makishima *et al.* 1984, Cook and Page 1987, Chitnis *et al.* 1993). Data from a Ginga observation of 4U1907–09 were fitted using the NPEX model (Negative and Positive power-laws EXponential) as continuum plus a Lorentzian shaped cyclotron absorption line at ~ 19 keV and an iron line at 6.6 keV with a flux of 1.7–0.5 ph s^{-1} (Mihara 1995). In the RXTE observation the spectrum of 'non dipping' data, subtracted by the 'dipping' spectrum, was fitted in the 2-30 keV range by an absorbed power law with high energy cut-off at 13.6 keV with no evidence of any absorption features (in 't Zand *et al.* 1997).

4U1907+09 was observed by the Narrow Field Instruments (NFIs) on board BeppoSAX (Boella *et al.* 1997) on 1997 September 27 and 28. We report the results of a spectral analysis of the broad band spectrum (1.6–80 keV) of 4U1907+09. We confirm the presence of the absorption feature at ~ 19 keV and we report the detection of a strong second harmonic.

2 SPECTRAL ANALYSIS

Spectral analysis was performed on the spectrum averaged over the complete observation. We do not consider LECS data because the MECS statistics is more than enough to model the continuum under the cyclotron lines. The total exposure time was 68576 s for the MECS, 33079 s for the HPGSPC and 34731 s for the PDS. HPGSPC and PDS were exposed about half as long as the MECS due to the rocking collimator observation mode. Due to the presence of the galactic ridge and the supernova remnant W49B ($\sim 0.8°$ from 4U1907+09) additional care has been applied in the determination of the background. The MECS local background spectrum can be well represented by the background of the archive blank fields increased by a factor 1.5. For the collimated instruments we use the local background accumulated in the off-source position. Anyway, from previous measurements of W49B (Fujimoto *et al.* 1995, Smith *et al.* 1985) and the galactic ridge (Yamasaki *et al.* 1997) and considering the strong reduction in the effective area for off axis sources we estimate that the contribution of these sources is negligible above 10 keV. The energy range used in the spectral analysis for each NFI was: 1.6–10 keV for MECS, 10–30 keV for HPGSPC and 15–80 keV for PDS. The continuum in the range 1–80 keV has been modeled adopting an absorbed power law with an exponential cut-off for energies above E_{cut}. The χ^2_{red} value with the above continuum model was 2.14 (221 dof). Figure 2 shows the spectra with the best fit continuum and the residuals. The excess at $\sim$ 6.4 keV in the residuals strongly suggests the presence of an iron emission line. Therefore we included an additional gaussian to model the iron line.

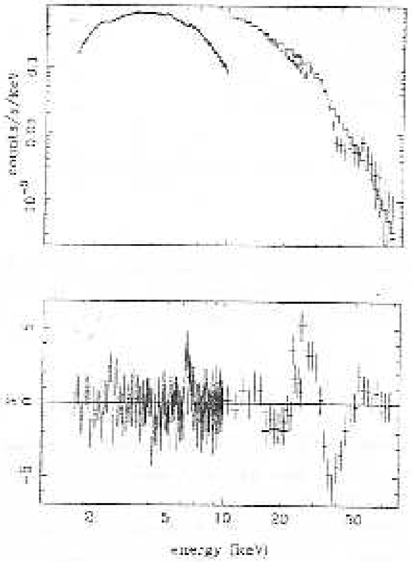

Fig. 1 1.6–80 keV spectrum of 4U1907+09 with the best fit continuum model (top panel) and residuals (bottom panel).

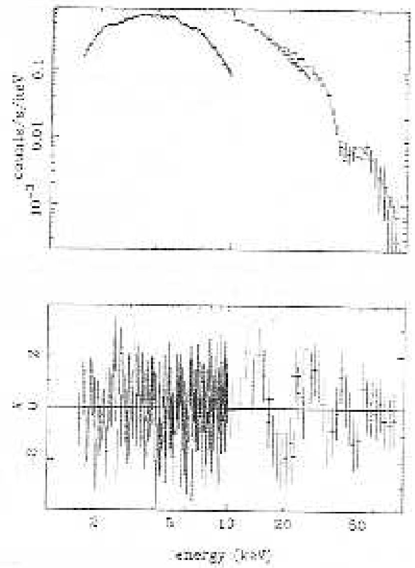

Fig. 2 1.6–80 keV spectrum of 4U1907+09 with the best fit continuum model plus an emission gaussian line at $\sim$ 6.4 keV and an absorption gaussian lines at 39.4 keV. The residuals show a feature at about 19 keV.

Other features are evident from the residuals above 10 keV. A feature at $\sim$ 40 keV is evident. We tried several models to fit this feature and we obtained the best fit including an absorption according to a gaussian shaped feature (Soong et al. 1990) centered at $\sim$ 39 keV. The χ^2_{red} value after the addition of the absorption gaussian feature was 1.27 (215 dof). A feature at $\sim$ 19 keV is also present in the residuals of Fig. 2. We tried to improve the fit adding an absorption gaussian feature to the above model (model 1). The χ^2_{red} value after addition of this last gaussian shaped feature was 1.06 (212 dof). Figure 3 shows the result of the fit. The residuals do not show significant structures. The F-test for three additional parameters gives a significance of the absorption feature at ~19 keV greater than 99.999%. The significance of the last feature and its energy that is compatible (Table 1) with half of the energy of the other absorption feature allow us to identify these two absorption features as the fundamental and the second harmonic of the cyclotron absorption line at $\sim$ 19 keV reported by

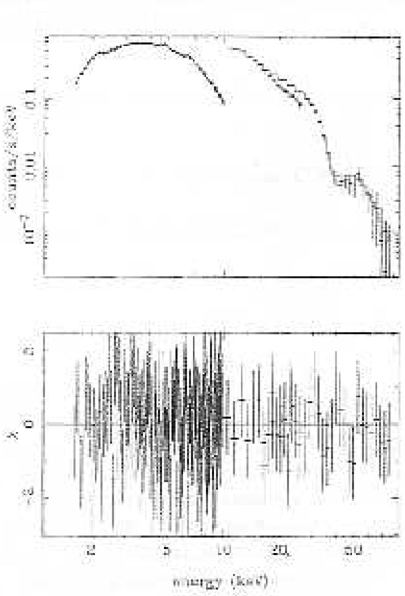

Fig. 3 1.6–80 keV spectrum of 4U1907−09 with the best fit continuum model plus an emission gaussian line at $\sim$ 6.4 keV and two absorption gaussian lines at 18.8 and 39.4 keV. The residuals do not show significant features.

Makishima and Mihara (1992) from *Ginga* observations. The Lorentzian absorption model of Mihara (1995) (model 2) was also tried to fit the two absorption features. Also in this case the fit gives an acceptable χ^2. Best fit parameters obtained with the models described above are reported in Table 1.

Other descriptions of the continuum (such as NPEX, Mihara 1995), together with the models for cyclotron lines described above, gave worse results.

3 CONCLUSION

We have reported the analysis performed on 4U 1907−09 observed by BeppoSAX. The broad band (1 - 80 keV) spectrum shows the presence of two cyclotron features at $\sim$ 19 and $\sim$ 39 keV, the fundamental and the second harmonic. The continuum is well fitted by an absorbed power-law with exponential cut-off and the absorption lines are well fitted by gaussians. Considering the relation between the cyclotron energy and the magnetic field $E_c/(1\ keV) = 11.6\ B/(10^{12}\ Gauss)$, the observed value of the cyclotron energy of 18.8 keV implies a magnetic field of $B_{obs} \simeq 1.6 \times 10^{12}$ Gauss. If the cyclotron absorption takes place near the neutron star surface, where the magnetic field is strong, the observed resonance energy

Table 1: Best fit parameters

	model 1	model 2
N_H	2.81 ± 0.04	2.81 ± 0.04
α	1.27 ± 0.01	1.27 ± 0.01
Norm	0.052 ± 0.001	0.052 ± 0.001
E_{iron} (keV)	6.47 ± 0.03	6.47 ± 0.03
σ_{iron} (keV)	≤ 0.15	≤ 0.15
I_{iron}	$(3.0 \pm 0.7) \times 10^{-4}$	$(3.0 \pm 0.7) \times 10^{-4}$
E_{cut} (keV)	12.0 ± 0.3	12.3 ± 0.4
E_{fold} (keV)	12.0 ± 0.3	13.3 ± 0.8
E_{CRF1} (keV)	18.8 ± 0.4	19.3 ± 0.2
σ_{CRF1} (keV)	2.2 ± 0.4	
EW_{CRF1} (keV)	2.3 ± 0.4	
D_{CRF1}		0.29 ± 0.05
W_{CRF1} (keV)		1.8 ± 0.8
E_{CRF2} (keV)	39.4 ± 0.6	$2 \times E_{CRF1}$
σ_{CRF2} (keV)	3.5 ± 0.7	
EW_{CRF2} (keV)	16.7 ± 2.1	
D_{CRF2}		2.7 ± 1.1
W_{CRF2} (keV)		2.8 ± 1.3
χ^2_{red} (d.o.f.)	1.06 (212)	1.03(213)

Norm is in unit of photons/keV/cm^2/s at 1 keV.
N_H is in unit of (10^{22} atoms cm^{-2}).
I is the total photons cm^{-2} s^{-1} in the line.
Quoted errors refer to single-parameter 68% confidence level
The upper limit to the σ_{iron} is at 90% confidence level.

will be affected by the gravitational redshift: $E_c^{obs} = E_c(1+z)^{-1}$, with

$$(1+z)^{-1} = \left(1 - \frac{2GM_{NS}}{Rc^2}\right)^{1/2} \quad (1)$$

where M_{NS} is the mass of the neutron star and R is the distance of the region where the line is formed from the center of the neutron star. Using $M_{NS} = 1.4 M_\odot$ and $R = 10^5$ cm, we get $(1+z)^{-1} = 0.76$ and $E_c \simeq 24.7$ keV. In this case the magnetic field should be $B_{surf} \simeq 2.1 \times 10^{12}$ Gauss.

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Pergamon
www.elsevier.nl/locate/asr
Adv. Space Res. Vol. 25, No. 3/4, pp. 413–416, 2000

Printed in Great Britain
0273-1177/00 $20.00 + 0.00
PII: S0273-1177(99)00769-3

BEPPOSAX observations of the massive X-ray pulsar Cen X-3 : Broad-band spectra and iron line diagnostic.

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ABSTRACT

The BeppoSAX satellite pointed to the massive X-ray pulsar Cen X-3 for the first time during the Science Verification Phase (SVP). The source was found in a low luminosity state ($L \simeq 3.8 \times 10^{36}$ ergs/s). Cen X-3 was observed again in the Guest Observer Program (GOP) and was found in a much higher luminosity state ($L \simeq 4.3 \times 10^{37}$ ergs/s). This second observation includes also the source eclipse and the eclipse egress. We present the pulse profiles and the average broad-band spectra (0.5 - 80 keV) of the two observations and discuss different overall continuum models to fit these spectra. In particular, we report results on the variation of the iron K-line parameters as a function of the different source states : eclipse, low luminosity state and high luminosity state. © 2000 COSPAR. Published by Elsevier Science Ltd.

1 INTRODUCTION

The discovery of Cen X-3 was made with a rocket-borne detector (Chodil et al. 1967) and was followed, 4 years later, by the discovery of its binary and pulsar nature with Uhuru (Giacconi et al. 1971; Schreier et al. 1972). This system contains a neutron star which emits pulsed X-rays every 4.8 s while orbiting its companion every 2.1 days. The companion star is the O-type supergiant V778. The luminosity of Cen X-3 has been reported to alternate between extended high states and low states on a timescale of months. However no evidence of periodicity has been found (Schreier et al. 1976; Priedhorsky & Terrell 1983). The pulse profile usually shows a single peak with a sharp rise and a more gradual decline ending in a shoulder that is more prominent at low energies (Ulmer 1976; van der Klis et al. 1980). However, on several occasions, a double-peaked pulse profile has been detected at low energies (Schreier et al. 1976; Nagase et al. 1992). The single-peaked pulse profile is strongly asymmetric, the double-peaked one moderately so.

The pulse phase averaged X-ray spectrum of Cen X-3 is usually modeled by a power-law continuum with photon index about 1 modified by interstellar absorption and high-energy turnover typical of X-ray pulsars (White et al. 1983; Nagase et al. 1992). In common with other X-ray pulsars Cen X-3 exhibits iron line features which are useful tools for probing the circumstellar matter. Nagase et al. (1992) observed an iron line at about 6.5 keV with an equivalent width of 180 eV. This line was found to be pulsating with an amplitude of about 50% of the mean intensity corroborating the fluorescent origin (Day et al. 1993) and implying that the fluorescent region does not uniformly surround the neutron star. An ASCA observation (Ebisawa et al. 1996) performed with the source in the eclipse state showed that the iron line is a blend of different components and in particular the 6.4 keV and the 6.7 keV ones. An iron K-edge was also observed at $\simeq 7.2$ keV with an optical depht of $\simeq 0.5$. This feature was observed during