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LETTER

Letter to the Editor

BeppoSAX detection of a Cyclotron Feature in the spectrum of Cen X-3

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Abstract. The High Mass X-ray Binary Pulsar Centaurus X-3 was observed by the *BeppoSAX* satellite during 1997 February 17, while the system was in a high-luminosity ($L_x = 4.3 \cdot 10^{37}$ erg s^{-1}) post-egress state. In this *Letter* we report the detection of an absorption-like feature, centered at ∼28 keV, in the broad band phase averaged spectrum. Interpreting the feature as due to cyclotron resonant scattering, we estimate the magnetic field strength close to the surface of the neutron star to be $B \sim (2.4 - 3.0) \cdot 10^{12}$ G.

Key words: magnetic fields – binaries: close – stars: neutron – pulsars: individual (Cen X-3) – X-rays: stars

1. Introduction

Centaurus X-3 was the first binary pulsar to be discovered in the X-ray sky (Giacconi et al. 1971, Schreier et al. 1972). The system contains a neutron star which exhibits a pulse period of 4.8 sec while orbiting a highly reddened O–type companion (Krzeminski 1974) every 2.09 days. Although a strong stellar wind emanates from the companion, due to the behaviour of its optical light curve (Tjemkes et al. 1986) Cen X-3 is thought to be powered by an accretion disk fed by Roche Lobe overflow. The discovery of QPOs at ∼40 mHz from the source (Takeshima et al. 1991; Audley et al. 1996) further implies the presence of an accretion disk. The X-ray luminosity of the system has been observed to vary by a factor of 8 on a timescale of months, from a high luminosity to a low luminosity state. Also the pulse shape is variable, changing both with the energy and luminosity (Nagase et al. 1992 and references therein). The continuum pulse phase averaged X-ray photon spectrum of this source, measured by *Ginga*, has been described (Nagase et al. 1992) by the standard model for X-ray pulsar: a flat power law with energy photon index around 1 up to a high energy exponential roll-off with a cut-off energy ∼15 keV. The spectrum shows also photoelectric absorption at lower energies and the presence of an iron line-like feature, which has been shown to be a blend of three different emission iron lines at 6.4 keV, 6.7 keV, and 6.97 keV (Ebisawa et al. 1996; Audley et al. 1996) and has been found to pulsate (Day et al. 1993).

It is an open question if a cyclotron feature is present in the spectrum of Cen X-3. Although Nagase et al. (1992) fits the spectrum of the source with a Lorenzian shape high energy turn over which resembles the cross section of cyclotron resonant scattering, the position of line centroid is found at $E_{\rm cyc} \sim 30$ keV, beyond the top end of the observable *LAC* energy range. More recently indication of a possible cyclotron scattering resonance feature between 20 and 30 keV has been reported by Audley et al. (1997) as a result of a *RXTE* satellite observation between 1996 September 10 and September 17. The Xenon edge around 35 keV which could affect data from *PCA* and the presence of a sharp systematic feature in both the *PCA* (below 15 keV) and *HEXTE* (between 30 and 40 kev) effective areas make the *RXTE* detection of line at $E_{\rm cyc} \sim 25$ keV not conclusive.

Cyclotron features, observed in the high energy X-ray spectra of strongly magnetized objects, provide a powerful diagnostic for determining the magnetic field strength close to the star surface. X-ray emission of mass-accreting X-ray binary pulsars is due to the funnelling of ionized hot plasma onto the magnetic polar caps of the neutron star. The electron-photon interaction in the plasma is dominated by cyclotron resonance scattering in strong magnetic field of the order of $B \sim 10^{12}$ G, and because the electron resonance energy is related to the magnetic field strength by $E_{\rm cyc} = 11.6 \cdot B_{12}$ keV (where B_{12} is the magnetic field strength in units of 10^{12} G), spectral features related to the scattering resonance are expected to be detected in the hard X-ray range. Since the historic discovery of such line feature in Her X-1 (Trümper et al. 1978), cyclotron features have been observed in eight more pulsars (Wheaton et al. 1979; Mihara 1995).

More recently The High Energy Instruments aboard *BeppoSAX* have detected Cyclotron Resonance Scattering Features (CRSFs) in Vela X-1 (Orlandini et al. 1998a), Her X-1 (Dal Fiume et al. 1997) and 4U1626–67 (Orlandini et al. 1998b). Detection of such a feature in the hard X-ray spectrum of Cen X-

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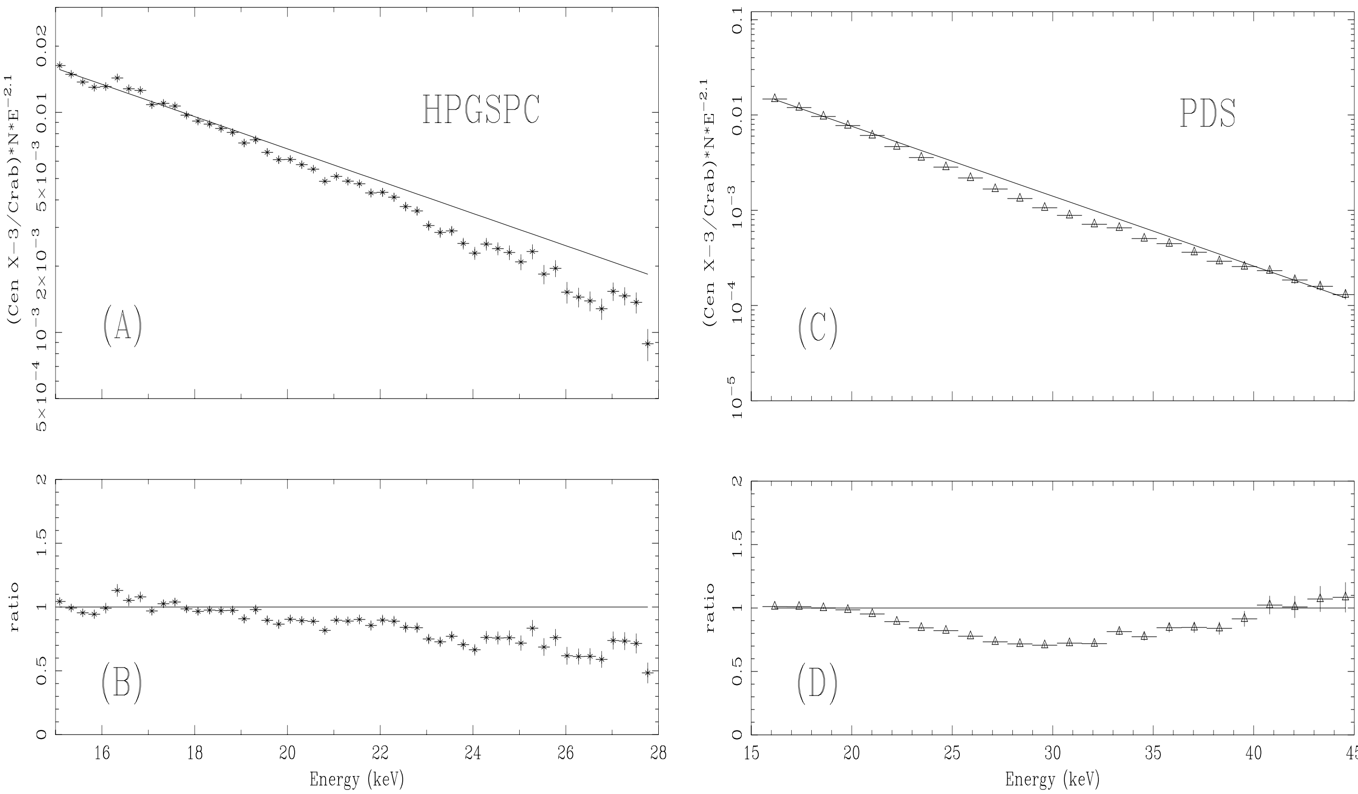

Fig. 1a–d. *BeppoSAX* observation of Cen X-3: in panel **a** and **c** the "Crab" count ratio multiplied by the functional form of the Crab spectrum is reported for the HPGSPC and PDS instruments respectively. Panel **b** and **d** shows the above ratio divided by the best fit of the local continuum. A clear absorption feature emerges in both HPGSPC and PDS centered at ∼28 keV. In the PDS data the upturn of the spectrum is observed.

3 would provide the first direct measurement of the magnetic field strength for this pulsar and could set further constraints on the emission model that more luminous highly magnetized HMXRBs must satisfy. Aim of this *Letter* is to report the discovery of an absorption feature centered at $E_{\rm cyc} \sim 28$ keV in the high luminosity post-egress pulse averaged spectrum of Cen X-3, which is interpreted to be a CRSF. From this observation, a magnetic field strength at the surface of the neutron star of $B \sim (2.4 - 3.0) \cdot 10^{12}$ G is inferred.

2. Observation

The Narrow Field Instruments (NFIs) aboard the Italian/Dutch satellite for X-ray astronomy *BeppoSAX* (Boella et al. 1997a) consist of the Low Energy Concentrator Spectrometer (LECS, Parmar et al. 1997) operating in 0.1–10 keV, the Medium Energy Concentrators Spectrometer operating in the 1–10 keV energy band (MECS, Boella et al. 1997b), the High Pressure Gas Scintillation Proportional Counter (HPGSPC, Manzo et al. 1997) operating in the 3–120 keV energy and the Phoswich Detection System (PDS, Frontera et al. 1997) with four scintillation detection units operating in the 15–300 keV energy band.

BeppoSAX observed Cen X-3 twice, finding the source in two different luminosity states. On 1996 August 14, the source was pointed in the framework of the Science Verification Phase Program and it was found, assuming a distance of 8 Kpc, at a 2–10 keV luminosity level of $L_x = 4.6 \cdot 10^{36}$ erg s^{-1}(Del Sordo et al. 1998). The source was observed again on 1997 February 17, in the framework of an AO1 proposal aimed to monitor the source in the orbital phase from 0.0 to 0.3. Part of the eclipse, the post-eclipse egress and the post-egress high state were monitored (Santangelo et al. 1998). Assuming again a distance of 8 Kpc, the 2–10 keV X-ray luminosity of the source during this second observation was $L_x = 4.3 \cdot 10^{37}$ erg s^{-1}. A detailed analysis of the time and spectral behaviour as a function of luminosity is behind the scope of this paper and will be reported elsewhere (Del Sordo et al. 1998). Data related to this *Letter* refers to the spectral study of the high luminosity post-egress state. Unfortunately during this observation the LECS was off for most part of the time and therefore its data will not used here. The net exposure times were ∼20 ks, ∼8 ks, and ∼9 ks for MECS, HPGSPC and PDS, respectively. These differences are due to different filtering criteria during passages in the South Atlantic Geomagnetic Anomaly and before and after Earth occultations, and to a different strategy of sampling the background.

3. Spectral analysis

Accumulated Pulse Height spectra of the MECS, HPGSPC and PDS were screened for corrupted data and corrected for electronic and telemetry effects. Standard background subtraction procedure was performed on the spectra from the three instruments. In order to search for features in the high energy phase

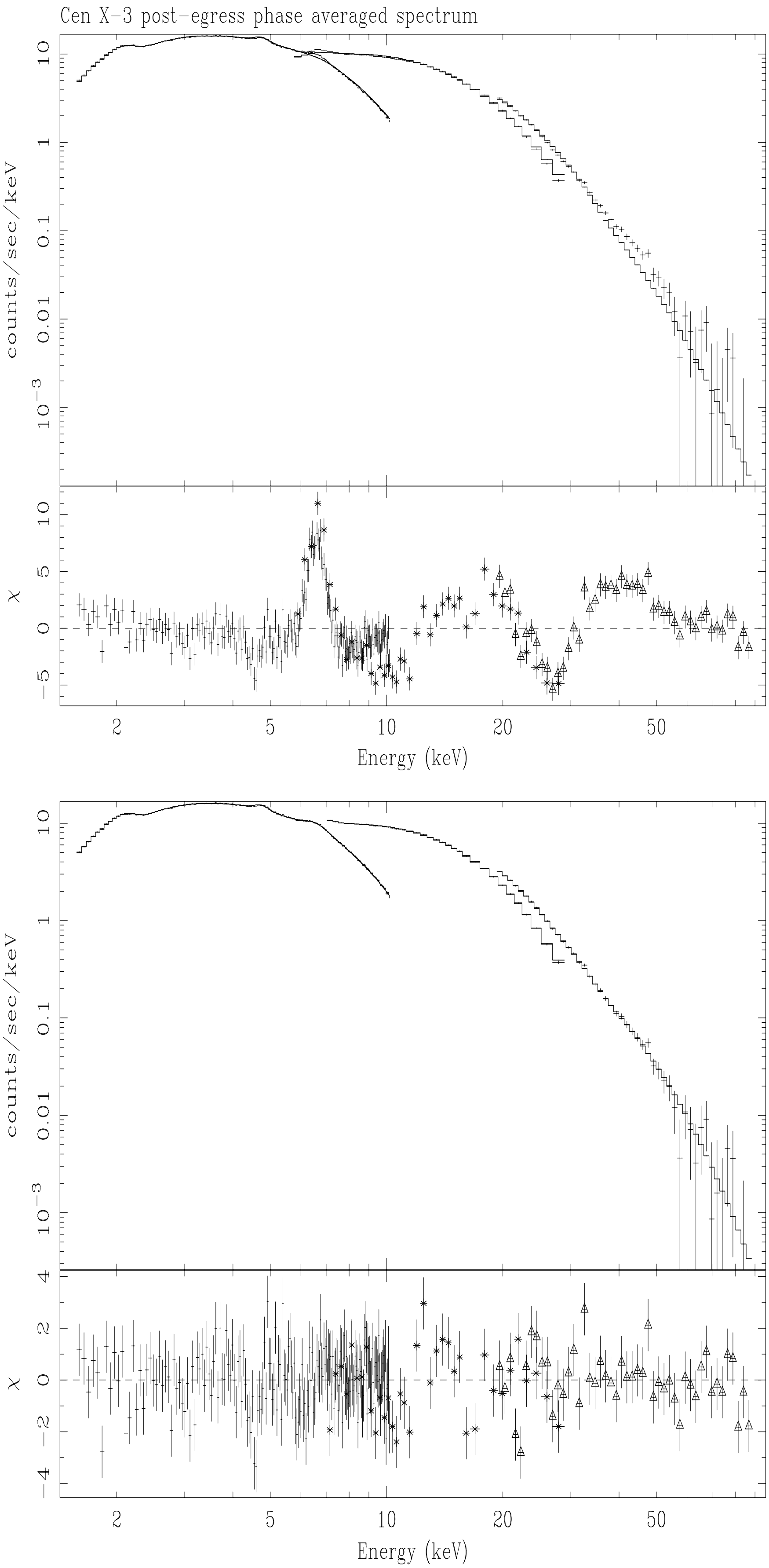

Fig. 2. The broad band post-egress high state spectrum of Cen X-3 observed by the *BeppoSAX* NFIs. *Upper panel:* The best fit of the broad band continuum: features emerge corresponding to an iron line at ∼6.6 keV and to an absorption-like feature at ∼28 keV. *Lower panel:* residuals after the introduction in the model of a gaussian for cold iron and a Lorenzian shape cyclotron feature.

averaged spectrum in a calibration independent way, we considered the ratio between the Cen X-3 spectra measured by the HPGSPC and PDS instruments respect to the Crab spectrum as observed by the same two instruments. Shape of this "Crab" count ratio, that is largely independent of uncertainties in effective area calibration and spectral reconstruction (Dal Fiume et al. 1997), multiplied by the functional form of the Crab nebula, a featureless power law with spectral index $\alpha = 2.10$ in this energy range, is reported in Fig. 1, panel (a) and (c). The continuous line in panel (a) and (c) is the best fit obtained assuming that locally the spectrum can be approximated by $\exp(-E/kT)$. A best fit value of $kT = 5.88$ keV is obtained. In both instruments a clear deviation from this exponential continuum is observed. In order to extract the shape of this possible absorption feature we perform the ratio of panels (a) and (c) data with respect to the best fit exponential continuum. As can be seen in panels (b) and (d) of Fig. 1, a clear absorption feature centered at ~ 28.5 keV emerges, still in both instruments. Moreover, while in the HPGSPC only the descending part of the line is observed, in the PDS data the upturn in the spectrum, that should be present if there is an absorption cyclotron feature is indeed detected.

To extract physical information, however, we searched for this feature, fitting the phase averaged spectrum of the post-egress high state with different theoretical models (Fig. 2). The only continuum model which came close to describe the observed spectrum was made by the following components: (1) a low energy absorption, N_H, using the coefficient of Morrison and McCammon (1983); (2) a power law continuum with photon index α_1 for $E < E_{\rm cutoff}$; (3) a high energy exponential cut-off multiplied by a power law with photon index α_2 for $E > E_{\rm cutoff}$, i.e. $f(E) = E^{-\alpha_2}\exp(-(E - E_{\rm cutoff})/E_{\rm folding})$.

As can be seen from Fig. 2 (upper panel), beside the cold iron emission line at ~6.6 keV, regardless of the continuum used, a persistent absorption-like feature was present at ~28 keV in the residuals of the fit. This prompted us to include a CRSF in the fitting model. To model the absorption line we used both the Lorenzian form (Mihara 1995) and the Gaussian filter in absorption used by Dal Fiume et al. (1998). Results of the fit are reported in Table 1. While the introduction of a gaussian in emission for cold iron emission improved the χ^2 from 7.6 (261 dof) to 2.25 (258 dof), adding an absorption cyclotron feature reduced the χ^2 to 1.39 (255 dof). An F–test shows that the improvement is significant at more than 99.99%.

Table 1. Best fit spectral parameters.

Parameter	Gaussian	Lorenzian
N_H (10^{22} cm^{-2})	2.0 ± 0.02	1.96 ± 0.02
$E_{\rm iron}$ (keV)	6.65 ± 0.03	6.65 ± 0.03
$I_{\rm iron}$	0.007 ± 0.001	0.007 ± 0.001
EQW$_{\rm iron}$ (ev)	117	116
$\sigma_{\rm iron}$ (kev)	0.29 ± 0.02	0.27 ± 0.02
α_1	1.21 ± 0.01	1.26 ± 0.01
α_2	2.4 ± 0.12	1.59 ± 0.13
$E_{\rm cutoff}$ (keV)	14.9 ± 0.2	14.5 ± 0.2
$E_{\rm folding}$ (keV)	12.1 ± 0.9	9.5 ± 0.8
$E_{\rm cyc}$ (keV)	27.9 ± 0.5	27.5 ± 0.5
$\sigma_{\rm cyc}$ (keV)	4.16 ± 0.8	...
Width$_{\rm cyc}$ (keV)	...	5.5 ± 2
χ^2_ν	1.6 (255)	1.38 (255)

I is the total photons cm^2 s^{-1} in the line
Errors refer to single-parameter 90% confidence level

4. Discussion and conclusion

Since their discovery in the spectrum of Her X-1 (Trümper et al. 1978) cyclotron resonant features have been detected in the hard X-ray spectrum of several X-ray pulsars. With this *Letter* we add Cen X-3 to this list. Using the NFIs aboard *BeppoSAX* , an absorption-like feature is definitely detected at $E_{\rm cyc} \simeq 28$ keV. Interpreting this feature as due to cyclotron resonance scattering, the magnetic field strength observed can be calculated from $E_{\rm cyc} = 11.6 \cdot B_{12}$ keV, which in the case of Cen X-3 gives a measured value of $B = 2.4 \cdot 10^{12}$ G. If one, however, wants to take into account the effects of the gravitational field close to the surface of the neutron star, the magnetic field strength at the accreting pole of the neutron star can be inferred from $E_{\rm cyc} = 11.6\, B_{12} \cdot (1+z)^{-1}$ keV where z, the gravitational redshift, is given by $(1+z)^{-1} = \left(1 - \frac{2GM_{\rm NS}}{Rc^2}\right)^{1/2}$ ($M_{\rm NS}$ is the mass of the neutron star and R the radius). Assuming, for Cen X-3, $M_{\rm NS} = 1.07\, M_\odot$ and $R = 10^6$ cm (Joss & Rappaport 1984), a value of $z \simeq 0.214$ is obtained. This implies a magnetic field at the surface of $B = 2.98 \cdot 10^{12}$ G. The latter value is in very good agreement with the value $3.0 \cdot 10^{12}$ G which can be inferred at a luminosity of $L_x = 4.3 \cdot 10^{37}$ erg s^{-1}using the beat frequency mass accretion model and based on the detection of QPOs from Cen X-3 at 40.7 mHz from BBXRT (Audley et al. 1996).

Our *BeppoSAX* measurement of cyclotron line in Cen X-3 is generally consistent with the predictions of the self-emitting atmospheres model developed by Mészáros & Nagel (1985a,b). According to that model, the cyclotron line appears in absorption, and the line FWHM, $\Delta\omega_B$, due to thermal Doppler broadening, increases for angles close to the field direction. We can use

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

where ω_B is the cyclotron line frequency, and $m_e c^2$ is the electron rest mass, and assuming $|\cos\theta| \approx 1$, to evaluate the electron temperature kT_e. Using the measured values in the case of gaussian filtering, we get a temperature for the emitting plasma $kT_e = 11.4$ keV, which is in fair agreement with the plasma temperature measured through the $E_{\rm cutoff}$ parameter.

Both values are higher with respect to what calculated by Harding et al. 1984, in the model of neutron star atmospheres heated by gradual proton deceleration via Coulomb collisions. The authors, however, confine the model for luminosities below $L_x \le 10^{37}$ erg s^{-1}, and obtain a temperature values of the order of $4 - 8 \cdot 10^7\ ^\circ K$, which corresponds to $kT_e \sim 3.5 - 7$ keV. Lamb et al. (1990) have computed the equilibrium Compton temperature T_e that results from cyclotron resonant scattering for a variety of models with different electron density and distribution and assuming that line heating and cooling dominate the thermal balance of the line forming region. Our estimation of the temperature does not fit however very well the relation $kT_e = 0.27\, E_{\rm cutoff}$ found for different models (Lamb et al. 1990), which is similar to the empirical relation, $kT_e = 0.25\, E_{\rm cutoff}$ obtained by Mihara (1995) on the basis of a plasma dominated by Comptonization.

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