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LETTER

Letter to the Editor

Detection of a cyclotron line and its second harmonic in 4U1907+09

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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 on 1997 September 27 and 28. The broad band spectral capability of BeppoSAX allowed a good determination of the continuum against which the two absorption features are evident at $\sim$ 19 and $\sim$ 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 that is typical for this kind of systems. We also detected an iron emission line at ~ 6.4 keV, with an equivalent width of $\sim$ 60 eV.

Key words: binaries: close – star: neutron – pulsars: individual: 4U 1907+09 – X-rays: stars

1. Introduction

4U1907+09 is an X-ray pulsar powered by wind accretion from a close blue supergiant companion star. It belongs to the class of the high-mass X-ray binaries (see, e.g., White, Nagase & Parmar 1995).

4U1907+09 was discovered in the Uhuru surveys (Giacconi et al. 1971, Schwartz et al. 1972). An observation of this source performed by the RXTE satellite has been recently analyzed by in 't Zand et al. (1998). The reported pulse period is 440.341 ± 0.006 s. No pulsations were found above 40 keV up to date. The reported orbital period is 8.3753 ± 0.0001 d and the eccentricity is 0.28 ± 0.04. The pulsar showed a fairly constant spin-down between 1983 and 1996 with a mean derivative of $\dot{P} = +0.225$ s yr^{-1}. Periodic flares, two per orbit, have been reported (Marshall & Ricketts 1980) with an increase of the intensity by about a factor 5. 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 1.5–5.7×10^{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 $\sim$ 19 keV and an iron line at 6.6 keV with a flux of 1.7±0.5 ph s^{-1}. 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).

In this paper we report the results of a spectral analysis of the broad band spectrum (1–80 keV) of 4U1907+09 observed with the BeppoSAX Narrow Field Instruments (NFIs). We confirm the presence of the absorption feature at ~ 19 keV and we report the detection of a strong second harmonic.

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2. Observation

4U1907+09 was observed by the NFIs on board BeppoSAX (Boella et al. 1997a) on 1997 September 27 and 28. The NFIs consist of four coaligned instruments: the Low Energy Concentrator Spectrometer (LECS) operating in the energy range 0.1–10 keV (Parmar et al. 1997), the Medium Energy Concentrator Spectrometer (MECS) having three units operating in the range 1–10 keV (Boella et al. 1997b), the High Pressure Gas Scintillation Proportional Counter (HPGSPC) operating in the range 4–120 keV (Manzo et al. 1997) and the Phoswich Detector System (PDS) with four scintillation units operating in the range 15–300 keV (Frontera et al. 1997). The energy resolution (ΔE/E) is 8% at 6 keV, 6% at 20 keV and 12% at 40.0 keV. 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. The MECS events were reduced using the SAXDAS v.1.1.0 package (BeppoSAX Cookbook, http://www.sdc.asi.it/software/cookbook) while HPGSPC and PDS data were reduced using the XAS v.2.0.1. package (Chiappetti & Dal Fiume 1997). Response matrices were used which were made publicly available on August 31, 1997.

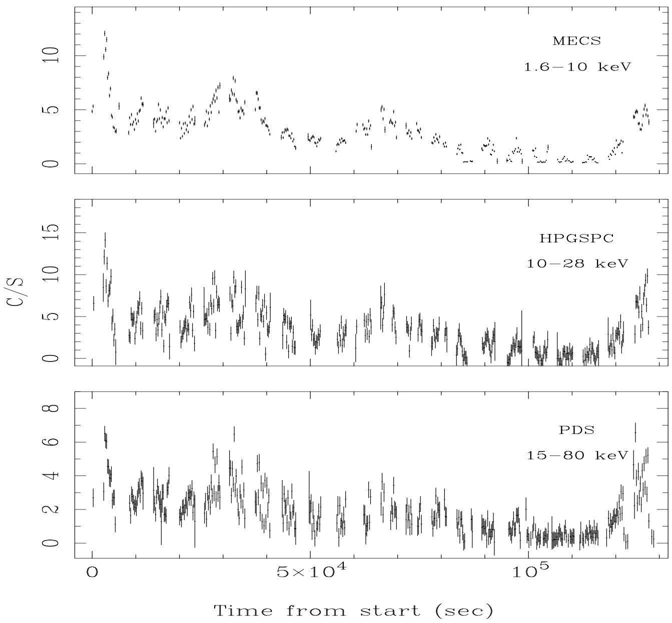

Fig. 1. Light–curves of the NFIs binned at the spin period of 4U1907+09

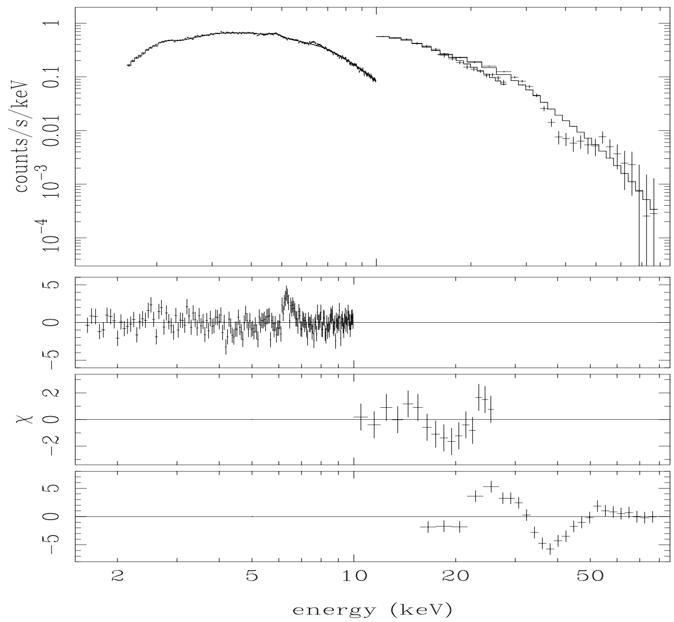

Fig. 2. 1.6–80 keV spectrum of 4U1907+09 with the best fit continuum model (top) and residuals (separately for each NFI in the bottom three panels).

The 4U1907+09 background subtracted light–curves of the three NFIs are reported in Fig. 1. The gaps in the light curves are due to non–observing intervals during passes over the South Atlantic Anomaly and during Earth occultations. An increase in intensity of about a factor two (up to 13 c/s, ~ 45 mCrab in the MECS) is observed at ~ 2500 s after the beginning of the observation. Using the P_{orb} reported by in 't Zand et al. (1998), the flux enhancement observed by BeppoSAX is found to occur 613.93 ± 0.05 orbital periods after the primary flare observed by Tenma (Makishima et al. 1984). Therefore we tentatively identified this episode with the periodic primary flare, confirming the occurrence of the phase-locked flares.

3. Spectral Analysis

Spectral analysis was performed on the spectrum averaged over the complete observation. 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 local background has been measured in a region of the image 20 arcminutes away from the source for the MECS, and compared with the background of the archive blank fields. The MECS local background spectrum can be well represented by the blank field increased by a factor 1.6. Therefore blank sky background has been used for the MECS, applying the above correction. 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}. To take into account the systematic differences in the normalization between the different NFIs (Cusumano et al. 1998) the relative normalizations have been kept as free parameters. The χ^2_{red} value with the above continuum model was 2.14 (221 dof). Fig. 2 shows the spectra with the best fit continuum and the residuals.

The excess at ~ 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.

Other features are evident from the residuals above 10 keV. A feature at ∼ 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 ~ 39 keV. The χ^2_{red} value after the addition of the absorption gaussian feature was 1.27 (215 dof). A feature at ∼ 19 keV is also present in the residuals of Fig. 2. We tried to improve the fit adding an absorption gaussian factor to the above model (model 1). The χ^2_{red} value after addition of this last gaussian shaped feature was 1.06 (212 dof). Fig. 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 ~ 19 keV reported by Makishima and Mihara (1992) from *Ginga* observations. The Lorentzian absorption model of

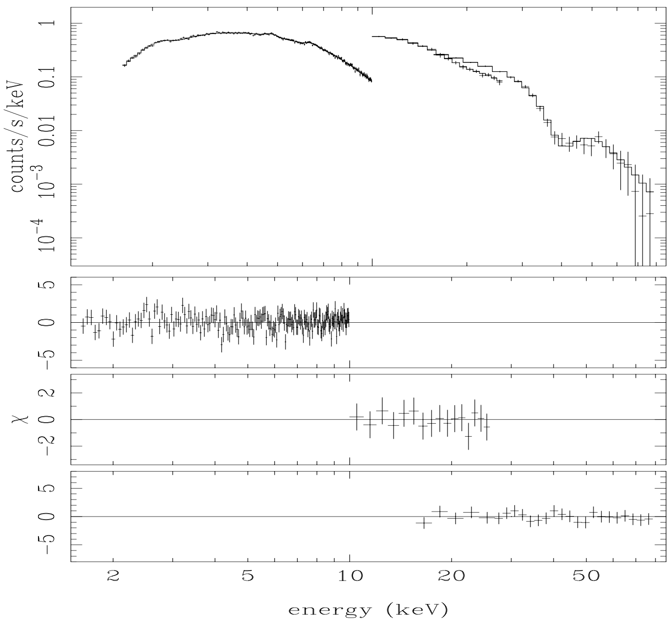

Fig. 3. 1.6–80 keV spectrum of 4U1907+09 with the best fit continuum model plus an emission gaussian line at ~ 6.4 keV and two absorption gaussian lines at 18.8 and 39.4 keV. The residuals do not show significant features.

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.

The luminosity of the source during the BeppoSAX observation was $4 \times 10^{34} D^2_{kpc}$ in the 2–10 keV energy range and $10^{35} D^2_{kpc}$ in the 2–80 keV range where D^2_{kpc}, the distance of 4U1907+09 in kpc, has been roughly estimated between 2.4 and 5.9 kpc (Van Kerkwijk et al. 1989).

4. Discussion

The detection of cyclotron lines in the hard X-ray spectrum of binary pulsars allows a direct measurement of the magnetic field of strong magnetized neutron stars. *Ginga*, with its relatively broad energy band (1-40 keV), allowed the detection of cyclotron absorption lines in several X-ray pulsars. Sometimes also the presence of a second harmonic was claimed. However the detection of these harmonics was often ambiguous, as in the case of 4U1538-52 (Clark et al. 1989). In fact only the red wing of the second harmonic (at ~ 40 keV) could be seen with *Ginga* and a high energy cut-off could also fit the spectrum. The very broad energy band of BeppoSAX NFIs allows to measure the X-ray spectrum of 4U1907+09 from 1 to 80 keV, well above the top end energy of Ginga Large Area Counter. So we can constrain the shape of the underlying continuum with great accuracy, allowing an easier measure of spectral features, when present. In the case of this source, we detect two absorption features

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	13.8±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)	3.6 ± 0.7	
EW_{CRF2} (keV)	16.7 ± 2.1	
D_{CRF2}		2.7±1.1
W_{CRF2} (keV)		2.8±1.3
χ^2_{rid} (d.o.f.)	1.06 (212)	1.03(213)

Norm is in unit of photons/keV/cm^2/s a 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.

at 18.8 keV and 39.4 keV respectively, which we interpret as two cyclotron lines, the fundamental and the second harmonic. In this case one might expect that the line at 19 keV would be deeper than the line at 39 keV because the cyclotron opacity decreases for higher harmonics. On the contrary for this source the second line appears deeper than the first line. A similar line structure was found in the spectrum of GB 880205 (e.g. Alexander and Meszaros 1989). According to Alexander and Meszaros (1989) this line structure can be explained through the process of Compton scattering with multiple photon emission. In fact, in the multiple emission case, each scattering removes a photon with $E \sim 2E_c$ and gives two photons with $E \sim E_c$. Thus photons at $\sim 2E_c$ are depleted, while those at $\sim E_c$ replenished, and the line at the second harmonic becomes deeper than the fundamental.

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 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 $R = 10^6$ cm, we get

$(1+z)^{-1}$ = 0.76 and $E_c \simeq 24.7$ keV. In this case the magnetic field should be $B_{\rm surf} \simeq 2.1 \times 10^{12}$ Gauss.

An estimate of the temperature of the region in which the cyclotron absorption is formed can be obtained from the width of the observed lines. In fact if the electrons have a temperature kT, the energy of the scattered photons distributes in a gaussian-like peak with Lorentzian wings (Voigt function). In this case the doppler broadening of a line $\Delta E/E$ is constant and is given by (see e.g. Rybicki and Lightman 1979):

$$\Delta E = E_c \sqrt{\frac{2kT}{mc^2}} \qquad (2)$$

a factor $\cos\theta$ – where θ is the angle between the magnetic field lines and the line of sight – arises if the plasma motion is confined by the field. Averaging this over angles between 0 and $\pi/2$ introduces corrections ~ 1. We observe that the obtained width of the second harmonic is double that of the fundamental, in agreement with the relation above. The obtained values of the parameters give a temperature of 4–7 keV.

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