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Letter to the Editor

A 0535+26 in the August/September 2005 outburst observed by *RXTE* and *INTEGRAL*

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ABSTRACT

Aims. In this Letter we present results from *INTEGRAL* and *RXTE* observations of the spectral and timing behavior of the High Mass X-ray Binary A 0535+26 during its August/September 2005 normal (type I) outburst with an average flux $F_{(5-100)\ \mathrm{keV}} \sim 400$ mCrab. The search for cyclotron resonance scattering features (fundamental and harmonic) is one major focus of the paper.

Methods. Our analysis is based on data from *INTEGRAL* and *RXTE* Target of Opportunity Observations performed during the outburst. The pulse period is determined. X-ray pulse profiles in different energy ranges are analyzed. The broad band *INTEGRAL* and *RXTE* pulse phase averaged X-ray spectra are studied. The evolution of the fundamental cyclotron line at different luminosities is analyzed.

Results. The pulse period P is measured to be 103.39315(5) s at MJD 53614.5137. Two absorption features are detected in the phase averaged spectra at $E_1 \sim 45$ keV and $E_2 \sim 100$ keV. These can be interpreted as the fundamental cyclotron resonance scattering feature and its first harmonic and therefore the magnetic field can be estimated to be $B \sim 4 \times 10^{12}$ G.

Key words. X-rays: binaries – stars:magnetic fields – stars: individual: A 0535+26

1. Introduction

Discovered in 1975 by Rosenberg et al. (1975), the Be/X-ray binary pulsar A 0535+26[1] consists of an X-ray pulsar with a pulse period of $P \sim 103$ s in an eccentric orbit ($e \sim 0.47$, Finger et al. 1994a) of $P_{\mathrm{orb}} \sim 111$ days (Motch et al. 1991) around the O9.7IIIe optical companion HDE 245770 (Li et al. 1979). The estimated distance of the system is $d \sim 2$ kpc (Steele et al. 1998); for a review see Giovannelli & Graziati (1992). The source was discovered during a giant outburst (type II), at a luminosity level of $L_{(3-7)\ \mathrm{keV}} \sim 1.2 \times 10^{37}$ erg s^{-1}. Since then, five giant outbursts have been detected: in October 1980 (Nagase et al. 1982), in June 1983 (Sembay et al. 1990), in March/April 1989 (Makino et al. 1989), in February 1994 (Finger et al. 1994b), and in May/June 2005 (Tueller et al. 2005). Unfortunately, during the last giant outburst the source was too close to the sun to be observed by most instruments. It was only observed by *RHESSI* (Smith et al. 2005). However, following the giant outburst, the source exhibited a normal type I outburst in August/September 2005, which led to our *INTEGRAL* and *RXTE* Target of Opportunity Observations. During the peak of the type I outburst, the source showed an average flux $F_{(3-50)\ \mathrm{keV}} \sim 1.9 \times 10^{-8}$ erg cm^{-2} s^{-1} which, assuming $d \sim 2$ kpc, gives $L_{(3-50)\ \mathrm{keV}} \sim 0.9 \times 10^{37}$ erg s^{-1}. Another normal outburst took place in December 2005 (Finger 2005). In quiescence, the pulsar behavior appears to be consistent with a spin-down trend (Finger et al. 1994b). During giant outbursts a spin-up has been observed. During the June 1983 giant outburst, a spin-up of $\dot{\nu} \sim 0.6 \times 10^{-11}$ Hz s^{-1} was measured (Sembay et al. 1990). During the February 1994 giant outburst, a spin-up of $\dot{\nu} \sim 1.2 \times 10^{-11}$ Hz s^{-1} was measured and quasi-periodic oscillations were detected, confirming the presence of an accretion disk (Finger et al. 1994b). The X-ray spectrum of the source has been modeled by an absorbed power law with a high energy cutoff. In the March/April 1989 giant outburst, two cyclotron resonance scattering features were detected at $E_1 \sim 45$ keV and $E_2 \sim 100$ keV (Kendziorra et al. 1994). In the February 1994 outburst, the presence of the fundamental line at $E_1 \sim 45$ keV was not clear (Grove et al. 1995). The presence of the fundamental line has been confirmed during the August/September 2005 outburst with *INTEGRAL* (Kretschmar et al. 2005), *RXTE* (Wilson & Finger 2005) and *Suzaku* (Inoue et al. 2005) observations.

[1] Referred to as 1A 0535+262 in SIMBAD.

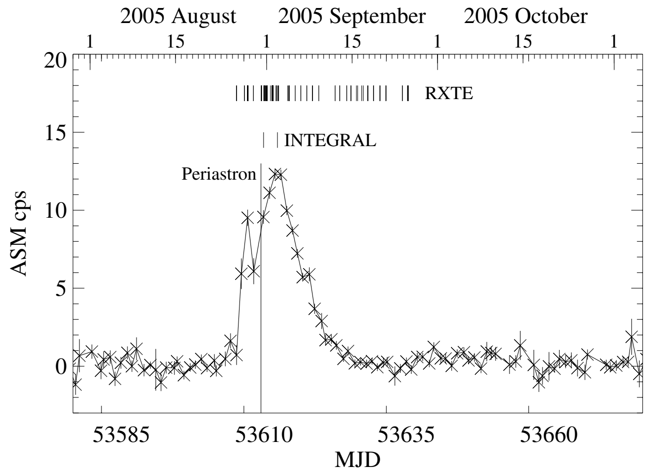

Fig. 1. *RXTE ASM* light curve of A 0535+26 during the normal outburst in August/September 2005. The start and stop times of our *INTEGRAL* observation are indicated, as well as each of the individual *RXTE* observations and the periastron passage.

In this paper we report on the analysis of *INTEGRAL* and *RXTE* observations of A 0535+26 performed during the August/September 2005 outburst. In Sect. 2 we describe the observations and data analysis. In Sect. 3 we present the pulse period determination of the source and pulse profiles in different energy ranges from ∼2 keV to 200 keV. In Sect. 4 we center on the analysis of the phase averaged spectra, on the measurement of cyclotron resonance scattering features and on the evolution of the fundamental line in different luminosity states. In Sect. 5 we present a summary and conclusions.

2. Observations and data analysis

2.1. Instruments: INTEGRAL and RXTE

INTEGRAL (Winkler et al. 2003) carries two main gamma ray instruments, the spectrometer *SPI* (20 keV–8 MeV, Vedrenne et al. 2003) and the imager *IBIS* (15 keV–10 MeV, Ubertini et al. 2003), as well as two monitoring instruments in the X-ray and optical ranges, *JEM-X* (3–35 keV, Lund et al. 2003) and *OMC* (Mas-Hesse et al. 2003).

RXTE (Bradt et al. 1993) carries three instruments: The Proportional Counter Array *PCA* (2–60 keV, Jahoda et al. 1996), the High Energy X-ray Timing Experiment *HEXTE* (20–200 keV, Rothschild et al. 1998) and the All-Sky Monitor *ASM* (2–10 keV, Levine et al. 1996).

INTEGRAL data were reduced using *OSA v5.1*. *IBIS (ISGRI)* spectral analysis was performed using alternative calibration files developed at *IFC-INAF* Palermo (see Mineo et al. 2006) and a response matrix calibrated with simultaneous Crab observations, which was in the same field of view as A 0535+26. For the spectral analysis we applied a systematic error of 3% to *JEM-X*. This has been evaluated on the basis of the Crab spectrum extracted for the same observation as A 0535+26, and agrees with the value suggested by Paizis et al. (2005). The analysis of *RXTE* data was performed using *FTOOLS 6.0.2*.

2.2. Observations

Figure 1 shows the *RXTE ASM* light curve of A 0535+26 during the August/September 2005 outburst. *INTEGRAL* observations were made close to the peak with an exposure time of 198.4 ks. The *RXTE* monitoring was performed between the 26th of August and the 24th of September 2005. In this paper we focus on observations performed during the peak of the outburst and its decline, for a total exposure time of 125.5 ks for *RXTE*. Table 1 shows a summary of the observations used in the analysis.

Table 1. Summary of *INTEGRAL* and *RXTE* observations used in our analysis. *RXTE* data are from 37 short observations. The start time of the first observation and the stop time of the last observation are given, as well as the total observation time.

Observation	start time-stop time (MJD)	duration (ks)
INTEGRAL		
31 Aug.–2 Sep. 2005	53613.46–53615.89	198.4
RXTE		
31 Aug.–24 Sep. 2005	53613.49–53637.84	125.5

3. Timing analysis

3.1. Pulse period search

Using epoch folding, we calculated the pulse period of A 0535+26 after barycentering the arrival times and correcting for the orbital effect. The new ephemeris of Finger et al. (2006) was used for the binary correction. To determine P and $\dot{P}$ with high accuracy, we divided the *INTEGRAL IBIS* observation into 27 intervals of ∼6 ks each and folded the light curve of each of those intervals over the period obtained from epoch folding. We then performed a phase connection analysis similar to Ferrigno et al. (2006). We found a period of $P = (103.39315 \pm 0.00005)$ s for MJD 53614.5137 and a formal (non-significant) value for a spin-up of $\dot{P} = (-3.7 \pm 2.0) \times 10^{-9}$ s s^{-1}.

3.2. Pulse profiles

Using the determined period, we folded *PCA* and *IBIS (ISGRI)* light curves extracted in different energy ranges. The resulting pulse profiles, which cover the energy range 1.75–200 keV, are presented in Fig. 2. Two pulse cycles are shown for clarity. Similar to other accreting pulsars, the source shows a complex profile in the low energy range (∼2–20 keV). A simpler double peak profile is observed from ∼15 keV to ∼60 keV. At higher energies the second peak is significantly reduced. The source is observed to pulsate up to ∼120 keV, while above 120 keV no modulation is detected. A detailed analysis of the energy dependent morphology of the pulse profiles is beyond the scope of this paper and will be presented in a forthcoming paper.

4. Spectral analysis

4.1. INTEGRAL

We extracted *INTEGRAL* phase averaged spectra for *JEM-X*, *IBIS (ISGRI)* and *SPI*. To model the continuum we used a power law with exponential cutoff (*XSPEC* `cutoffpl`). We also added to the model an Fe Kα fluorescence line at 6.4 keV and a blackbody component of $k_{\rm B}T \sim 1.2$ keV. When fitting this continuum to our data, two significant absorption-like features are seen in the residuals at $E_1 \sim 45$ keV and $E_2 \sim 100$ keV (see Fig. 3). We modeled these lines using Gaussian lines in absorption as described in Coburn et al. (2002). After the inclusion of the first line at $E \sim 45$ keV, $\chi^2_{\rm red}$ improves from 27.88 (for 218 d.o.f.) to $\chi^2_{\rm red} = 1.88$ (for 215 d.o.f.). The improvement in the fit when

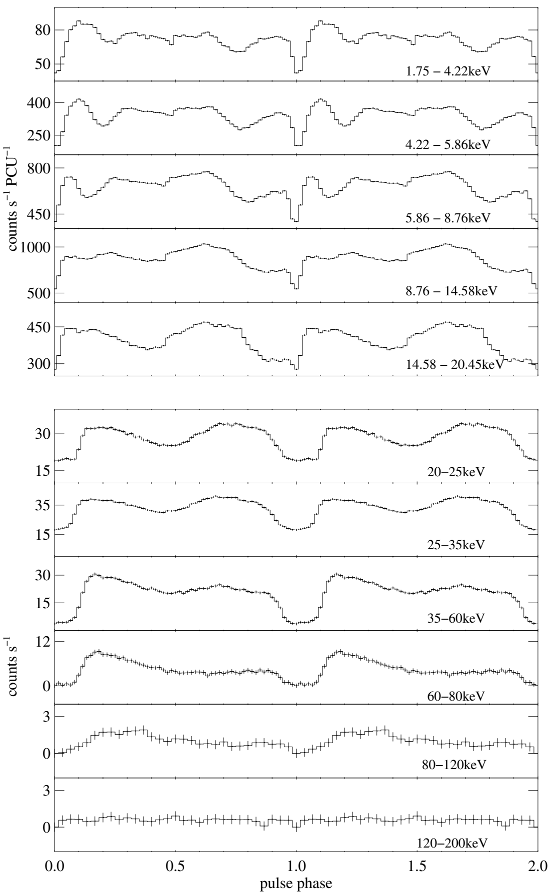

Fig. 2. *PCA* (*top*) and *IBIS (ISGRI)* (*bottom*) pulse profiles of A 0535+26.

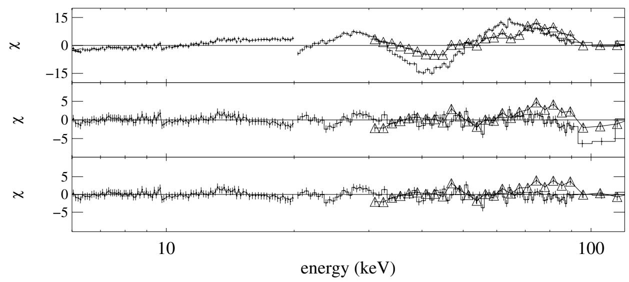

Fig. 3. *INTEGRAL* residuals, corresponding to *JEM-X* (6–20 keV), *IBIS* (20–120 keV) and *SPI* (30–120 keV, triangles). Top panel shows the residuals of a spectral fit without including cyclotron lines ($\chi^2_{\rm red}$ = 27.88/218 d.o.f.). Middle panel shows the residuals of a fit including one cyclotron line at ~45 keV ($\chi^2_{\rm red}$ = 1.88/215 d.o.f.). Bottom panel shows the residuals for a fit including two cyclotron lines at ~45 keV and ~100 keV ($\chi^2_{\rm red}$ = 1.37/212 d.o.f.).

including a second line is less dramatic. However, including the second line it further reduces the χ^2 to 1.37 (for 212 d.o.f.). The best fit parameters are reported in Table 2.

4.2. RXTE

RXTE phase averaged spectra for *PCA* and *HEXTE* data corresponding to different luminosity states of the source during the outburst were extracted (Table 2). We modeled the continuum using the same model as for *INTEGRAL* data, i.e., a power law with an exponential cutoff, as well as a blackbody component ($k_{\rm B}T$ ~ 1.2 keV) and an Fe Kα fluorescence line at 6.4 keV.

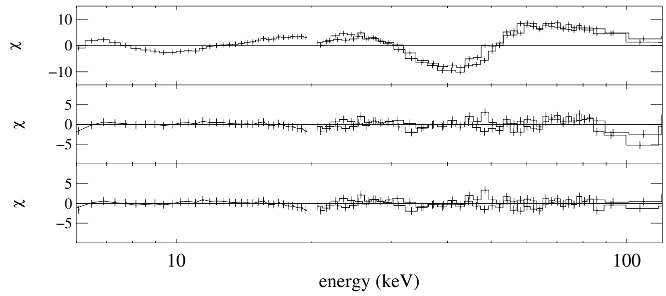

Fig. 4. *RXTE* residuals from observation performed on 1 September 2005. The upper panel shows the residuals of a fit without absorption lines ($\chi^2_{\rm red}$ = 14.24 for 204 d.o.f.). The middle panel shows the residuals of a fit including one cyclotron line at ~45 keV ($\chi^2_{\rm red}$ = 1.37 for 201 d.o.f.). The bottom pannel shows the residuals for a fit including two cyclotron lines at ~45 keV and ~100 keV ($\chi^2_{\rm red}$ = 1.03 for 198 d.o.f.).

For the observations with higher flux and good statistics, two Gaussian absorption lines at E_1 ~ 45 keV and E_2 ~ 100 keV were necessary in the model. In some of the observations only one line at E_1 ~ 45 keV was included in the model. For the observations during the decay of the outburst (low luminosity), no absorption lines were added to the model.

In Fig. 4 we show the residuals from fitting *RXTE* data from a ~12 ks observation close to the peak of the outburst, performed on 1 September 2005, where the two cyclotron lines were measured (see figure's caption for details).

Table 2 shows the best fit parameters for a selected sample of *RXTE* data. The sample corresponds to observations around the peak, where two lines are detected, and at the end of the outburst.

5. Summary and discussion

Based on *RXTE* and *INTEGRAL* observations of A 0535+26 during its August/September 2005 type I outburst, we detected two absorption-like features in the phase averaged spectrum of the source. These features can be interpreted as electron cyclotron resonance scattering features (CRSF): a fundamental line at E_1 ~ 45 keV and its first harmonic at E_2 ~ 100 keV. Our findings confirm previous results from Kendziorra et al. (1994) based on *TTM & HEXE* observations taken during the March/April 1989 giant outburst and firmly establish the fundamental line at E_1 ~ 45 keV, implying a magnetic field of ~4×10^{12} G, from $E_{\rm cyc} \simeq 11.6\, B_{12}$ keV. During the February 1994 giant outburst, observations from *OSSE* on *CGRO* clearly show an absorption feature at ~110 keV, but the presence of the fundamental line at ~55 keV was not clear (Grove et al. 1995). It was concluded that if the 55 keV line was present, its optical depth should have been smaller than that of the line at 110 keV, with a ratio <1:3.5 (at 95% confidence). Analysis of the August/September 2005 outburst shows a different relative strength of the lines, with the fundamental line deeper than in the previous giant outburst. The ratio of the depth between the fundamental and the first harmonic is ~1:2 for *INTEGRAL* and *RXTE* data. One possible explanation for these differences could be a different optical depth distribution of the electrons in the accretion column, hinting at a different geometry of the accretion column. Further analysis is ongoing to study the variability of the line parameters as a function of pulse phase.

We added to our model a single blackbody component with $k_{\rm B}T_{\rm bb}$ ~ 1.2 keV. Phase dependent blackbody components with $T_{\rm bb}$ ~ 10^{6-7} K have been observed in the spectra of several

Table 2. Best fit parameters from simultaneous observations of *INTEGRAL* and *RXTE*. *INTEGRAL* data corresponds to observations between 31 August and 2 September, close to the peak. The *RXTE* data corresponds to observations performed on 31 August, 1 and 2 September 2005, and one observation performed in the declining phase of the outburst on 10 September 2005. The model used for the continuum is the same for all luminosity states. Uncertainties are 90% confidence for one parameter of interest (corresponding to $\chi^2_{\rm min}$ + 2.7).

	α	$E_{\rm fold}$(keV)	E_1(keV)	σ_1(keV)	τ_1	E_2(keV)	σ_2(eV)	τ_2	$\chi^2_{\rm red}$/d.o.f.
INTEGRAL	$0.54^{+0.05}_{-0.05}$	$16.7^{+0.4}_{-0.4}$	$45.9^{+0.3}_{-0.3}$	$9.5^{+0.3}_{-0.3}$	$0.415^{+0.015}_{-0.015}$	102^{+4}_{-3}	8^{+3}_{-2}	$1.1^{+0.4}_{-0.3}$	1.37/212
RXTE 31 Aug.	$0.59^{+0.14}_{-0.01}$	$18.6^{+1.0}_{-0.6}$	$46.7^{+0.6}_{-0.7}$	$10.8^{+0.9}_{-0.8}$	$0.56^{+0.16}_{-0.05}$	103^{+6}_{-4}	11^{+4}_{-5}	$0.9^{+0.4}_{-0.3}$	1.12/360
RXTE 1 Sept.	$0.51^{+0.05}_{-0.03}$	$17.3^{+0.3}_{-0.2}$	$45.9^{+0.4}_{-0.3}$	$10.3^{+0.5}_{-0.4}$	$0.50^{+0.02}_{-0.02}$	103^{+3}_{-3}	8^{+2}_{-2}	$1.1^{+0.4}_{-0.3}$	1.02/360
RXTE 2 Sept.	$0.51^{+0.02}_{-0.04}$	$17.2^{+0.1}_{-0.3}$	$45.5^{+0.4}_{-0.4}$	$10.1^{+0.5}_{-0.4}$	$0.47^{+0.02}_{-0.02}$	105^{+5}_{-4}	9^{+4}_{-3}	$0.7^{+0.2}_{-0.2}$	1.11/360
RXTE 10 Sept.	$0.51^{+0.11}_{-0.07}$	$14.0^{+1.4}_{-0.8}$	–	–	–	–	–	–	0.94/372

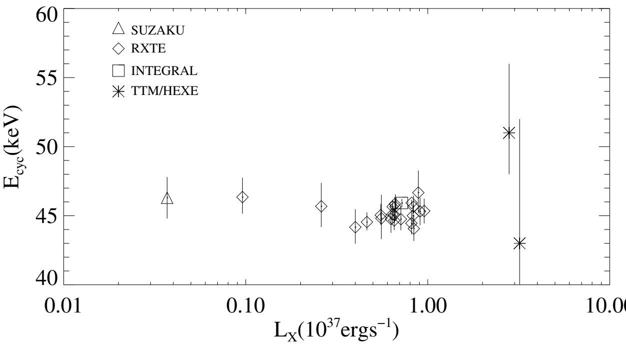

Fig. 5. Evolution of the energy of the fundamental line in different luminosity states in the 3–50 keV range for our *INTEGRAL* and *RXTE* values. We included data points from *Suzaku* (Terada et al. 2006) from the declining phase of the August/September 2005 outburst and values from *TTM/HEXE* (Kendziorra et al. 1994) from the March/April 1989 giant outburst.

accreting pulsars and are generally interpreted as due to the reprocessing of the hard component by an opaque shell located at the magnetosphere (Oosterbroek et al. 1997). However, it was recently shown by Becker & Wolff (2005) that blackbody-like components could emerge in the spectra of accreting X-ray pulsars at low energies. Phase resolved analysis will possibly distinguish between the two options.

Analysis of accreting pulsars with *Ginga* (Mihara et al. 2004) and more recently with *INTEGRAL* (Mowlavi et al. 2006) has shown that the CRSF energy centroid increases with the decrease of luminosity. This has been interpreted as due to a variation in the height of the CRSF forming region. On the other hand, a positive correlation between the energy of the fundamental line and the luminosity has been observed in GX 301-2 (La Barbera et al. 2005) and recently discovered by Staubert et al. (2006) in Her X-1, where it was quantitatively explained with the decreasing of the height of the line forming region with luminosity when the source is in the sub-Eddington accretion regime. The centroid energy of the fundamental CRSF versus luminosity is shown in Fig. 5 ($d \sim 2$ kpc; Steele et al. 1998). In Fig. 5 we include values from *Suzaku* observations of the declining phase of the outburst (Terada et al. 2006), as well as values from a *TTM & HEXE* observation of the April 1989 giant outburst (Kendziorra et al. 1994). Considering all data from *RXTE*, *INTEGRAL*, *Suzaku* and *TTM & HEXE*, no correlation is detected, suggesting that the line forming region does not vary with the luminosity of the system; further investigation is needed.

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