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 $F_{45-100}$ 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 103.3915(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 consists of an X-ray pulsar with a pulse period of $P = 103$ s in an eccentric orbit ($e \sim 0.47$, Finger et al. 1994a) of $P_{\text{orb}} \sim 111$ 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 $L_{(3-7)}$ 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 RXTE (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 $F_{(3-50)}$ keV $\sim 1.9 \times 10^{-6}$ erg cm$^{-2}$ s$^{-1}$ which, assuming $d \sim 2$ kpc, gives $L_{(3-50)}$ 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.
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 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.

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 $P$ 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 $P = (103.39315 ± 0.00005) \text{s}$ for MJD 53614.5137 and a formal (non-significant) value for a spin-up of $P = (−3.7 ± 2.0) \times 10^{-9} \text{s}^{-1}$.

Using the period obtained, 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 up 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.

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 $P$ 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 $P = (103.39315 ± 0.00005) \text{s}$ for MJD 53614.5137 and a formal (non-significant) value for a spin-up of $P = (−3.7 ± 2.0) \times 10^{-9} \text{s}^{-1}$.

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 up 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 cutoffp1). We also added to the model an Fe Kα fluorescence line at 6.4 keV and a blackbody component of $k_B T \sim 1.2 \text{keV}$. When fitting this continuum to our data, two significant absorption-like features are seen in the residuals at $E_1 \sim 45 \text{keV}$ and $E_2 \sim 100 \text{keV}$ (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 $E \sim 45 \text{keV}$, $\chi^2_{\text{red}}$ improves from 27.88 (for 218 d.o.f.) to $\chi^2_{\text{red}} = 1.88$ (for 215 d.o.f.). The improvement in the fit when
and \( 2.0 \sim 10 \) ff = \( \chi \) ff \observations taken during the March \sim 1.0 \sim 1 \) HEXTE \K \have been observed in the spectra of several \sim \sim \E \PCA \INTEGRAL \INTEGRAL / \the phase averaged spectrum of \( \TTM \simeq \sim \sim \) and \( \alpha \sim \sim \) \RXTE \sim \residuals, corresponding to \( \JEM-X \) (\( \alpha \sim \sim \G \), from \clearly show an absorption \data. One possible explana- \E \CGRO \1.5 \sim \sim \data. The sample corresponds to \observations around the \sim \sim \E \PCA < \sim \sim \HEXE \( 30–120 \) keV , triangles). Top panel shows \sim \sim \data corre- \to 1.37 (for 212 d.o.f.). The \sim \sim \E \OSSE \B / \PCA \( < \sim \sim \HEXE \) (\( 212 \) d.o.f.). The middle panel shows the residuals of a fit including one cyclotron line at \( \sim 45 \) keV (\( \chi_{\text{red}} = 1.37 \) for 201 d.o.f.). The bottom panel shows the residuals for a fit including two cyclotron lines at \( \sim 45 \) keV and \( \sim 100 \) keV (\( \chi_{\text{red}} = 1.03 \) for 198 d.o.f.).

For the \observations with higher flux and good statistics, two \Gaussian absorption lines at \( E_1 \sim 45 \) keV and \( E_2 \sim 100 \) keV \were necessary in the model. In some of the \observations only \one line at \( E_1 \sim 45 \) 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 \sim 12 \) ks \observation \close to the peak of the \outburst, \performed on 1 September 2005, where the \two cyclotron lines \were mea- \ured (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 the \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 \( E_1 \sim 45 \) keV \and its \first \harmonic at \( E_2 \sim 100 \) keV. \Our \findings \confirm \previous \results \from \Kendziorra \et al. (1994) based on \ITM \& \HEXE \observations \taken during the March/April 1989 \outburst \and \firmly establish the \fundamental \line at \( E_1 \sim 45 \) keV, \implying \a magnetic \field \of \sim 4 \times 10^{12} \) G, \from \( E_{\text{cyc}} \simeq 11.6 \) \( B_{\text{G}} \). \During the \February 1994 \giant \outburst, \observations \from \OSSE \on \CGRO \clearly \show an \absorption \feature \at \sim 110 \) keV, \but \the \presence \of \the \fundamental \line \at \sim 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 \( \text{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 \sim 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, \hiding \at \a \different \geometry \of \the \accretion \column. \Further \analysis is \ongoing \\to study \the \variability \of \the \line \parameters \as \a \func- tion \of \phase \phase.

We \added to \our \model \a \single \blackbody \component \with \( k_{\text{bb}} T_{\text{bb}} \sim 1.2 \) keV. \Phase \dependent \blackbody \components \with \( T_{\text{bb}} \sim 10^{6–7} \) K \have been \observed \in \the \spectra \of \several

\begin{itemize}
  \item \textbf{PCA} \( \text{(top)} \) \and \text{IBIS (ISGRI)} \( \text{(bottom)} \) \pulse profiles of \A 0535+26.
  \item \textbf{INTEGRAL} \residuals, \corresponding \to \text{JEM-X} \( (6–20 \) keV), \text{IBIS} \( (20–120 \) keV) \and \text{SPI} \( (30–120 \) keV, triangles). \Top \panel shows the \residuals of a \spectral \\fit without \including \cyclotron \lines \( \chi_{\text{red}} = 27.88/218 \) d.o.f.). \Middle \panel shows the \residuals of a \fit \including \one \cyclotron \line \at \sim 45 \) keV \( \chi_{\text{red}} = 1.88/215 \) d.o.f.). \Bottom \panel shows the \residuals \for a \fit \including \two \cyclotron \lines \at \sim 45 \) keV \and \sim 100 \) keV \( \chi_{\text{red}} = 1.37/212 \) d.o.f.).
\end{itemize}
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 \( \chi^2_{\text{min}} + 2.7 \)).

|        | \( \alpha \) | \( E_{\text{fold}} \) (keV) | \( E_1 \) (keV) | \( \sigma_1 \) (keV) | \( r_1 \) | \( E_2 \) (keV) | \( \sigma_2 \) (eV) | \( r_2 \) | \( \chi^2 / \text{d.o.f.} \) |
|--------|-------------|----------------|---------------|----------------|------|----------------|----------------|------|----------------|
| INTEGRAL | 0.54\( \pm 0.05 \) | 16.7 \( \pm 0.4 \) | 45.9 \( \pm 0.3 \) | 9.7 \( \pm 0.3 \) | 0.41 \( \pm 0.05 \) | 102 \( \pm 3 \) | 8 \( \pm 2 \) | 1.15 \( \pm 0.4 \) | 1.37 / 212 |
| RXTE 31 Aug. | 0.59\( \pm 0.01 \) | 18.6 \( \pm 0.6 \) | 46.7 \( \pm 0.7 \) | 10.8 \( \pm 0.8 \) | 0.56 \( \pm 0.05 \) | 103 \( \pm 3 \) | 11 \( \pm 5 \) | 0.9 \( \pm 0.3 \) | 1.12 / 360 |
| RXTE 1 Sept. | 0.51\( \pm 0.03 \) | 17.3 \( \pm 0.2 \) | 45.9 \( \pm 0.4 \) | 10.7 \( \pm 0.5 \) | 0.50 \( \pm 0.02 \) | 103 \( \pm 3 \) | 8 \( \pm 2 \) | 1.1 \( \pm 0.4 \) | 1.02 / 360 |
| RXTE 2 Sept. | 0.51\( \pm 0.02 \) | 17.2 \( \pm 0.1 \) | 45.5 \( \pm 0.4 \) | 10.1 \( \pm 0.5 \) | 0.47 \( \pm 0.02 \) | 105 \( \pm 3 \) | 9 \( \pm 4 \) | 0.7 \( \pm 0.2 \) | 1.11 / 360 |
| RXTE 10 Sept. | 0.51\( \pm 0.02 \) | 14.0 \( \pm 0.4 \) | 45.4 \( \pm 0.4 \) | 9.8 \( \pm 0.4 \) | 0.40 \( \pm 0.02 \) | 103 \( \pm 3 \) | 8 \( \pm 4 \) | 1.0 \( \pm 0.4 \) | 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.

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