PULSE PERIOD HISTORY AND PHASE RESOLVED SPECTRA OF 1A 0535+262

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ABSTRACT

The Be/X-ray binary 1A 0535+262 was discovered in 1975 during a giant outburst. Afterwards it has shown periods of quiescence (flux below 10 mCrab), normal outbursts (10 mCrab-1Crab) and occasionally giant outbursts (several Crab). Ending 11 years of quiescence, the last giant outburst took place in May/June 2005, but the source was too close to the Sun to be observed by most satellites. A subsequent normal outburst took place in August 2005, which was observed by *INTEGRAL* and *RXTE* TOO observations. Based on *INTEGRAL* data, we present results on the long term pulse period history of the source, on their energy dependent pulse profiles and on phase resolved spectra.

Key words: neutron stars; X-ray binaries; X-ray pulsars; 1A 0535+262.

1. INTRODUCTION

Since its discovery in 1975 [1], the Be/X-ray binary 1A 0535+262 has been intensely studied. Further details may be found in a review by [2]. The source has shown giant outbursts in April/May 1975 [1], October 1980 [3], March/April 1989 [4], February 1994 [5], and in May/June 2005 [6]. Then the source showed a normal outburst in August/September 2005, observed by *INTEGRAL* and *RXTE* . During this outbusrt, the averge flux was 300 mCrab in the energy range 5-100 keV [7]. The last normal outburst took place in December 2005 [8]. Fig. 1 shows the *RXTE ASM* long term light curve of the source during the last three outbursts. In this paper, we present preliminary results on the timing and spectral behaviour of the source based on *INTEGRAL IBIS (ISGRI)* data from the August/September 2005 outburst. All data were reduced and analysed using *INTEGRAL* OSA v5.1. Pulse phase resolved spectroscopy was performed using additionally the software provided by IASF/INAF Palermo.

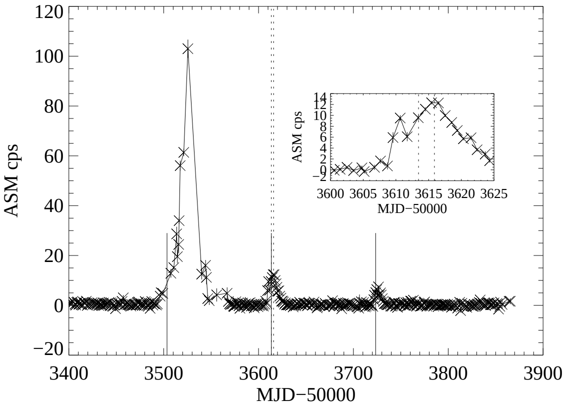

Figure 1. RXTE ASM long term light curve of the last three outbursts. The dotted lines indicate the time of our INTEGRAL observation, the inset gives a blow-up. The vertical lines indicate the times of periastron passage.

2. PULSE PERIOD HISTORY AND PULSE PROFILES

Using epoch folding techniques, we calculated the pulse period of the source, after applying barycentric correction and a correction for the binary orbit. The orbital parameters were taken from [9] and [10]. In order to find a $\dot{P}$, we divided the observation into 27 intervals of $\sim$ 6ks each. We folded the light curve of each of those intervals over the period obtained from epoch folding, and checked that the pulse profiles obtained are shifted by an integer number of periods. We find a constant period of P=103.3920 $\pm$ 0.0004s for MJD 53613.460475. For comparison, in Fig. 2 we plot the pulse period history of the source since its first determination in 1975. Using the above pulse period obtained, we folded the light curves for *IBIS (ISGRI)* data in different energy ranges. The resulting pulse profiles are plotted in Fig. 3. Two pulse phases are shown for clarity. A double peak pattern is seen up to at least 60 keV, while at higher energies one of the peaks appears to be strongly reduced. The source is observed to pulsate up to $\sim$ 120 keV. It is evident form Fig. 3 the strong variation of the pulsed fraction with the energy.

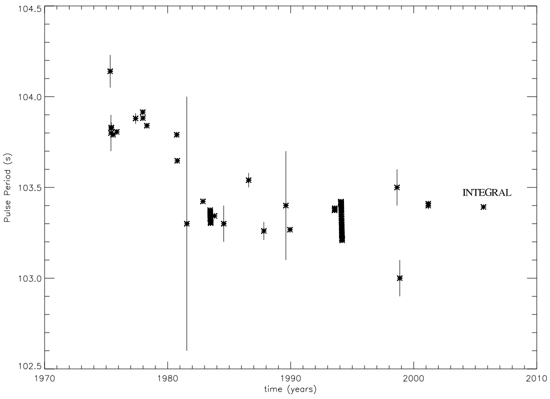

Figure 2. Pulse period history of 1A 0535+262.

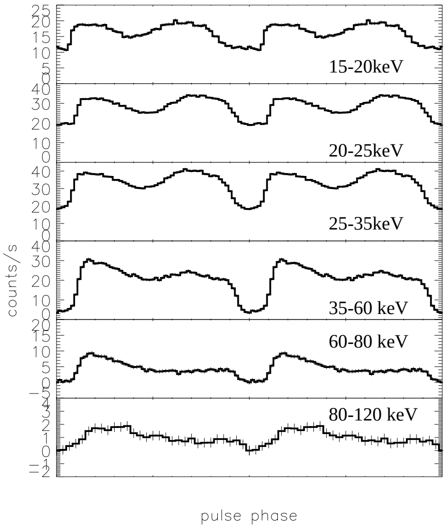

Figure 3. 1A 0535+262 IBIS (ISGRI) pulse profiles.

3. PHASE AVERAGE SPECTRA

We extracted the phase average spectra for *IBIS (ISGRI)* . To model the continuum we use a powerlaw with a high energy cutoff (*XSPEC* HighECut), freezing the photon index to $\alpha \sim 1$ and the cutoff energy to $E_c \sim 20$ keV (theses values, typical for accreting pulsars, were taken from the literature, see [11]). When fitting this continuum we detected two absorption like features in the residuals, that we interpret as cyclotron resonance scattering features. We modeled those features using Gaussian lines in absorption [12]. The $\chi^2_{\rm red}$ obtained for a fit without absoprtion lines is 32.14 for 132 d.o.f. Including one Gaussian absorption line at ~ 45keV the $\chi^2_{\rm red}$ improves to 3.315 for 129 d.o.f. By including two Gaussian absoprtion lines at ~ 45keV and ~ 100keV, the $\chi^2_{\rm red}$ further reduces to 1.7 for 126 d.o.f. We therefore included in our model two absorption lines (see Fig. 4). The best fit parameters for the lines are listed in Table 1.

Table 1. Parameters of the cyclotron lines obtained from the phase average spectra. Uncertainties are 90 % confidence for one parameter of interest ($\chi^2_{min} + 2.706$).

$E_1(keV)$	$46.1^{+0.5}_{-0.5}$
$\sigma_1(keV)$	8^{+1}_{-3}
τ_1	$0.35^{+0.03}_{-0.01}$
$E_2(keV)$	106^{+7}_{-4}
$\sigma_2(keV)$	12^{+3}_{-2}
τ_2	$1.1^{+0.3}_{-0.2}$
$\chi^2_{\rm red}$/dof	$1.7/126$

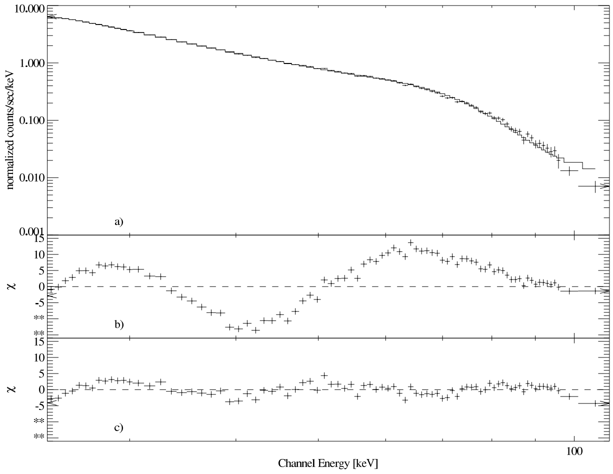

Figure 4. (a) IBIS (ISGRI) phase average spectra and model (powerlaw with a high energy cutoff and two cyclotron lines at $\sim$ 45 keV and $\sim$ 100 keV), (b) residuals for a fit without cyclotron lines ($\chi^2_{\rm red}$=32.138/132dof) (c) residuals for a fit including two cyclotron lines ($\chi^2_{\rm red}$=1.7/126dof).

4. PHASE RESOLVED SPECTRA

To perform phase resolved spectroscopy we divided the pulse profile into six phase intervals: main peak rise (MPR), main peak fall (MPF), secondary peak rise (SPR), secondary peak fall (SPF), and the two minima (min1, min2) (Fig. 5). *IBIS (ISGRI)* spectra were accumulated for each phase interval (Fig. 6). To model the continuum, we again used a powerlaw with a high energy cutoff (*XSPEC* HighECut) in the same way as we did for phase average spectroscopy. We clearly detect one cyclotron resonance scattering feature at $\sim$ 45 keV in the residuals of all phase intervals. Furthermore, we find in most phases ('SPR', 'SPF', 'MPR', 'MPF') a second cyclotron line at $\sim$ 100 keV. For the phase intervals 'SPR', 'SPF', 'MPR' we freeze the energy of the second line to 100 keV for the fitting. For the phase interval 'MPF' we can fit the two lines well. The best fit parameters are listed in Table 2. Fig. 7(a) shows the spectrum and model for the main peak fall 'MPF' (powerlaw with a

Table 2. Best fit parameters for the cyclotron lines. From these preliminary results, the centroid of the fundamental cyclotron line seems to be rather constant within the phase. However the width and depth of the line changes with phase.

	min1	**SPR**	**SPF**	**min2**	**MPR**	**MPF**
$E_1(keV)$	$47.2^{+0.9}_{-0.9}$	$47.5^{+0.9}_{-0.8}$	$45.9^{+0.6}_{-0.}$	$45.7^{+1.3}_{-1.2}$	$44.3^{+0.9}_{-0.7}$	$45.8^{+0.6}_{-0.5}$
$\sigma_1(keV)$	$5.0^{+0.9}_{-0.8}$	$7.1^{+1.0}_{-0.9}$	$8.8^{+0.7}_{-0.7}$	$7.8^{+0.9}_{-0.9}$	$9.5^{+0.9}_{-0.8}$	$9.5^{+0.7}_{-0.6}$
τ_1	$0.22^{+0.03}_{-0.03}$	$0.34^{+0.05}_{-0.04}$	$0.58^{+0.07}_{-0.04}$	$0.70^{+0.09}_{-0.09}$	$0.36^{+0.03}_{-0.03}$	$0.36^{+0.03}_{-0.02}$
$E_2(keV)$	–	100	100	–	100	102^{+4}_{-3}
$\sigma_2(keV)$	–	24^{+4}_{-3}	27^{+3}_{-2}	–	10^{+2}_{-2}	10^{+3}_{-2}
τ_2	–	$1.1^{+0.3}_{-0.2}$	$1.6^{+0.3}_{-0.2}$	–	$1.3^{+0.6}_{-0.3}$	$1.4^{+0.4}_{-0.3}$
χ^2_{red}/dof	1.09/129	1.02/127	1.4/127	1.4/129	1.40/127	1.09/126

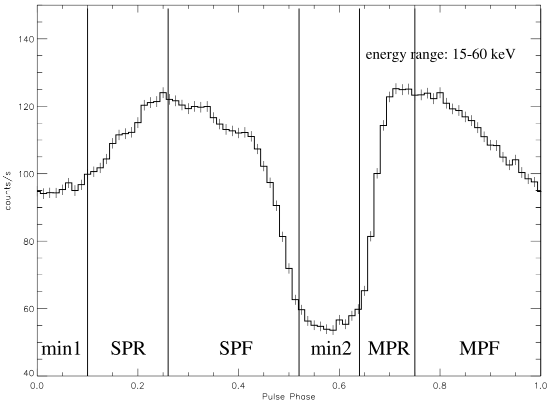

Figure 5. phase selection for phase resolved spectroscopy.

high energy cutoff and two cyclotron lines at ~ 45 keV and ~ 100 keV). Fig. 7(b) shows the residuals for a fit without the cyclotron lines. Fig. 7(c) shows the residuals for a fit including two cyclotron lines ($\chi^2 = 1.16$).

5. SUMMARY

In this poster we show some first results of our analysis of the *INTEGRAL* 1A 0535+262 data from the August/September 2005 outburst. The source is found to pulsate up to 120 keV and energy dependent pulse profiles are observed. We also detect the presence of two phase dependent cyclotron lines at $\sim$ 45 keV and $\sim$ 100 keV in the hard X-ray spectrum of the source. This therefore confirms previous results by Kendziorra et al. [11] based on *TTM* & *HEXE* data taken during the March/April 1989 giant outburst. We wish to outline however that observation from *OSSE* on *CGRO* during the February 1994 giant outburst clearly detected only the 110 keV line. The presence of the fundamental line was not clear, but it was concluded that if the line was present, its optical depth should be significantly smaller than that of the 110 keV line [13]. Based on our results we can estimate from the fundamental line at ~ 45 keV the magnetic field of the source to be ~ 4 x10^{12} G. Further detailed analysis of this outburst is ongoing. The next step will be to try different models for fitting the broad band continuum making use of observational data from *JEM-X* and *SPI*.

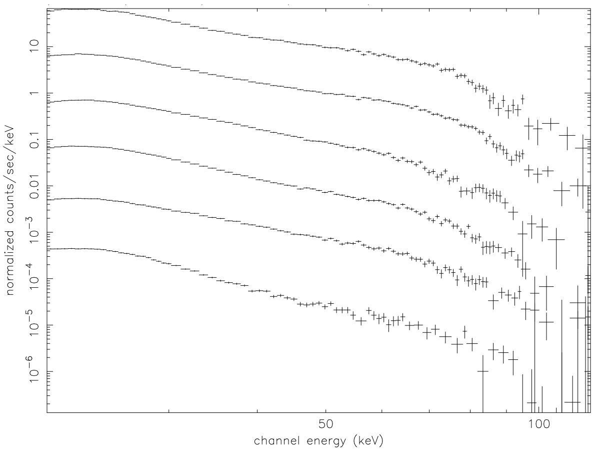

Figure 6. Phase resolved spectra for all phases (from top spectrum to bottom, corresponds to 'MPR', 'MPF', 'SPR', 'SPF', 'min1', 'min2', with normalisation factors for plotting 10, 1, 10^{-1}, 10^{-2}, 10^{-3}, 10^{-4} respectively). A clear variation with phase is seen.

REFERENCES

[1] Rosenberg, F.D. et al., *Nature*, 256, 628, 1975

[2] Giovannelli,F. & Graziati,L. S.,*Space Science Reviews*, 59, 1, 1992

[3] Nagase,F. et al., *ApJ*, 263, 814, 1982

[4] Sunyaev,*IAU Circ*, 4769, 1982

[5] Finger,M.H. et al., *IAU Circ*, 5931,1994

[6] Tueller, J. *ATel*, 504, 2005

[7] Kretschmar,P.,*Proceedings of "The X-ray Universe 2005"*, 2005

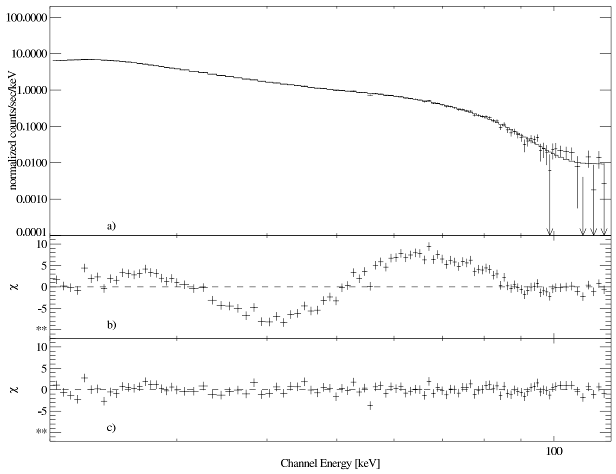

Figure 7. (a) IBIS (ISGRI) spectrum and model and for the main peak fall 'MPF' (power law with a high energy cutoff and two cyclotron lines at ~ 45 *keV and* ~ 100 *keV). (b) residuals for a fit without the cyclotron lines. (c) residuals for a fit including two cyclotron lines (*$\chi^2 = 1.16$*).*

[8] Finger,M.H. et al., *ATel*, 676, 2005

[9] Finger,M.H. et al., *ApJ*, 459, 288, 1996

[10] Coe,M.J. et al., *MNRAS*,368,447-453, 2006.

[11] Kendziorra,E. et al., *A&A*, 291, L31, 1994

[12] Coburn, W. et al., *ApJ*, 580, 394, 2002

[13] Grove, J.E et al., *ApJ*, 438L, 25G, 1995