An unexpected outburst from A0535+262

A. B. Hill,* A. J. Bird, A. J. Dean, V. A. McBride, V. Sguera,† D. J. Clark, M. Molina, S. Scaringi and S. E. Shaw

School of Physics & Astronomy, University of Southampton, Highfield, Southampton SO17 1BJ

Accepted 2007 August 6. Received 2007 August 2; in original form 2007 June 8

ABSTRACT

A0535+262 is a transient Be/X-ray binary system which was in a quiescent phase from 1994 to 2005. In this paper we report on the timing and spectral properties of the INTEGRAL detection of the source in 2003 October. The source is detected for ~6000 s in the 18–100 keV energy band at a luminosity of ~3.8 × 10^{37} \text{erg s}^{-1}; this is compatible with the high end of the range of luminosities expected for quiescent emission. The system is observed to be outside of the centrifugal inhibition regime and pulsations are detected with periodicity, P = 103.7 ± 0.1 s. An examination of the pulse history of the source shows that it had been in a constant state of spin-down since it entered the quiescent phase in 1994. The rate of spin-down implies the consistent presence of an accretion disc supplying torques to the pulsar. The observations show that the system is still active and highly variable even in the absence of recent Type I or Type II X-ray outbursts.

Key words: stars: neutron – pulsars: individual: A0535+262 – gamma-rays: observations – X-rays: binaries.

1 INTRODUCTION

A0535+262 is a high-mass X-ray binary system comprising a neutron star primary and an O9.7IIIe donor star (Giangrande et al. 1980). A0535+262 is an example of the Be X-ray binary subclass. Be/X-ray binaries show two types of X-ray outbursts which are regularly referred to as Type I and Type II (Stella, White & Rosner 1986). Type I outbursts are associated with the time of periastron passage as the neutron star passes closest to the Be donor. The X-ray luminosity is typically 10^{36}–10^{37} \text{erg s}^{-1} and they last for several days. Type II outbursts can occur at any phase of the orbit, they have X-ray luminosities of >10^{37} \text{erg s}^{-1} and they can last for several weeks (Negueruela 1998).

A0535+262 was discovered by Ariel V during a large Type II outburst in 1975 (Coe et al. 1975; Rosenberg et al. 1975). Since then the source has been observed to undergo numerous outbursts; however, there were no reported detections of X-ray outburst activity from 1994 to 2005 (Kretschmar et al. 2005; Coe et al. 2006). The source reappeared in a Type II outburst in 2005 May/June and was detected by Swift (Treuher et al. 2005) and RHESSI (Smith et al. 2005). It was subsequently seen to undergo a Type I outburst in 2005 August (Kretschmar et al. 2005; Caballero et al. 2007).

The orbital parameters of the system were first determined by Finger, Wilson & Harmon (1996) following the 1994 outburst:

(i) \( P_{\text{orbital}} = 110.3 \pm 0.3 \text{ d} \);
(ii) \( a_\text{s} \sin i = 267 \pm 13 \text{ light-second} \);
(iii) \( e = 0.47 \pm 0.02 \).

The orbital ephemeris, which corresponds to the time of periastron, and the orbital period have been more recently estimated by Coe et al. (2006):

(i) \( \tau_{\text{periastron}} = 245 0094 \pm 1 \text{ JD} \);
(ii) \( P_{\text{orbital}} = 110.0 \pm 0.5 \text{ d} \).

Measurements of the cyclotron features by RXTE and INTEGRAL during the 2005 outburst estimated the magnetic field strength of the neutron star as \(~4 \times 10^{12} \text{ G}\) (Caballero et al. 2007). A distance to the source of 2 kpc was estimated by Steele et al. (1998) through the observation of the spectral type and the reddening of the optical counterpart of A0535+262.

A number of observations have been made of A0535+262 whilst it is in the quiescent phase. EXOSAT observations were made in 1985–1986 between outbursts by Motch et al. (1991); pulsations were detected and a luminosity of 0.7–1.4 \( \times 10^{35} \text{ erg s}^{-1} \) for a source at 2 kpc was measured. During the 1994–2005 quiescent phase the system was observed by the RXTE-PCA instrument in 1998 and by BeppoSAX in 2000 (Negueruela et al. 2000; Mukherjee & Paul 2005); both telescopes reported luminosities of \(~1.5–4.5 \times 10^{33} \text{ erg s}^{-1} \) which indicated the system was in the centrifugally inhibited regime despite both telescopes detecting pulsations in some of their observations. In this paper we present soft γ-ray observations of A0535+262 during a flare whilst the source was in a quiescent state. A timing and spectral analysis is performed on the
INTEGRAL data and the results interpreted in the context of previous observations. The long-term pulse history of the source is discussed.

2 INTEGRAL DATA

Since its launch in 2002 October, INTEGRAL (the INTeRnational Gamma-Ray Astrophysics Laboratory) has been performing regular scans of the Galactic plane. The IBIS imaging instrument is sensitive in the 15 keV–10 MeV energy range (Ubertini et al. 2003) and includes the INTEGRAL Soft Gamma-Ray Imager (ISGRI). Recently, the IBIS Survey Team released the 3rd IBIS/ISGRI soft γ-ray survey catalogue comprising 40 Ms of data from the first 3.5 yr of core and public programme observations (Bird et al. 2007). Included in this catalogue was the first announced detection of A0535+262 by the IBIS Survey Team; they observed that it was seen at 9.4σ in their all sky mosaic with an average flux of 3.0 ± 0.3 mCrab in the 20–40 keV energy band and an exposure of ∼400 ks. However, the data set used by the IBIS Survey Team did not include any observations of A0535+262 during the 2005 outbursts.

As A0535+262 is known to be a transient source we searched back through the INTEGRAL data archive to identify any outbursts in the catalogue 3 data set. The INTEGRAL data are organized in short pointings, known as science windows, of approximately 2000 s. The source was only significantly detected in three science windows during INTEGRAL orbit number 127; this corresponds to the source being detected on 2003 October 28 from 09:45:10 to 12:39:54 UT. Prior and post to this the source was outside of the field of view of the telescope. During the observation and afterwards there was increased solar activity; an X17 solar flare on October 28 and an X10 flare on October 29 (Hurford et al. 2006). The flare on 2003 October 28 began at 09:41 UT, was at maximum at 11:10 UT and ended around 11:24 UT; SPI, the spectrometer onboard INTEGRAL, showed a strong increase in counting rate at ∼11:02 (Kiener et al. 2006). Consequently there is significant background noise, especially in the latter half of the observation. After the end of the observation there are no further observations of this field.

3 ANALYSIS

The IBIS/ISGRI data were analysed using the Offline Standard Analysis, OSA, software version 5.1. The 20–40 keV IBIS/ISGRI light curve of A0535+262 is shown in Fig. 1. It is clear that the quality of the data during the latter half of the observation has been compromised by the increased background resulting from the solar flare activity. This is also evident in the increasing amount of instrument dead time throughout the observation. Fig. 1 does not show any general trend with time such that there is no indication whether the source is beginning or ending an outburst. The lack of data prior to and post of the observation means that we cannot place any real limits on the outburst duration. The IBIS/ISGRI mosaic of the three science windows detected A0535+262 with a flux of 62 ± 3 mCrab (a 9σ detection) in the 20–40 keV band and a 32 ± 5 mCrab (a 6σ detection) in the 40–60 keV energy band.

An investigation of the RXTE All Sky Monitor (ASM) light curve of A0535+262 shows no observations of the source were made between 04:48 and 19:12 UTC on 2003 October 28. The few observations made prior and post of these times show no clear indication of any outbursting behaviour. The sparsity of the ASM data around the INTEGRAL observation is potentially due to the high solar activity.

![Figure 1. The IBIS/ISGRI 20–40 keV 100-s binned light curve of A0535+262 on 2003 October 28. The poor data quality in the latter half of the light curve is attributed to contamination from solar flare activity.](https://example.com/image1)

![Figure 2. The Lomb–Scargle periodogram of the 1-s binned light curve of A0535+262. The dashed line represents the 99.9 per cent significance level. There is a clear spike at ∼9.64 × 10⁻³ Hz.](https://example.com/image2)

3.1 Timing analysis

A light curve with 1-s binning was generated using the OSA light tool in the 20–40 and 40–60 keV energy bands. The light curves were barycentre corrected for the orbital motion of the INTEGRAL satellite using the OSA barycentric command. The 1-s binned 20–40 keV light curve was analysed for any periodic signals using the Lomb–Scargle periodogram method by means of the fast implementation (Scargle 1982; Press & Rybicki 1989). The resulting power spectrum is shown in Fig. 2; a peak is clearly evident at 0.00964 Hz with a power of ∼15.1. This corresponds to a period of 103.7 s; A0535+262 has been observed to have a spin period of between 103 and 104 s (Mukherjee & Paul 2005).

Having confirmed the INTEGRAL source as A0535+262 the light curve was corrected for the orbital motion of the neutron star around the donor using the orbital parameters of Finger et al. (1996) and the outburst ephemeris of Coe et al. (2006). The observation occurred at an orbital phase 0.81 ± 0.07 when the neutron star was moving perpendicular to the line of sight. The timing analysis was then reperformed and a series of Monte Carlo methods used to verify the periodicity detection. The spin period is measured to be 103.7 ± 0.1 s; the period error is calculated using the method of Horne & Baliunas (1986) and is confirmed using the bootstrap method of Kawano & Higuchi (1995). To confirm the significance of the Lomb–Scargle peak a randomization test was performed.
The 18–100 kev IBIS/ISGRI spectrum was fitted using the XSPEC software, version 12.3, a systematic error of 2 per cent was included. The best fit was obtained by an absorbed thermal bremsstrahlung model (see Table 1).

| Parameter          | Power law | Thermal bremsstrahlung |
|--------------------|-----------|------------------------|
| Normalization      | $8.0^{+13}_{-5}$ | $25^{+0.08}_{-0.06}$ |
| Photon index       | $2.9 \pm 0.3$    | $\gamma$               |
| $kT$               | $23^{+4}_{-3}$   | $23^{+5}_{-4}$ keV      |
| $\chi^2$/d.o.f.    | 31.1/25      | 29.2/25                |

(Hill et al. 2005). The 1-s binned light curve was randomized and the resulting periodogram inspected; 200 000 light curves were simulated and indicated that a Lomb–Scargle power of 15.1 represented a 5.2$\sigma$ detection of these pulsations.

3.2 Spectral analysis

Using the standard XSPEC software, a spectrum was extracted from the IBIS/ISGRI data. Unfortunately, A0535+262 was outside of the field of view of the INTEGRAL X-ray monitor, JEM-X, and hence only the IBIS/ISGRI spectrum was available for analysis. The 18–100 keV IBIS/ISGRI spectrum was fitted using the XSPEC software, version 12.3, a systematic error of 2 per cent was included. The best fit was obtained by an absorbed thermal bremsstrahlung model ($\chi^2 = 1.17$) with $kT = 23^{+4}_{-3}$ keV (see Fig. 3); however, an absorbed simple power law provided a reasonable fit ($\chi^2 = 1.24$). In both cases the absorption was fixed to the expected Galactic line-of-sight column density of $0.6 \times 10^{22}$ cm$^{-2}$. The results of the fits are shown in Table 1. The 18–100 keV flux for the source is $\sim 7.9 \times 10^{-10}$ erg cm$^{-2}$ s$^{-1}$.

4 DISCUSSION

It was believed that the A0535+262 system had been in a period of inactivity for the 10 yr prior to the 2005 outburst (Coe et al. 2006). In the 1994–2005 period a number of X-ray observations were made of the system whilst it was in quiescence. These include the observations made by the RXTE-PCA instrument in 1998 August and November which detected the source at a luminosity of 0.2–4.5 $\times 10^{35}$ erg s$^{-1}$ (Negueruela et al. 2000). The luminosity of the source at this time was so low as to indicate that the source had entered the centrifugal inhibition phase despite the detection of pulsations.

Observations by BeppoSAX in 2000 September and October and 2001 March also observed the source during a state of very low luminosity, 1.5–4.0 $\times 10^{35}$ erg s$^{-1}$ and again detected pulsations (Mukherjee & Paul 2005).

Despite a significant level of exposure on this region of the sky, $\sim 400$ ks, IBIS/ISGRI only detects A0535+262 on one occasion for a duration of $\sim 6$ ks at a level of $\sim 62$ mCrab in the 20–40 keV energy band; this indicates that IBIS/ISGRI observed some level of flaring behaviour. No other X-ray instrument reports a detection at this time; however, this may be attributable to the high level of solar activity which occurred. The time of the IBIS/ISGRI detection corresponds to a phase of $0.81 \pm 0.07$ using the ephemeris of Coe et al. (2006) and orbital period of Finger et al. (1996); this is $\sim 21$ d prior to periastron and is somewhat early to be a Type I outburst. However, the calculated phase is within 3$\sigma$ of periastron and Be X-ray binary systems have been known to undergo Type I outbursts prior to and post periastron. EXO 2030+375, for example, has been seen to outburst between 4 d prior to and 6 d post periastron (phase 0.91 and 0.09, respectively) in its $\sim 46$ d orbit (Wilson et al. 2002). This shift is explained by a density perturbation in the Be star’s equatorial disc. Coe et al. (2006) show that the Hα profiles of A0535+262 in 2002 December and 2005 March exhibit some asymmetry in the double peaked structure which may indicate a density perturbation in the Be disc; density perturbations in the disc of A0535+262 have previously been reported by Negueruela et al. (1998). However, in 2003 at the time of the INTEGRAL observation, (Coe et al. 2006) estimate the Be disc size to be at the 7:1 resonance radius of the model of Okazaki & Negueruela (2001). For a Type I outburst to occur the neutron star must accrete matter through Roche lobe overflow, this is possible when the circumstellar disc reaches the 4:1 resonance radius, which in the case of A0535+262 did not happen until early 2005 (Okazaki & Negueruela 2001; Coe et al. 2006).

It is possible that the activity observed by IBIS occurs each periastron passage and that it has not previously been noticed because it is short lived and requires a high-sensitivity instrument to be able to look at it. Looking through the INTEGRAL archive we note that A0535+262 has been observed on numerous other occasions by INTEGRAL between 2003 and 2005 and in two additional instances the pointings coincided with a periastron passage; however, in neither of these instances there was a significant detection of A0535+262 made by INTEGRAL. Analysis of the X-ray spectra during 10 yr of quiescence of A0535+262 by Coe et al. (2006) finds a modulation in the X-ray flux on the orbital period with maximum flux at periastron.

The flux of the source is measured as $7.9 \times 10^{-10}$ erg cm$^{-2}$ s$^{-1}$ in the 18–100 keV band. Taking a distance of 2 kpc (Steele et al. 1998) implies a luminosity of $\sim 3.8 \times 10^{35}$ erg s$^{-1}$. This luminosity is at the lower end of what could be expected of a Type I outburst which have typical luminosities of $\sim 10^{39}$ erg s$^{-1}$ and is vastly underluminous for a Type II outburst which is typically in excess of $10^{37}$ erg s$^{-1}$. Earlier estimates of the source distance range from 1.3 to 2.4 kpc (Steele et al. 1998); within this range the source is still underluminous for either Type I or Type II bursts. Additionally, Type II outbursts typically last for approximately a month, consequently we would expect detections by other instruments despite the high solar activity if this were an example of a Type II outburst. Whilst the luminosity of the source is compatible with a Type I outburst the time of outburst does not correspond to the periastron passage. As discussed above this may suggest that the source activity is not attributable to a Type I outburst. We suggest that the INTEGRAL detection may have been a brief flare during the quiescent phase. This could potentially have
been triggered by an increased density of the material thrown out by the stellar wind of the Be star.

Assuming an efficiency $\eta = 1$ in the conversion of gravitational energy into luminosity then we can calculate the mass accretion rate:

$$\dot{m} = 2.0 \times 10^{15} \text{g s}^{-1}$$
$$= 3.2 \times 10^{-11} \text{M}_\odot \text{yr}^{-1}.$$  

The magnetic field strength of the neutron star in A0535+262 is $\sim 4 \times 10^{12}$ G (Caballero et al. 2007). For the known magnetic field strength, the mass accretion rate and the spin period of the pulsar the corotation radius is estimated using the formulation of Stella et al. (1986):

$$r_{\text{co}} \sim 3.8 \times 10^{9} \text{cm}$$

and the magnetospheric radius is estimated using the formulation of Frank, King & Raine (2002):

$$r_{\text{m}} \sim 1.5 \times 10^{9} \text{cm}.$$  

The corotation radius defines the distance at which the neutron star rotation velocity is equal to the Keplerian velocity. The magnetospheric radius defines the region in which the magnetic field strongly affects the dynamical properties of infalling material. If the magnetospheric radius is larger than the corotation radius, then accreted material is stopped at the magnetospheric boundary and may be ejected beyond the accretion radius via the propeller effect; this is known as the centrifugal inhibition regime.

As $r_{\text{co}} > r_{\text{m}}$ the pulsar can be expected to be outside of the centrifugally inhibited regime and consequently should exhibit X-ray pulsations. However, our estimates of the magnetospheric and corotation radii are within a factor of 2 indicating that the source may have recently transitioned from the centrifugally inhibited regime. However, there are a number of uncertainties in the calculation of the magnetospheric radius; a larger distance or an $\eta < 1$ would imply a higher mass accretion rate and reduce the estimate of $r_{\text{m}}$ as would a lower magnetic field strength.

IBIS/ISGRI clearly measures the spin period of the pulsar in the A0535+262 system as $103.7 \pm 0.1$ s. If we add this to previous measurements of the spin period of the pulsar we see the long-term pulse period history shown in Fig. 4. It is clear that since the BATSE observations of Finger et al. (1996) the pulsar underwent a period of consistent spin-down, slowing from $\sim 103.2$ to $\sim 103.7$ s by the IBIS/ISGRI measurement in 2003. Based upon these measurements we estimate a spin-down rate of $\dot{P} \sim 1.5 \times 10^{-9} \text{s}^{-1}$. Spin-down is to be expected as the system has been in a period of inactivity with no reported X-ray outbursts from 1994 to 2005; the lack of X-ray activity implies that no substantial accretion disc has formed around the pulsar to provide any accretion torques to spin up the pulsar. The Type II outburst in 2005 May/June followed by the Type I outburst in 2005 August/September spin the pulsar up to a period of $P = 103.39315 \pm 0.00005$ s (Caballero et al. 2007).

From the magnetic field strength we calculate the expected spin-down through magnetic dipole losses as $9.4 \times 10^{-16} \text{s}^{-1}$; this is many orders of magnitude less than the observed spin-down and hence cannot be the cause of the change in the pulsar period. Additionally, the spin-down is of too high a magnitude to be explained by the ejection of matter by the neutron star. Consequently, the spin-down of the pulsar must be the result of torques imparted from an accretion disc around the neutron star; this implies that the existence of a disc around the neutron star is not restricted to periods immediately surrounding Type I or Type II outbursts.

5 CONCLUSIONS

The results presented here examine the high-energy emission from A0535+262 during a period in which the source was believed to be quiescent. The source is observed to be transient in the 18–100 keV energy band by INTEGRAL. The source luminosity is completely

![Figure 4](https://academic.oup.com/mnras/article-abstract/381/3/1275/1065676)
An unexpected outburst from A0535+262

An unexpected outburst from A0535+262

incompatible with Type II outbursting behaviour, is at the low end for a Type I outburst and is at the high end for quiescent emission. The outburst occurs \(\sim21\) d prior to periastron. Although it may be a Type I outburst we examine the possibility that the source activity is attributable to a flare during the quiescent phase. Coe et al. (2006) report that during the flare the Be star circumstellar disc was not of sufficient size to support a Type I outburst. The flaring nature of the source may be attributable to a brief period of increased mass transfer. We suggest that this increased mass transfer could originate in a period of increased stellar wind density from the Be donor star although a low-level Type I outburst cannot be completely ruled out.

Measurements of the spin period of the pulsar indicate that the source has continued the spin-down trend which has been observed in the source since it entered the quiescent phase in 1994. A pulse period of \(103.7 \pm 0.1\) s is longer than any other period estimates made since 1994 and suggests a continuous process of spin-down at a rate of \(\dot{P} \sim 1.5 \times 10^{-9}\) ss\(^{-1}\). Such a level of spin-down can only be achieved through torquing drag processes which implies the regular presence of a residual accretion disc around the pulsar.

A0535+262 is a well-observed system during periods of typical Type I and Type II outbursts; however, few measurements have been made of it during its quiescent phases. The INTEGRAL observations imply that during the quiescent phase this system remains active and, by the nature of the detection, is highly variable. Extrapolating the IBIS/ISGRI spectrum using the HEASARC webPIMMS tool estimates that the count rate in the RXTE-ASM would have been \(\sim2.4\) counts s\(^{-1}\) had it observed the source. However, examining the ASM observations of A0535+262 in the week before and after the INTEGRAL observations indicate that the light curve had a mean of 0.75 and a standard deviation of 2.4 counts s\(^{-1}\). Consequently, it is unlikely that had the ASM observed A0525+262 at the time of the flare the instrument sensitivity would have been sufficient to identify the activity.

ACKNOWLEDGMENTS

Based on observations with INTEGRAL, an ESA project with instruments and science data centre funded by ESA member states (especially the PI countries: Denmark, France, Germany, Italy, Switzerland, Spain), Czech Republic and Poland, and with the participation of Russia and the USA.

We acknowledge funding via PPARC grant PP/C000714/1.

REFERENCES

Bird A. J. et al., 2007, ApJS, 170, 175
Caballero I. et al., 2007, A&A, 465, L21
Coe M. J., Carpenter G. F., Engel A. R., Quenby J. J., 1975, Nat, 256, 630
Coe M. J., Reig P., McBride V. A., Galache J. L., Fabregat J., 2006, MNRAS, 368, 447
Finger M., Wilson R. B., Harmon B. A., 1996, ApJ, 459, 288
Frank J., King A. R., Raine D. J., 2002, Accretion Power in Astrophysics, 3rd edn. Cambridge Univ. Press, Cambridge, p. 159
Giangrande A., Giovannelli F., Bartolini C., Guarnieri A., Piccioni A., 1980, A&A, 40, 289
Grove J. E. et al., 1995, ApJ, 438, L25
Hill A. B. et al., 2005, A&A, 439, 255
Horne J. H., Baliunas S. L., 1986, ApJ, 302, 757
Hurford G. J., Krucker S., Lin R. P., Schwartz R. A., Share G. H., Smith D. M., 2006, ApJ, 644, L93
Kawano H., Higuchi T., 1995, Geophys. Res. Lett., 22, 307
Kiener J., Gros M., Tatischeff V., Weidenspointner G., 2006, A&A, 445, 725
Kretschmar P. et al., 2006, ESASP, 604, 273
Motch C., Stella L., Janot-Pacheco E., Mouchet M., 1991, ApJ, 369, 490
Mukherjee U., Paul B., 2005, A&A, 431, 667
Negueruela I., 1998, A&A, 338, 505
Negueruela I., Reig P., Coe M. J., Fabregat J., 1998, A&A, 336, 251
Negueruela I., Reig P., Finger M. H., Roche P., 2000, A&A, 356, 1003
Okazaki A. T., Negueruela I., 2001, A&A, 377, 161
Press W. H., Rybicki G. B., 1989, ApJ, 338, 277p
Rosenberg F. D., Eyles C. J., Skinner G. K., Willmore A. P., 1975, Nat, 256, 628
Scargle J. D., 1982, ApJ, 263, 835
Smith D. M. et al., 2005, ATel, 557, 1
Stella L., White N. E., Rosner R., 1986, ApJ, 308, 669
Steele I. A., Negueruela I., Coe M. J., Roche P., 1998, MNRAS, 297, L5
Tueller J., Ajello M., Barthelmy S., Krim H., Makwardt C., Skinner G., 2005, ATel, 504, 1
Ubertini P., Lebrun F., Di Cocco G. et al., 2003, A&A, 411, 131
Wilson C. A., Finger M. H., Coe M. J., Laycock S., Fabregat J., 2002, ApJ, 570, 287

This paper has been typeset from a \TeX/\LaTeX file prepared by the author.