Discovery of the orbital period in the supergiant fast X-ray transient IGR J17544–2619

D. J. Clark,1* A. B. Hill,2 A. J. Bird,1 V. A. McBride,1 S. Scaringi1 and A. J. Dean1

1School of Physics and Astronomy, University of Southampton, Southampton SO17 1BJ
2Laboratoire d’Astrophysique de Grenoble, UMR 5571 CNRS, Université Joseph Fourier, BP 53, 38041 Grenoble, France

Accepted 2009 August 5. Received 2009 August 5; in original form 2009 July 16

ABSTRACT
The supergiant fast X-ray transient (SFXT) system IGR J17544–2619 has displayed many large outbursts in the past and is considered an archetypal example of SFXTs. A search of the INTEGRAL/ISGRI data archive from MJD 52698–54354 has revealed 11 outbursts and timing analysis of the light curve identifies a period of 4.926 ± 0.001 d which we interpret as the orbital period of the system. We find that large outbursts occasionally occur outside of periastron and place an upper limit for the radius of the supergiant of <23 R☉.

Key words: gamma-rays: observations – X-rays: binaries – X-rays: individual: IGR J17544-2619.

1 INTRODUCTION
Discovered on the 2003 September 17 by the IBIS/ISGRI instrument (Lebrun et al. 2003; Ubertini et al. 2003) onboard the INTEGRAL satellite (Winkler et al. 2003), IGR J17544–2619 has become the archetypal example of the supergiant fast X-ray transient (SFXT) class of objects (Sguera et al. 2005; Negueruela et al. 2006). Around 20 SFXTs are known to date and as the name suggests this class of object is characterized by rapid outbursts, lasting typically a few hours, with a flux 10³–10⁴ times the faint quiescent emission X-ray of the object. Subsequently, more bursts from the source were also discovered in older BeppoSAX data (in’t Zand et al. 2004), Swift (Krimm et al. 2007; Krimm, Romano & Sidoli 2009), and Suzaku data (Rampy et al. 2009). Due to observation strategies and the relatively rare occurrences, only a few bursts are observed a year and, therefore, identification of any binary system parameters is challenging. IGR J17544–2619 is situated ∼3° from the Galactic centre (l = 3.24°, b = −0.34°), a region shown to contain many recurrent transient sources (Kuulkers et al. 2007). The location of IGR J17544–2619 is in a well-studied region covered by a large amount of INTEGRAL archive data and is now covered by the Galactic Center Bulge Monitoring campaign. In this Letter, we report on the detection of a modulation of the gamma-ray flux interpreted as the orbital motion and report new outbursts discovered by a search of the INTEGRAL light curve.

2 PREVIOUS OBSERVATIONS
The first reported detection of IGR J17544–2619 was on 2003 September 17 (Sunyaev et al. 2003) when two flares reaching a maximum of 160 mCrab (18–25 keV) were detected by IBIS/ISGRI (Grebenev, Lutovinov & Sunyaev 2003; Sunyaev et al. 2003). A further five bursts were seen when looking back at the older BeppoSAX-Wide Field Camera (WFC) data (in’t Zand et al. 2004, see table 1) and another from 6 d before the INTEGRAL observation in XMM–Newton data (González-Riestra et al. 2004). In total eight bursts have been previously reported in the INTEGRAL data (Walter & Zurita Heras 2007), although the exact times have not been published for all the bursts.

Observations using XMM–Newton and Chandra provided precise positional errors of 4 and 0.6 arcsec, respectively, supporting
the optical/NIR counterpart Two Micron All Sky Survey (2MASS) J17542527−2619526 (Rodriguez 2003) over the ROSAT candidate 1RXS J175428.3−2620 (Wijnands 2003). Using combined optical and X-ray observations Pellizza, Chaty & Negueruela (2006) classified the counterpart of IGR J17544−2619 to be a O9Ib with a mass of 25–28 M⊙. Using optical and NIR data, Pellizza et al. (2006) estimated a distance of 2.1–4.2 kpc based on extinction measurements. Rahouei et al. (2008) used the data from Pellizza et al. (2006) to fit the spectral energy distribution and obtain a radius range for the donor star of 12.7 R⊙ < R < 26.6 R⊙.

An analysis of Chandra data during quiescence by in’t Zand (2005) produced a power-law fit with Γ = 5.9 ± 1.2, much softer than that expected for a black hole, suggesting that the compact object was a neutron star. If the accretor is a black hole, then a radio flux of ~10–35 mJy is expected. However, an upper limit of 7 mJy has been placed on the radio emission of IGR J17544−2619 adding to the evidence that the compact object is a neutron star (Pellizza et al. 2006). In the analysis of Suzaku observations, Rampy et al. (2009) found that the absorption showed varied rapidly on timescales of minutes by a factor of ~2 during flaring, interpreted as a wind clump passing though the line of sight. However, longer integrations showed stable values of N_H compatible with the stable absorption seen by in’t Zand (2005), but this may simply be the result of averaging.

The initial bursts found by INTEGRAL led to a prediction of a 165 ± 3 d period in the source (Walter et al. 2006). This period was supported by the few bursts found in BeppoSAX and Swift data. Long period systems can be difficult to explain (Brandt & Podsiaджowski 1995). A long period requires a large eccentricity to explain any substantial accretion, but this would decay quickly and require fine tuning not to disrupt the binary. Therefore, it would be unlikely to see too many of these systems. No evidence for spin or orbital periods has been observed in XMM–Newton or Chandra data.

### 3 DATA ANALYSIS

Archival IBIS data from MJD 52698 to MJD 54354, giving an on source exposure of ~8 Ms, were processed with the INTEGRAL Off-line Science Analysis (OSA; Goldwurm et al. 2003) version 7.0. A light curve for IGR J17544−2619 was generated on science window time-scales (~300 s) over the 18–60 keV energy range. The light curve was then searched for bursts. The shortest time-scale region of the light curve that produces the highest detection significance greater than 4σ is found. This is the brightest burst in the light curve. This section of the light curve is then removed from the total light curve and the next highest significant section is searched for. In total, 11 bursts have been found in the light curve (Table 1) which can be added to the list of bursts found in the literature. The bursts range from short flares of 0.5 h to periods of flaring activity up to 35 h. The time between bursts ranges from less than 9 to 197 d. By folding the burst times on different periods, an estimation of the duty cycle required over the orbit to explain all the bursts can be made. There is a clear minimization of ~40 per cent duty cycle at a period of 185 d in our data. However, this period can be shown to be a result of the observing strategy for the source (Fig. 1). INTEGRAL is restricted in observing the Galactic centre due to visibility constraints including the 40° solar aspect angle due to the fixed solar arrays and so there is a ~6 month period to the observations of IGR J17544−2619. Overlaying this period and duty cycle on the ISGRI light curve, it is clear that this period is a result of the observing strategy, and with only a few points of reference, this could be mistaken for a 165 d period suggested by

| Date (MJD) | Orbital phase | Duration (h) | Sig | Peak flux (10^{−11} erg cm^{-2} s^{-1}) | Instrument | Reference |
|-----------|---------------|--------------|-----|----------------------------------|------------|----------|
| 50320.6   | 0.39          | 3.3          |     |                                  | SAX/WFC    | in’t Zand et al. (2004) |
| 51229.7   | 0.94          | 0.2          |     |                                  | SAX/WFC    | in’t Zand et al. (2004) |
| 51248.8   | 0.81          | 0.4          |     |                                  | SAX/WFC    | in’t Zand et al. (2004) |
| 51807.5   | 0.23          | 8.3          |     |                                  | SAX/WFC    | in’t Zand et al. (2004) |
| 51825.1   | 0.80          | 1.0          |     |                                  | SAX/WFC    | in’t Zand et al. (2004) |
| 52893.8   | 0.75          | ~2.0         |     | 4.0†                             | XMM–Newton | González-Riestra et al. (2004) |
| 52999.05  | 0.81          | 12.94        | 33.24| 111.2 ± 4                       | INTEGRAL/ISGRI | Sunyaev et al. (2003) |
| 53062.59  | 0.01          | 1.12         | 5.76 | 28.6 ± 6                        | INTEGRAL/ISGRI | Grebenev et al. (2004) |
| 53072.35  | 0.99          | 5.34         | 30.13| 119.7 ± 6                       | INTEGRAL/ISGRI | Grebenev et al. (2004) |
| 53189     | 0.67          | 0.8          | 230.0|†                               | Chandra     | in’t Zand (2005) |
| 53269.88  | 0.09          | 4.22         | 10.41| 39. ± 11                        | INTEGRAL/ISGRI | Sguera et al. (2006) |
| 53441.23  | 0.88          | 0.56         | 10.59| 62.6 ± 6                        | INTEGRAL/ISGRI | Sguera et al. (2006) |
| 53481.26  | 0.00          | 1.88         | 12.20| 42.1 ± 5                        | INTEGRAL/ISGRI | |
| 53628.67  | 0.93          | 5.06         | 6.13 | 44.1 ± 9                        | INTEGRAL/ISGRI | |
| 53656.92  | 0.66          | 34.69        | 12.99| 73.5 ± 6                        | INTEGRAL/ISGRI | |
| 53806.87  | 0.10          | 3.75         | 16.91| 70.4 ± 7                        | INTEGRAL/ISGRI | |
| 53987.52  | 0.77          | 2.06         | 8.32 | 34.5 ± 5                        | INTEGRAL/ISGRI | |
| 53998.38  | 0.98          | 4.59         | 12.61| 102.4 ± 17                      | INTEGRAL/ISGRI | |
| 54364.3   | 0.26          |             |     |                                  | INTEGRAL/ISGRI | Kuulkers et al. (2007) |
| 54412.2   | 0.96          |             |     |                                  | Swift       | Krimmel et al. (2007) |
| 54556.9   | 0.35          | 0.13         |     |                                  | Swift, Suzaku | Sidoli et al. (2009), Rampy et al. (2009) |
| 54570.4   | 0.10          |             |     |                                  | INTEGRAL/ISGRI | Kuulkers et al. (2007) |
| 54708.1   | 0.05          |             |     |                                  | INTEGRAL/ISGRI | Kuulkers et al. (2007) |
| 54713     | 0.05          |             |     |                                  | Swift       | Sguera et al. (2006) |
| 54905     | 0.02          | ~0.55        |     |                                  | Swift       | Krimmel et al. (2009) |

Note. The peak flux is the 18–60 keV maximum average science window flux, assuming an N_H = 3.8 × 10^{22} and power-law index α = 2.25 (González-Riestra et al. 2004). ‘*’ represents bursts found in our light curve; (1) not seen in INTEGRAL light curve due to observation gap; † 0.5–10 keV.
Figure 1. Overlaying a 185 d 40 per cent duty cycle period on the 18–60 keV ISGRI science window light curve clearly shows that this period is a result of the INTEGRAL observing strategy.

Walter et al. (2006). No other significant periods were found by the initial folding analysis.

4 PERIODICITY ANALYSIS

The science window light curve (containing 6443 independent data points) was searched for signs of periodicity using the Lomb–Scargle periodogram method (Lomb 1976; Scargle 1982, 1989). The Lomb–Scargle periodogram is shown in Fig. 2 with a clear peak evident at a frequency of 0.203 d$^{-1}$, corresponding to a period of 4.926 d. The significance of the peak was confirmed by performing a randomization test (Hill et al. 2005): the flux points of the light curve are randomly re-ordered and a new Lomb–Scargle periodogram generated, the distribution of the power of the largest peak is an indicator of the significance of detection. From 200,000 simulations, we estimate the 99.9, 99.99 and the 99.999 per cent significance levels which are shown in Fig. 2; note that the maximum power achieved in any of the randomized light curves was <22.

The error on the identified period was estimated using a Monte Carlo simulation. Each flux measurement was adjusted using Gaussian statistics within its individual error estimate to generate a simulated light curve of the source. The corresponding periodogram was produced and the location of the maximum peak near the frequency of 0.203 d$^{-1}$ was recorded. From 200,000 simulations, we estimate the period and its error to be 4.926 ± 0.001 (1$\sigma$) d.

Fig. 3 shows the phase folded light curve using a period of 4.926 d and using an ephemeris of MJD 52702.9 to centre the fold at phase 0.0. Since we would expect any enhancement to the emission to coincide with the neutron stars closest approach to the donor, we consider phase 0.0 to be periastron for the rest of the Letter. Between phases 0.25 and 0.85, the folded light curve is consistent with zero which could be interpreted as an eclipse. However, this eclipse would last 3 d, 60 per cent of the orbit and so is unlikely. To see the effect of the outbursts on the phase folded curve a new fold was performed excluding all of the outbursts detected (Table 1). This second phase folded light curve is also shown in Fig. 3, and shows no substantial difference in shape, demonstrating that there is an underlying periodicity in the flux aside from the bursts when then entire light curve is considered. The public light curves for IGR J1755–2619 from the RXTE-All Sky Monitor (ASM) and Swift-Burst Alert Telescope (BAT) missions were also analysed using the Lomb–Scargle periodogram to see if there was any indication of the 4.926 d periodicity. Neither data set showed an indication of a periodic signal. Folding the RXTE-ASM and Swift-BAT light curves on the INTEGRAL period similarly showed no indication of a modulation.

5 OUTBURST RECURRENCE

Aside from the bursts that have been reported in Table 1, there is the possibility of lower level emission occurring at each periastron pass that does not show up as a burst during our search. In order to test the recurrence of emission at periastron, we carry out a recurrence analysis (Bird et al. 2009). For this test, we calculate the light curve significance for a region around the orbital period and at the midpoint of the period. This will then show the recurrence of bursts at periastron and if we are missing any low-level emission seen at every periastron.

In the case of IGR J17544–2619, the bursts do not all occur at periastron, reducing the sensitivity of this test. Since this orbit is
short (∼5 d), we take a region of 1 d either side of periastron (Fig. 4). Comparing the distributions of significances for apastron and periastron using a Kolmogorov–Smirnov (KS) test, we find them to be different at the 99 per cent level. Out of the 79 periastrons seen, only 11 produce a significance over 3σ. The difference between the distributions at periastron and apastron can be explained by the bursts seen and not an underlying longer time-scale variation as seen in SAX J1818.6−1703 or the Suzaku data for IGR J17544−2619. If we repeat this with the known bursts removed, the KS test finds that the two distributions are not significantly different demonstrating the underlying emission, which can be seen with all the phase data added together in the Lomb–Scargle analysis, cannot be seen when considering individual periastrons.

6 DISCUSSION

This is the third SFTX with a period of a few days. The other two having very similar properties to IGR J17544−2619. IGR J16418−4532 (Corbet et al. 2006) and IGR J16479−4514 (Jain, Paul, & Dutta 2009) have periods of 3.75 and 3.32 d, respectively. This contradicts the view that SFXTs have different orbital geometries to the classical high mass X-ray binaries (HMXBs) (Walter & Zurita Heras 2007) and suggests that a difference in the stellar wind may lead to the difference between SFXTs and HMXBs.

Using the ephemeris calculated by the timing analysis, a histogram of burst times with respect to orbital phase can be produced (Fig. 5). This shows while bursts may occur at any time during the orbital period, they are most likely in the last 20 per cent of the orbit, suggesting that this phase is the point of closest approach of the orbit between the two bodies. Since we have a mass for the supergiant of 25–28 M⊙ and assuming a mass of 1.4 M⊙ for the compact object, which is probably a neutron star, Kepler’s third law gives a semimajor axis of 36–38 R⊙ for the 4.9 d period. The range of possible radii for an O9Ib star are 12.7–26.6 R⊙ (Pellizza, Chaty & Negueruela 2007; Rahoui et al. 2008).

Fig. 6 shows how the Lagrange point between the two stars changes with orbit for different eccentricities (Paczyński 1971). We do not see any persistent or regular emission every orbit and so there should be no Roche-lobe overflow in the system. This limits the size of the star to <23 R⊙ with no eccentricity in the orbit. If the minimum possible radius of the star is used, then this limits the eccentricity of the orbit to less than <0.4.

In SAX J1818.6−1703, Zurita Heras & Chaty (2009) proposed that the wind and compact object velocities will limit the region over which the neutron star (NS) can accrete to less than a few stellar radii. With the short period detected in IGR J17544−2619, the neutron star will stay relatively close to the donor star. Zurita Heras & Chaty (2009) describe how the accretion rate will vary strongly with distance from the supergiant, which may be the cause of the underlying modulation seen in the folded light curve (Fig. 3). With bursts seen at all phases, this suggests the neutron star is within this accretion envelope and the variation could be due to the change in wind/NS velocity. This variation could also be due to eccentricity affecting the probability of seeing a burst.

The 10^{32} ergs s^{-1} quiescent emission seen by Suzaku (Rampy et al. 2009) is very low and not easily explained by steady, spherically symmetric Bondi–Hoyle accretion (Bondi & Hoyle 1944) which gives a mass-loss rate for the O-type star of...
it moves out will be proportional to $r^{-2}$. Ducci et al. (2009) showed a clump being proportional to $r^{-1}$, assumed to be 1.0. This will result in the probability of interacting with $1.5^{\beta}$ dependent on the supergiant and for the rest of this Letter as-
are caused by a clumpy wind or a similar outflow, the probability of clearly not homogeneous and isotropic. If we suggest that the bursts
This change cannot be explained simply by the change between pe-
riastron and apastron. One interpretation would be that the wind is
more common $10^{-10} M_\odot$ yr$^{-1}$ based on a NS at $\sim 2 R_\star$. The increase in luminosity to $10^{36}$ ergs s$^{-1}$ during a burst would require a 4 mag increase in the accretion rate, bringing the mass-loss rate up to the more common $10^{-6} M_\odot$ yr$^{-1}$ usually seen from a supergiant donor. This change cannot be explained simply by the change between peri-
astro and apastron. One interpretation would be that the wind is clearly not homogeneous and isotropic. If we suggest that the bursts are caused by a clumpy wind or a similar outflow, the probability of the neutron star interacting with a clump that keeps a constant size as it moves out will be proportional to $1/r^2$. Ducci et al. (2009) showed that the size of a clump changes as it moves away from the donor star, $R_{cl} \propto [r^2 (1 - (1/r)^{2/3})^4]^{1/2}$; where $\beta$ is a constant in the range $0.5$–$1.5$ dependent on the supergiant and for the rest of this Letter as-
sumed to be 1.0. This will result in the probability of interacting with a clump being proportional to $(r^{2/3} - r^{1/3})/r^2$ resulting in a change in the probability even with a slight eccentricity in the orbit (Fig. 7). If we take the normalized probabilities under these curves between 0.8 to 0.2 at periasteron and 0.3 to 0.7 at apastron, we can compare these probabilities calculated from the distribution of phase folded bursts. We observe 18 bursts at periasteron and two at apastron out of a total of 23 bursts. This results in relative probabilities of 0.8 and 0.1 for the phases of 0.8 to 0.2 and 0.3 to 0.7, respectively, although the low number of observed bursts, especially at apastron, will skew the probabilities in favour of more bursts being seen at periasteron. The low statistics in our sample for this letter currently prohibit any realistic attempt at testing this model. However, with a larger sample of bursts from a large number of systems, the models for a clumpy structured wind could be tested.

7 CONCLUSIONS

We have shown that IGR J17544–2619 has an orbital period of $\sim 4.9$ d resulting in a semimajor axis of 36–38 $R_\odot$. As there is no evidence of Roche-lobe overflow, this puts an upper limit on the size of the donor star of $\sim 23 R_\odot$ with no eccentricity in the orbit. However, some eccentricity is required to explain the variation of emission around the orbit and so the supergiant radius must be closer to its lower limit of 12.7 $R_\odot$. With a larger sample of bursts and with the techniques explained here, it may be possible to better constrain the eccentricity and, therefore, the supergiant, radius, and lead to a much better understanding of the SFXT systems seen by INTEGRAL.

ACKNOWLEDGMENTS

Based on observations with INTEGRAL, an ESA project funded by 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. A. B. Hill acknowledges support from the European Community via contract ERC-StG-200911.

REFERENCES

Bird A. J. et al., 2009, MNRAS, 393, L11
Bondi H., Hoyle F., 1944, MNRAS, 104, 273
Brandt N., Podsiadlowski P., 1995, MNRAS, 274, 461
Bozzo E., Falanga M., Stella L., 2008, ApJ, 683, 1031
Corbet R. et al., 2006, Astron. Telegram, 779, 1
Ducci L. et al., 2009, preprint (arXiv:0906.3185)
Goldwurm A. et al., 2003, A&A, 411, L223
González-Riestra R. et al., 2004, A&A, 420, 589
Grebenev S. A. et al., 2003, Astron. Telegram, 192, 1
Grebenev S. A. et al., 2004, Astron. Telegram, 252, 1
Hill A. B. et al., 2005, A&A, 439, 255
in’t Zand J. J. M., 2005, A&A, 441, L1
in’t Zand J. et al., 2004, in Schönfelder V., Lichti G., Winkler C., eds, ESA SP-552, Proc. 5th INTEGRAL Workshop, The INTEGRAL Universe.
ESA, Noordwijk, p. 427
Jain C., Paul B., Dutta A., 2009, MNRAS, 397, L11
Krimm H. A. et al., 2007, Astron. Telegram, 1265, 1
Krimm H. A. et al., 2009, Astron. Telegram, 1971, 1
Kuulkers E. et al., 2007, A&A, 466, 595
Lebrun F. et al., 2003, A&A, 411, L141
Leyder J. et al., 2007, A&A, 465, L35
Lomb N. R., 1976, Ap&SS, 39, 447
Negueruela I. et al., 2006, in Wilson A., ed., ESA SP-604, Proc. The X-ray Universe 2005, ESA, Noordwijk, p. 165
Negueruela I. et al., 2008, in Bandypadhyay R. M., Wachtler S., Gelino D., Gelino C. R., eds, AIP Conf. Ser. Vol. 1010, A Population Explosion: The Nature & Evolution of X-ray Binaries in Diverse Environments.
Am. Inst. Phys., New York, p. 252
Paczynski B., 1971, ARA&A, 9, 183
Pellizza L. J. et al., 2006, A&A, 455, 653
Pellizza L. J., Chaty S., Negueruela I., 2007, Rev. Mex. Astron. Astrofís., 27, 225
Rahoui F. et al., 2008, A&A, 484, 801
Rampy R. A. et al., 2009, preprint (arXiv:0904.1189)
Rodríguez J., 2003, Astron. Telegram, 194, 1
Scargle J. D., 1982, ApJ, 263, 835
Scargle J. D., 1989, ApJ, 343, 874
Sguera V. et al., 2005, A&A, 444, 221
Sguera V. et al., 2006, ApJ, 646, 452
Sidoli L. et al., 2007, A&A, 476, 1307
Sidoli L. et al., 2009, ApJ, 690, 120
Sunyaev R. A. et al., 2003, Astron. Telegram, 190, 1
Ubertini P. et al., 2003, A&A, 411, L131
Walter R., Zurita Heras J., 2007, A&A, 476, 335
Walter R. et al., 2006, A&A, 453, 133
Wijnands R., 2003, Astron. Telegram, 191, 1
Winkler C. et al., 2003, A&A, 411, L1
Zurita Heras J. A., Chaty S., 2009, A&A, 493, L1

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