Discovery of a short orbital period in the Supergiant Fast X-ray Transient IGR J16479–4514

Chetana Jain¹,²*, Biswajit Paul² and Anjan Dutta¹
¹Department of Physics and Astrophysics, University of Delhi, Delhi 110007, India
²Raman Research Institute, Sadashivnagar, C. V. Raman Avenue, Bangalore 560080, India

31 March 2009

ABSTRACT
We report here discovery of a 3.32 day orbital period in the Supergiant Fast X-ray Transient (SFXT) source IGR J16479–4514. Using the long term light curve of this source obtained with Swift-BAT in the energy range of 15–50 keV, we have clearly detected an orbital modulation including a full eclipse of duration ∼ 0.6 day. In the hard X-ray band of the BAT instrument, the eclipse ingress and egress are rapid. We have also used the long term light curve obtained with the RXTE-ASM in the energy range of 1.5–12 keV. Taken independently, the detection of orbital modulation in the RXTE-ASM light curve is not significant. However, considering a clear detection of orbital modulation in the BAT light curve, we have used the ASM light curve for a more precise determination of the orbital period. IGR J16479–4514 has the shortest orbital period among the three SFXTs with measured/known orbital period. We discuss the implication of a short orbital period with the various mechanisms proposed to explain the transient nature of this class of sources.

Key words: X-ray: Neutron Stars - X-ray Binaries: individual (IGR J16479–4514)

1 INTRODUCTION
High Mass X-ray binaries (HMXBs) are binary stellar systems with a compact object and an early type massive star. Some HMXBs are the brightest X-ray sources in the sky. HMXBs display a wide range of X-ray behaviour and luminosities. The X-ray emission varies from a persistent nature to a transient behaviour. Outbursts occur on timescales ranging from hours to months, and some sources also show short term flaring activity. Periodic modulation and eclipses are also seen in many HMXBs. The HMXBs can be split into two main categories as the companion star can be either a Be star or an OB supergiant (van Paradijs 1983). The majority of HMXBs (∼ 80%) belong to the first class of Be binary systems (Kaper, van der Meer & Tijani 2004). In Be system, mass transfer is effected by intermittent mass ejection from the equatorial region of a rapidly rotating Be star. The compact object is a neutron star and is typically in a wide (P_orb ∼ 20–100 days) and eccentric orbit (e ∼ 0.3–0.5) (Liu, van Paradijs & van den Heuvel 2000; Negueruela & Coe 2002). The X-ray emission is highly variable, ranging from complete absence to giant transients lasting weeks to months. In contrast to Be-star binaries, the supergiant systems are bright persistent sources in which the compact object is in orbit around an OB-supergiant (Walter et al. 2006).

Accretion is powered either by the stellar wind from the supergiant and/or through Roche lobe overflow. The neutron stars orbiting wind-fed supergiant binaries are generally less luminous (L_x ∼ 10^{35} – 10^{37} ergs s^{-1}). The orbital periods of the supergiant systems are shorter than the Be-star systems and the orbits are more circular. However, during the past few years, the IBIS instrument (Ubertini et al. 2003) onboard the INTEGRAL γ-ray satellite (Winkler et al. 2003) has discovered many new supergiant systems that occasionally exhibit a fast X-ray transient activity. These systems were termed as Supergiant Fast X-ray Transients (SFXTs) (Negueruela et al. 2006; Smith et al. 2006).

SFXTs are characterised by short and bright X-ray flares which last for a few hours and reach a peak luminosity of ∼ 10^{36} ergs s^{-1} (Negueruela et al. 2006; Smith et al. 2006). This new class of X-ray binaries is probably a connecting link between the Be and OB systems. They harbor a supergiant companion, similar to persistent accreting pulsars, but show bright X-ray emission only during short outbursts. These systems show recurrent outbursts, but orbital period has been measured in only two SFXTs, IGR J11215–5952 (Romano et al. 2007; Sidoli et al. 2007) and SAX J1818.6–1703 (Bird et al. 2009; Zurita Heras & Chaty 2009). Several models have been suggested to explain the origin of bright short duration flares. Bozzo, Falanga & Stella (2008a) explained that flares occur due to interaction of the inflowing wind with the neutron star magnetosphere. in't

* E-mail: chetanajain11@gmail.com
ergs s$^{-1}$) and during quiescence in SFXTs is due to the fact that these systems have wider orbits as compared to persistent supergiant HMXBs, due to which the compact object accretes from a less dense environment. The quiescent state of SFXTs is characterised by a soft-spectrum and an X-ray luminosity of $10^{32}$ ergs s$^{-1}$. SFXTs are expected to be hosting a neutron star, but pulsations have been detected only in two such systems, namely, AX J1841.0−0536 ($4.74$ s; Bamba et al. 2001) and IGR J11215−5952 ($186.78$ s; Swank, Smith & Markwardt 2007). Pulsations have also been detected in intermediate SFXTs: IGR J16465−4507 ($227$ s; Rutnin et al. 2005; Walter et al. 2006) and IGR J18483−0311 ($21$ s: Sguera et al. 2007).

The X-ray transient IGR J16479−4514 was discovered with the INTEGRAL satellite in August 2003 (Molkov et al. 2003), with an average flux of $12$ mCrab in the $18−25$ keV band and $8$ mCrab in the $25−50$ keV band. Several fast flares were later reported from the IBIS/ISGRI observations by Sguera et al. (2005, 2006). The bright variable X-ray source is associated with a supergiant (O8.5I) star, located at a distance of $4.9$ kpc (Chatty et al. 2008; Rahoui et al. 2008). IGR J16479−4514 was regularly monitored with Swift-XRT, to study the quiescent behaviour and outburst properties (Romano et al. 2008). The X-ray emission is highly variable on timescales from seconds to weeks, both during outbursts and in quiescence (Sidoli et al. 2008). The spectrum during the bright flares is well described with an absorbed power-law model with a photon index of 0.98 (Romano et al. 2008). However, Romano et al. (2008) found that a high energy cut off powerlaw model fits well to the wide band spectrum. During the fainter emission, the spectrum was well modeled by an absorbed Comptonised spectrum, with an intrinsic column density of $7.7 \times 10^{22}$ cm$^{-2}$. Similar spectral features are also seen in the persistent accreting X-ray pulsars. Typical SFXTs have low quiescent X-ray luminosities of about $10^{32}$ erg s$^{-1}$, as compared to persistent supergiant systems, which have X-ray luminosities $10^{36}$ erg s$^{-1}$. In the case of IGR J16479−4514, Sguera et al. (2008) determined a quiescent X-ray luminosity of $10^{34}$ erg s$^{-1}$, which is about 2 orders of magnitude higher than that of a typical SFXT. The source was observed in a low-emission phase in 2004 March with XMM-Newton (Walter et al. 2006). The recurrent and short outbursts, the spectral properties and the association with an O-type supergiant star, confirm that IGR J16479−4514 is a member of the growing class of SFXTs. In addition to these features, Bonzo et al. (2008b) detected an obscuration of the X-ray source by the supergiant companion. This indicate that IGR J16479−4514 is possibly an eclipsing SFXT. The eclipsing nature was further supported by an increase in the EW of the iron fluorescent line at $\sim 6.5$ keV.

Here we report the timing analysis of the Supergiant Fast X-ray Transient source, IGR J16479−4514. Using the data obtained from Swift-BAT and RXTE-ASM observations, we have discovered a $3.32$ d orbital period with clear detection of orbital modulation.

2 OBSERVATIONS AND ANALYSIS

We have analysed data from the Swift observatory (Gehrels et al. 2004) which was launched in 2004. The scientific payload consists of a wide field instrument, the gamma ray Burst Alert Telescope (BAT; Barthelmy et al. 2005) and two co-aligned narrow field instruments: X-ray Telescope (XRT, Burrows et al. 2005) operating in the 0.2-10 keV energy band and the Ultraviolet/ Optical Telescope (UVOT, Roming et al. 2005). The $15−50$ keV Swift-BAT light curve was obtained from the BAT Transients Monitor Program (Krimm et al. 2006) and the observations covered the time range from MJD 53413 to MJD 54857. IGR J16479−4514 was also monitored regularly by the All Sky Monitor (ASM) on board Rossi X-ray Timing Explorer (RXTE). The ASM (Levine et al. 1996) comprises three wide-field scanning shadow cameras (SSCs) which are mounted on a rotating boom. The SSCs are rotated in a sequence of “dwells” with an exposure typically of 90 s, so that most of the sky can be covered in one day. The dwell data are also averaged for each day to yield a daily-average. The data used here covered the time between MJD 50088 to MJD 54756.

The long term light curves obtained from Swift-BAT and RXTE-ASM, were corrected for the earth motion using earth2sun tool of the HEASARC software package “FTOOLS” ver6.5.1. We searched for the orbital period using the tool - efsearch, which folds the light curve with a large number of trial periods around an approximate period. The folded light curves for each trial period are fitted to a constant, and $\chi^2$ is determined. The trial period corresponding to the maximum $\chi^2$ represents the true period in the light curve, if any. For the Swift-BAT light curve, we searched for period over a range of 0.1 to 20 days and found a peak at 286796 s and multiples of this period. The top panel of Figure 1 shows the efsearch results from the Swift-BAT light curve, centered at the peak $\chi^2$. A gaussian fit around the peak yielded a period of 286796 ± 89 s (3.3194 ± 0.0010 d) (inset of Figure 1). This is most likely to be the orbital period of the binary system and is similar to many other supergiant systems, such as, 4U 1538−52 (3.73 d; Becker et al. 1977), 4U 1700−37 (3.41 d; Jones et al. 1973), IGR J18027−1926 (4.6 d; Augello et al. 2003), Cen X-3 (2.09 d; Giacconi et al. 1971) and SMC X-1 (3.89 d; Schreier et al. 1972). Considering a clear detection of orbital modulation from the BAT light curve, we have used the ASM light curve for a more precise determination of the orbital period. The period search in the RXTE-ASM light curve was done on a narrow period range and the highest peak in the “efsearch” result on the ASM light curve is at 286816 s (bottom panel of Figure 1) but the detection significance is poor in the energy band ($1.5−12$ keV) of the RXTE-ASM. We also created the Lomb-Scargle periodogram by means of the fast implementation of Press & Rybicki (1989) and Scargle (1982) technique on the Swift-BAT light curve. The long term Swift-BAT light curve covered a span of 1335 d, with 15495 discrete pointings covering a total exposure time of $\sim$124 days. Figure 2 shows the Lomb-Scargle periodogram created from the entire Swift-BAT light curve. A clear peak
is seen in the periodogram corresponding to a frequency of 0.3012 d$^{-1}$, i.e., a period of 3.32 d, with a false alarm probability of 5e-14.

Figure 3 shows the folded light curve IGR J16479−4514, obtained from Swift-BAT and RXTE-ASM observations. From the RXTE-ASM observations, we have also folded the 5−12 keV light curve. The folded light curves shows clear orbital modulation. A sharp eclipse is seen from the Swift-BAT folded light curve. From a long XMM-Newton observation, Bozzo et al. (2008b) detected a sudden reduction in the X-ray flux and they proposed it to be due to an eclipse ingress. From the Swift-BAT observations (which covered the time range analyzed by Bozzo et al. (2008b)), we have also detected a ∼0.6 d eclipse at the same orbital phase as reported by Bozzo et al. (2008b). The arrow in the bottom panel of Figure 3 shows the ingress phase of the eclipse as reported by Bozzo et al. (2008b). The long term average count rate, during the out-of-eclipse phase of IGR J16479−4514 for the Swift-BAT light curve is $1.264 \times 10^{-3}$ counts/s (5.7 mCrab). For the entire RXTE-ASM energy range, the out-of-eclipse count rate is 0.17 counts/s (2.2 mCrab), while for the energy range 5−12 keV, it is 0.07 counts/s (2.8 mCrab). The Swift-BAT light curve, when plotted with a binsize equal
to the orbital period of the system, has a total of 402 data points and 10 (6) of them are above 3 (4) $\sigma$ level. For the entire light curve, the source is detected in the Swift-BAT (RXTE-ASM) with a signal to noise ratio of 18 (11). The ASM orbital profile is not as significant as observed from the Swift-BAT observations. We emphasize the presence of the eclipse at the same phase as obtained from the Swift-BAT data and the duration of the eclipse from the two observations is also equal. The clear detection of orbital modulation shows that long term monitoring with Swift can yield interesting results even for faint sources. Good sensitivity of Swift combined with broad band coverage over a long timescales is crucial to determine the periodic/non-periodic phenomena in such sources.

3 DISCUSSION

Using the Swift-BAT and RXTE-ASM long term light curves, we have discovered an orbital X-ray modulation in the Supergiant Fast X-ray transient source, IGR J16479−4514. We have found an orbital period of 286796 ± 89 s (3.3194 ± 0.0010 d) and an eclipsing phase lasting ∼0.6 d.

To date, the orbital periodicity is known only in two other SFXTs - SAX J1818.6−1703 (Bird et al. 2009; Zurita Heras & Chaty 2009) and IGR J11215−5952 (Sidoli, Paizis & Mereghetti 2006). However, the periodicity observed in these systems is considerably longer than that observed in IGR J16479−4514. While IGR J11215−5952 shows outbursts on a ∼165 d period, SAX J1818.6−1703 is known to exhibit a periodicity of ∼30 d.

The frequency of occurrence of long and bright flares mainly depends on the geometry of the system, wind characteristics and probably some parameter of the compact object. Different mechanisms have been proposed to explain the flaring activity in SFXTs. The long periodicity observed in IGR J11215−5952 is in sync with the accretion model suggested by Negueruela et al. (2006), in which they proposed that SFXTs have wide and eccentric orbits due to which the quiescent X-ray emission is very low. However, the quiescent luminosity of IGR J16479−4514 is two orders of magnitude higher than that of a typical SFXT (Negueru-
that in a short orbital period binary system, the accretion onto the compact object should continue for a large fraction of the orbit or the entire orbit. The average mass accretion rate should also be high and yield a relatively higher quiescent luminosity. Grebenev & Sunyaev (2007) proposed that due to propeller effect, the compact object do not emit during quiescence, but are active when the wind density increases. However, since the magnetosphere is not an ideal propeller, therefore, some fraction of the accreting matter is able to fall on the magnetic poles and quiescent emission level is detectable. In a unified “clumpy winds” model, Negueruela et al. (2008) proposed that different orbital configurations lead to different subclasses of supergiant systems. According to their model, in short orbital period supergiant systems, neutron star is embedded in a quasi-continuous wind and receives a significant fraction of clumps from the companion. Whereas, in long orbital period systems, the wind fills a large volume and therefore, the clump density is small. Bozzo et al. (2008a) also explained the flaring mechanism in the context of gated accretion. They proposed that accretion onto the compact object is inhibited when the magnetospheric radius becomes larger than the corotation radius. They showed that the large luminosity swings between the quiescent and outburst phase are due to the interaction of massive infalling wind with the neutron star magnetosphere. This in turn depends on the spin period of the neutron star and the magnetic field. However, the nature of the compact object is still unknown in a majority of SFXTs. Moreover, in a short orbital period binary with an eclipse lasting for ~ 20% of the period, it is interesting to explore whether gated accretion mechanism can occur at a few stellar radii where the matter density and radiation pressure are high. Further, in view of the results presented here, it is also important to explore the model put forth by Negueruela et al. (2008), specially in the case of short orbital period systems. The unified “clumpy” wind model suggests that the short period systems should be bright for most of the time, but the SFXT IGR J16479−4514 spends most of the time in a quiescent phase, with luminosity well below the persistent bright state of normal supergiant systems.

The observed short orbital period and the orbital modulation opens up many questions regarding the true nature of the Super Fast X-ray Transients. SFXTs share many properties with persistent accreting X-ray pulsars in supergiant HMXBs. The spectral properties of SFXTs are similar to those of accreting X-ray pulsars and the compact object is expected to be a neutron star. But, pulsations have been detected only from two such systems. In particular, the quiescent and long term average luminosity of IGR J16479−4514 is higher that other SFXTs but it is fainter as compared to persistent HMXBs. Therefore, a short orbital period of IGR J16479−4514 and a relatively higher quiescent luminosity sheds light on the probable link between the classical persistent supergiant systems (small and circular orbit) and other classical SFXTs (large and eccentric orbits). The sharp eclipse of IGR J16479−4514 shows that it will also be possible to determine the orbital evolution of the X-ray binary by measuring the mid-eclipse times (Jain, Paul & Dutta 2009), even if the X-ray emission does not show pulsations. Long term monitoring of all the SFXTs is therefore important to study the physical phenomena behind their unusual behaviour.

Figure 3. Light curves from data obtained with Swift-BAT and RXTE-ASM, folded with 16 phase bins per orbit. The light curves were folded with a period of 286816 s. The top panel is the folded light curve from the entire energy range of the RXTE-ASM data. The 5−12 keV folded light curve of the RXTE-ASM observation is shown in the middle panel. The folded light curve obtained with Swift-BAT is shown in the bottom panel. Here, the arrow corresponds to the ingress phase of the eclipse as determined by Bozzo et al. (2008b) from the XMM-Newton observations.
ACKNOWLEDGMENTS

We thank the Swift-BAT and RXTE-ASM teams for provision of the data. We also thank the anonymous referee for some useful comments.

REFERENCES

Augello G., Iaria R., Robba N. R., Di Salvo T., Burderi L., Lavagetto G., Stella, L., 2003, ApJ, 596, L63
Bamba A., Yokogawa J., Ueno M., Koyama K., Yamauchi S., 2001, PASJ, 53, 1179
Barthelmy S. D., et al., 2005, SSRv, 120, 143
Becker R. H., Swank J. H., Boldt E. A., Holt S. S., Serlemitsos P. J., Pravdo S. H., Saba, J. R., 1977, ApJ, 216, L11
Bird A. J., et al., 2009, MNRAS, 393, L11
Bozzo E., Falanga M., Stella L., 2008a, ApJ, 683, 1031
Bozzo E., Stella L., Israel G., Falanga M., Campana S., 2008b, MNRAS, 391, L108
Burrows D. N., et al., 2005, SSRv, 120, 165
Chaty S., Rahoui F., Foellmi C., Tomskick J. A., Rodriguez J., Walter R., 2008, A&A, 484, 783
Gehrels N., et al., 2004, ApJ, 611, 1005
Giacconi R., Gursky H., Kellogg E., Schreier E., Tananbaum H., 1971, ApJ, 167, L67
Grebenev S. A., Sunyaev R. A., 2007, AstL, 33, 149
Howk J. C., Cassinelli J. P., Bjorkman J. E., Lamers H. J. G. L. M., 2000, ApJ, 534, 348
in’t Zand J. J. M., 2005, A&A, 441, L1
Jain C., Paul B., Dutta, A, 2009, ApJ, submitted
Jones C., Forman W., Tananbaum H., Schreier E., Gursky H., Kellogg E., Giacconi R., 1973, ApJ, 181, L43
Kaper L., van der Meer A., Tijani A. H., 2004, RMxAC, 21, 128
Krimm H. A., et al., 2006, HEAD, 9, 1347
Levine A. M., Bradt H., Cui W., Jerriegan J. G., Morgan E. H., Remillard R., Shirey R. E., Smith D. A., 1996, ApJ, 469, L33
Leyder J. C., Walter R., Lazos M., Masetti N., Produit N., 2007, A&A, 465, L35
Liu Q. Z., van Paradijs J., van den Heuvel E. P. J., 2000, AAS, 147, 25
Lutovinov A., Revnivtsev M., Gilfanov M., Shtykovskiy P., Molkov S., Sunyaev R., 2005, A&A, 444, 821
Molkov S., Molvani N., Goldwurm A., Strong A., Lund N., Paul J., Oosterbroek T., 2003, ATel, 176, 1
Negueruela I., Coe M. J., 2002, A&A, 385, 517
Negueruela I., Smith D. M., Reig P., Chaty S., & Torrejon J. M., 2006, ESASP, 604, 165
Negueruela I., Torrejon J. M., Reig P., Ribo, M., Smith, D. M., 2008, AIPC, 1010, 252
Oskinova L. M., Hamann W. R., Feldmeier A., 2007, A&A, 476, 1331
Rahoui F., Chaty, S., Lagage P., Pantin E., 2008, A&A, 484, 801
Romano P., Sidoli L., Manganov V., Mereghetti S., Cusumano G., 2007, A&A, 469, L5
Romano P., et al., 2008, ApJ, 680, L137
Roming P. W. A., et al., 2005, SSRv, 120, 95
Schreier E., Giacconi R., Gursky H., Kellogg E., Tananbaum H., 1972, ApJ, 178, L71
Sguera V., et al., 2005, A&A, 444, 221
Sguera V., et al., 2006, ApJ, 646, 452
Sguera V., et al., 2007, A&A, 467, 249
Sguera V., et al., 2008, A&A, 487, 619
Sidoli L., Paizis A., Mereghetti S., 2006, A&A, 450, L9
Sidoli L., Romano P., Mereghetti S., Paizis A., Vercellone S., Manganov V., Gotz D., 2007, A&A, 476, 1307
Sidoli L., et al., 2008, ApJ, 687, 1230
Smith D. M., Heindl W. A., Markwardt C. B., Swank J. H., Negueruela I., Harrison T. E., Huss L., 2006, ApJ, 638, 974
Swank J. H., Smith D. M., Markwardt C. B., 2007, ATel, 999, 1
Ubertini P., et al., 2003, A&A, 411, L131
van Paradijs J., 1983, in ADXS Conf. Ser., ed. Lewin W. H. G. & van den Heuvel E. P. J., 231
Walter R., et al., 2006, A&A, 453, 133
Walter R., Zurita Heras, J, 2007, A&A, 476, 335
Winkler C., et al., 2003, A&A, 411, L1
Zurita Heras, J. A., Chaty, S., 2009, A&A, 493, L1