IGR J17354−3255 as bench test for investigation of γ-ray emission from Supergiant Fast X-ray Transients

Sguera V.
INAF/IASF Bologna, Via Piero Gobetti 101, Bologna

Abstract

Among the different types of sources shining in the high energy sky, gamma-ray binaries are rapidly becoming the subject of major interest. In fact, in the last few years a number of High Mass X-ray Binaries (HMXBs) have been firmly detected from MeV to TeV energies, providing secure evidences that particles can be efficiently accelerated up to very high energies in such galactic systems. Similarly to this general and emerging class of gamma-ray binaries, in principle Supergiant Fast X-ray Transients (SFXTs) have all the “ingredients” to be transient high energy emitters. In this context, the SFXT IGR J17354−3255 is a good bench test and we present intriguing hints likely suggesting that it is a transient gamma-ray source flaring on short timescales. If fully confirmed by further studies, the implications stemming are huge, both theoretically and observationally, and would add a further extreme characteristic to the already extreme class of SFXTs.

Keywords:

1. Introduction

During the last few years, AGILE and Fermi observations of the Galactic plane have indicated the existence of a possible population of unidentified transient MeV-GeV sources characterized by flares lasting no more than a few days at most e.g. [1], [2]. Notably, no blazar-like counterparts are known within their error boxes so they could represent a completely new class of Galactic high energy transients. The task of identifying their counterparts at lower energies is very challenging, mainly because of their fast transient nature and large positional uncertainty (e.g radii typically from 10 arcmin to 0.5 degrees). However these difficulties are compensate by the fact that it is most probably within this group of gamma-ray sources that peculiar objects (or even a new class of objects) could emerge, leading to novel and unexpected discoveries. The IBIS instrument onboard the INTEGRAL satellite is particularly suited to search for reliable best candidate counterparts in the energy range 20–100 keV thanks to i) a large field of view (30′×30′) which ensure a total coverage of the gamma-ray error box ii) a good angular resolution (12 arcminutes) which is mandatory to disentangle the hard X-ray emission of different sources in crowded fields such as those on the Galactic plane iii) a good sensitivity above 20 keV (~ 10 mCrab during a typical IBIS observation lasting ~ 2,000 seconds). In particular, recent INTEGRAL/IBIS results [3], [4], [5] provided intriguing hints that best candidate counterparts could be found among the members of the Supergiant Fast X-ray Transients population (SFXTs).

SFXTs are a new subclass of High Mass X-ray Binaries (HMXBs) unveiled in the last few years mainly thanks to INTEGRAL observations of the Galactic plane [6], [7], [8]. They host a massive OB supergiant star as identified by optical spectroscopy, the compact object is generally assumed to be a neutron star because of the broad band X-ray spectral shape (0.2–100 keV) strongly resembling those of accreting X-ray pulsars in classical HMXBs. As support to this assumption, X-ray pulsations have been firmly detected in several SFXTs.
e.g. [9]. As for their X-ray behavior, SFXTs are intriguingly characterized by remarkable fast X-ray flares lasting from few hours to no longer than a few days at most and reaching typical peak X-ray luminosities of \( L_x \sim 10^{36} \) erg s\(^{-1}\). The duty cycles of activity are very low (0.1\%–3\%), conversely SFXTs spend most of their time in a low level X-ray activity with typical \( L_x \sim 10^{33} - 10^{34} \) erg s\(^{-1}\), rarely they are also observed in X-ray quiescence at much lower X-ray luminosities (\( L_x \lesssim 10^{32} \) erg s\(^{-1}\)). The typical dynamic range of classical SFXT spans three to five order of magnitude, however some systems show a lower value of the order of \( \sim 10^2 \) and so they have been named as intermediate SFXTs [10], [11]. The extreme case of fast variability and high dynamical range characterizing SFXTs is at odds with the behavior of their historical parent population of classical wind-fed supergiant HMXBs which, since more than 40 years of X-ray astronomy, are known to be bright and persistent X-ray sources always detectable around \( L_x \sim 10^{36} \) erg s\(^{-1}\). Although SFXT hunting is not an easy task, in a very few years \( \sim 10 \) firm systems have been reported in the literature (see list in [12]) plus a similar number of candidates: SFXTs could represent a major population of transient HMXBs hidden on the Galactic plane of our Galaxy. The physical mechanism driving their peculiar fast X-ray transient behavior is unclear and still highly debated. Several models have been proposed in the literature (see [13] for a review).

It is worth noting that in the last few years observations performed by Fermi, AGILE and Cherenkov telescopes have provided secure evidences that particles can be efficiently accelerated to very high energies in some HMXBs. In fact, a number of classical HMXBs have been firmly detected from MeV to TeV energies as persistent and variable sources e.g. [14]. In addition, the two microquasar HMXB Cygnus X-1 and Cygnus X-3 have been detected as transient MeV-GeV emitters whose flaring activity lasted typically 1-2 days [15], [16], [17]. Similarly to this general and emerging class of gamma-ray HMXBs, in principle SFXTs could be able to produce photons up to MeV-TeV energies since they have the same “ingredients” in term of a neutron star compact object as well as a bright and massive OB star which could act as a source of seed photons (for the Inverse Compton emission) and target nuclei (for hadronic interactions). In particular, the high energy emission from SFXTs should be in the form of fast flares (from few hours to few days duration) and the duty cycle of activity should be very small, this would make their high energy detection very challenging. Despite this drawback, some observational evidences have been recently reported in the literature on SFXTs as best candidate counterparts of unidentified transient MeV-GeV sources located on the Galactic plane [3], [4], [5]. These evidences are merely based on intriguing hints such as a spatial correlation and a common transient behaviour on similar, though as yet not simultaneous, short time scales. This scenario is also supported from an energetic standpoint by a theoretical model based in the microquasar accretion/jet framework [3]. The so far proposed associations represent an important first step towards obtaining reliable candidates on which to concentrate further efforts in order to obtain quantitative proofs for a real physical association. In this respect, so far, the best test case is represented by the proposed association between the two sources IGR J17354–3255 and AGL J1734–3310.

2. The SFXT IGR J17354–3255

IGR J17354–3255 is a hard X-ray transient discovered by INTEGRAL in 2006 during an outburst having average flux of \( \sim 2.1 \times 10^{-10} \) erg cm\(^{-2}\) s\(^{-1}\) (20–60 keV) and unconstrained duration [18], [19]. Subsequent studies with the Swift satellite showed that its broad band X-ray spectrum (0.2–100 keV) is characterized by a spectral shape very similar to that of accreting X-ray pulsars in HMXBs, in addition a periodicity of \( \sim 8.4 \) days was unveiled in the Swift/BAT data [20]. In the soft X-ray domain (0.2–10 keV), the source has been observed by Swift/XRT [21], Chandra [22] and XMM [23]. Specifically, during two observations (March 2008 with XRT and March 2011 with XMM)
the source was not detected leading to an inferred 3σ upper limit of $7 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$, conversely during two other observations (February 2009 with Chandra and April 2009 with XRT) the source was indeed detected and it was strongly variable as well, being the average flux and the peak flux equal to $\sim 1.3 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$ and $\sim 9 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$, respectively. In addition, Chandra provided a very accurate positioning which allowed to pinpoint a single bright 2MASS infrared source as counterpart [22]. Subsequent infrared spectroscopic performed by [24] unveiled its nature of supergiant star with spectral type O9.5Iab.

The temporal X-ray behavior of IGR J17354−3255 above 20 keV, which is crucial to allow a proper and firm classification as classical persistent supergiant HMXB or alternatively as a SFXT, is largely unknown. We performed a detailed temporal study with INTEGRAL in the energy band 18–60 keV [4]. As result, we found that IGR J17354−3255 is a weak persistent hard X-ray source spending a major fraction of the time in a out-of-outburst state with an average 18–60 keV flux of $\sim 1.4 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$. This is occasionally interspersed with fast hard X-ray flares having duration in the range 0.5–60 hours, a total of 16 hard X-ray flares have been detected by INTEGRAL/IBIS over a total exposure of $\sim 115$ days though not in sequence. Fig. 1 shows an example of a fast flare lasting only half an hour and detected with a significance of about 6σ (18–60 keV). The dynamic range of the source in the hard X-ray band (18–60 keV) is as high as 200, it is even higher ($>1,250$) in the softer X-ray band (0.2–10 keV). Based on the above findings, IGR J17354−3255 can be classified as a member of the SFXT population. In the framework of the clumpy wind scenario, the fast X-ray flares could be explained as due to accretion onto the compact object of dense clumps of material in the highly structured wind of the supergiant companion donor star. Conversely, during the weak persistent out-of-outburst X-ray state, accretion is likely still at work although at much lower rate, e.g. the compact object is likely accreting from the much less dense background wind. This is supported by the fact that the 18–60 keV spectral shape, as measured by INTEGRAL/IBIS, is identical during both the flaring and out-of-outburst X-ray states, i.e. a power law shape with $\Gamma=2.4\pm0.4$.

Our investigation of the INTEGRAL/IBIS long-term light curve using the Lomb-Scargle periodogram method strongly confirmed the 8.4 days orbital period. Fig. 2 shows the corresponding phase folded light curve where it is evident a smooth orbital modulation of the flux; it peaks during the periastron passage and becomes consistent with zero around apastron. The red crosses indicate the 16 outbursts detected by INTEGRAL/IBIS within these orbital ephemeris. As clearly evident their occurrence is consistent with the region of orbital phase around periastron. We note that the shape of the orbital...
Figure 3: Recurrence analysis for periastron and apastron detections of IGR J17354−3255 within a set window of 3 days.

Figure 3: Recurrence analysis for periastron and apastron detections of IGR J17354−3255 within a set window of 3 days. The profile is rather smooth and appears to be dominated by lower level X-ray emission rather than by the bright X-ray outbursts. To test this assumption we employed the recurrence analysis technique which searches for periastron detections by summing the X-ray emission during each periastron passage within a set window of 3 days (periastron ± 1.5 days). The source could then be detected even though a significant detection is not achieved in the individual IBIS pointing lasting 2,000 seconds. The same process was performed for each apastron passage and the distributions compared. Fig. 3 shows the recurrence analysis results, there is a clear excess in detections above $3\sigma$ during the periastron passages, corresponding to detectable emission on about 26% of periastron passages covered by the data set. This value is taken as a lower limit as there may still be emission that is occurring during other periastron passages that is below the sensitivity of IBIS. On the contrary no detections above $3\sigma$ are recorded during apastron passages. Our recurrence analysis suggests that the 16 individual outbursts detected by IBIS/ISGRI cannot explain the smooth shape seen in the phase folded light curve. In fact, assuming a source distance of 8.5 kpc (the distance is still unknown and the source is located in the direction of the Galactic center) these outbursts all have X-ray luminosities of the order of $10^{36}$ erg s$^{-1}$ and so represent the most luminous X-ray outburst events. Hence we would not expect these events to define the orbital emission profile over the extent of these long baseline observations. Instead we attribute the shape to lower level X-ray emission that is below the instrumental sensitivity of IBIS in an individual ScW (i.e. ~ 10 mCrab). However when the whole data set, covering about 300 orbital cycles of 8.4 days, is folded this emission sums to a significant detection and reveals the smooth profile shown in Fig. 2. This emission could be the superposition of many lower intensity X-ray flares at luminosity values of $\sim 10^{33}$–$10^{34}$ erg s$^{-1}$.

3. The SFXT IGR J17354−3255 as test case of gamma-ray emitter

Interestingly, the SFXT IGR J17354−3255 is located in the sky region of two unidentified gamma-ray sources: AGL J1734−3310 and 3EG J1734−3232 (see Fig. 4):

- AGL J1734−3310 was discovered by the AGILE gamma–ray satellite on 2009 April 14 during a flare lasting only 1 day and detected with a significance of 4.8$\sigma$ at $E>100$ MeV [2]. After its discovery, extensive searches for further flaring gamma-ray emission have been carried out by the AGILE team [25]. As a result, several additional gamma-ray flares have been discovered in the AGILE data archive 2007–2009. They have a similar duration (about 1 day) and significance detection in the range (3–5)$\sigma$. This clearly shows that AGL J1734−3310 is a recurrent transient gamma-ray source. The significance of the sum of all the flares detected by AGILE is 7.3$\sigma$ with a 95% statistical and systematic positional error radius of 0.46 degrees. Fig. 4 shows the 18–60 keV INTEGRAL/IBIS significance mosaic map (~10 Ms exposure) of the sky region surrounding IGR J17354−3255 with superimposed the positional uncertainty of AGL J1734−3310 (green circle). Clearly, IGR J17354−3255 is the only hard X-ray source detected inside the AGILE error circle, the same holds in the softer X-ray band (3–10 keV) from an INTEGRAL/JEM–X deep mosaic (~700 ks exposure). We took into account the possibility of a chance coincidence and to this aim we calculated the probability of finding a supergiant HMXB, such as IGR J17354−3255, inside the AGILE error circle by chance. Given the number of supergiant HMXBs detected by IBIS within the Galactic plane [26], defined here as restricted to a latitude range of $\pm 5^\circ$, we estimated a probability of $\sim 1\%$.

- 3EG J1734−3232 is a still unidentified gamma-ray source listed in the third EGRET catalog with average flux of $(40\pm 6.7) \times 10^{-8}$ photons cm$^{-2}$ s$^{-1}$ ($E>100$ MeV) and significance detection of $6.2\sigma$.
Figure 4: The INTEGRAL/IBIS mosaic significance map (18–60 keV, ~ 10 Ms exposure time) of the sky region including IGR J17354−3255. The other two bright sources detected in the field are the LMXBs GX 354−0 and 4U 1730−335. The green error circle represents the MeV-GeV source AGL J1734−3310 and the red contours (from 50% to 99%) refer to 3EG J1734−3232. The persistent gamma-ray sources detected by Fermi/LAT are indicated by means of yellow gamma-ray error circles.

It is also designated as confused source, which means that it may have significant uncertainties due to the overlapping PSFs. It is in fact possible that 3EG J1734−3232 is the blend of more than one gamma-ray source, this is particularly evident thanks to recent observations performed by AGILE and Fermi whose excellent angular resolution allowed to pinpoint the two gamma-ray sources likely responsible for the entire emission from 3EG J1734−3232 (see Fig. 4): AGL J1734−3310 (discussed above) and 2FGL J1732.5−3131. The latter is a firmly identified gamma-ray pulsar with average flux ∼ 20×10^{-8} photons cm^{-2} s^{-1} (100 MeV–100 GeV). Such hypothesis is strongly supported by i) the blending of 3EG J1734−3232 elongated towards the direction of both AGL J1735−3258 and 2FGL J1732.5−313 and ii) the average EGRET gamma-ray flux compatible with the sum of the gamma-ray fluxes from the AGILE and Fermi sources (i.e. ∼45×10^{-8} photons cm^{-2} s^{-1} at E >100 MeV). In addition, 3EG J1734−3232 is likely variable as suggested by the value of its variability index I. The spatial match, the possible variability, the gamma-ray flux values, all strongly suggest that at least a fraction of the entire gamma-ray emission from 3EG J1734−3232 might well be associated with AGL J1735−3258. The remaining part is very likely coming from 2FGL J1732.5−3131.

For the sake of completeness, we note that in the surroundings of AGL J1734−3310 and 3EG J1734−3232 there are two other persistent gamma-ray sources as detected by Fermi (see Fig. 4): i) 2FGL J1737.2−3213 is an unidentified gamma-ray source with average flux ∼ 11×10^{-8} photons cm^{-2} s^{-1} (300 MeV–100 GeV), it is not variable and it is likely associated with a supernova remnant or pulsar wind nebula and ii) 2FGL J1731.6−3234c is still unidentified with average flux of ∼ 6×10^{-8} photons cm^{-2} s^{-1} (300 MeV–100 GeV), however it is found in a region with possibly incorrected diffuse emission. As such, its position and even existence may not be reliable, i.e. it could be a fake source potentially confused with interstellar emission. We note that none of the above three Fermi gamma-ray sources is spatially associated with AGL J1734−3310 and/or IGR J17354−3255. Moreover, despite 2FGL J1737.2−3213 and 2FGL J1731.6−3234c are in the surroundings of 3EG J1734−3232, they likely give no significant contribution to the flux measured by EGRET since both are very weak gamma-ray sources.
4. Conclusions

Based on spatial correlation as well as on a flaring nature on similar short timescales (although not simultaneous yet), we propose the SFXT IGR J17354−3255 as the best candidate counterpart of AGL J1734−3310, to date. Although such proposed association is merely based on intriguing hints, it represents an important first step towards obtaining a reliable test case on which to concentrate further efforts to obtain quantitative proofs for a real physical association. In this respect, further AGILE, Fermi and INTEGRAL studies of IGR J17354−3255/AGL J1734−3310 are under way. If fully confirmed, the implications of SFXTs producing gamma-ray emission are huge, both theoretically and observationally since i) it would open the study to an unexplored energy window, ii) it would allow a deep inspection of the extreme physical mechanisms able to accelerate particles up to relativistic energies in HMXBs, iii) it would add a further extreme characteristic to the already extreme class of SFXTs.

5. acknowledgments

V. Sguera is very grateful to Andrea Bulgarelli and the AGILE team for sharing the results on AGL J1734−3310 before publication

References

[1] Hays et al. 2009, AAS Meeting 213, 612.04
[2] Bulgarelli et al. 2009, ATel 2017
[3] Sguera, V.,Romero,G.E.,Bazzano, A.,et al. 2009, ApJ, 697,1194
[4] Sguera, V., Drave, S. P., Bird, A. J., et al. 2011, MNRAS, 417, 573
[5] Sguera, V. 2009, arXiv 0902.0245, proceedings of the 7th INTEGRAL Workshop, PoS Integral08:082.2008
[6] Sguera, V.,Barlow, E. J., Bird, A. J., et al. 2005, A&A, 444, 221
[7] Sguera, V.,Bazzano, A., Bird, A. J., et al. 2006, ApJ, 646, 452
[8] Negueruela, I.; Smith, D. M.; Reig, P., et al. 2006, ESA SP, 604, 165
[9] Sguera, V., Hill, A. B.; Bird, A. J., et al. 2007, A&A, 467, 249
[10] Clark, D.J., Sguera, V., Bird, A.J. et al. 2010, MNRAS, 406L,75
[11] Walter, R. & Zurita Heras, J., 2007, A&A, 476, 335
[12] Grebenev 20120, arXiv 1004.0293, Proceedings of the Workshop "The Extreme sky: Sampling the Universe above 10 keV", PoS, 96, 60
[13] Sidoli, L., 2009, AdSpR, 43, 1464
[14] Mirabel 2012, Science, 335, 175
[15] Tavani, M., Bulgarelli, A., Piana, G., et al. 2009, Nature, 462, 620
[16] Abdo et al. 2009, Science, 326, 1512
[17] Sabatini S. et al., 2010, ApJ, 712, L10
[18] Kuulkers, E. et al., 2006, ATel 874
[19] Kuulkers, E.; Shaw, S. E.; Paizis, A.; et al. 2007, A&A, 466, 595
[20] D’Ai et al. 2011, A&A, 529, 30
[21] Vercellone, S., D’Ammando, F., Striani, E., et al. 2009, ATel 2019
[22] Tomsick, J.A., Chaty, S., Rodriguez, J. et al. 2009, ApJ, 701, 811
[23] Bozzo, E.; Pavan, L.; Ferrigno, C., et al. 2012, A&A, 544, 118
[24] Coleiro et al. 2012, poster presented at the 9th INTEGRAL conference held in Paris, 15-19 October 2012
[25] Bulgarelli et al. in preparation
[26] Bird, A. J., Bazzano, A., Bassani, L., et al. 2010, ApJS, 186, 1
[27] Hartman, R. C. et al. 1999, ApJS, 123, 79
[28] Nolan et a. 2012, ApJs, 199, 2, 31
[29] Han & Zhang 2005, Chinese Journal of Astronomy and Astrophysics, 5, 3, 256