Accretion disc by Roche lobe overflow in the supergiant fast X-ray transient IGR J08408–4503

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ABSTRACT

Supergiant fast X-ray transients (SFXTs) are X-ray binary systems with a supergiant companion and a likely neutron star, which show a fast (∼10−3 s) and high variability with a dynamic range up to 10^5–6. Given their extreme properties, they are considered among the most valuable laboratories to test accretion models. Recently, the orbital parameters of a member of this class, IGR J08408–4503, were obtained from optical observations. We used this information, together with X-ray observations from previous publications and new results from Swift and optical data collected by INTEGRAL, and presented in this work, to study the accretion mechanisms at work in IGR J08408–4503. We found that the high eccentricity of the compact object orbit and the large size of the donor star imply Roche lobe overflow (RLO) around the periastron. It is also likely that a fraction of the outer layers of the photosphere of the donor star are lost from the Lagrangian point L1 during the periastron passages. On the basis of these findings, we discuss the flaring variability of IGR J08408–4503 assuming the presence of an accretion disc. We point out that IGR J08408–4503 may not be the only SFXT with an accretion disc fueled by RLO. These findings open a new scenario for accretion mechanisms in SFXTs, since most of them have so far been based on the assumption of spherically symmetric accretion.

Key words. accretion, accretion disks – stars: neutron – X-rays: binaries – X-rays: individuals: IGR J08408–4503

1. Introduction

Supergiant fast X-ray transients (SFXTs) are a subclass of very high mass X-ray binaries (HMXBs) composed of a compact object, that is a neutron star (NS) or black hole, accreting material from an OB supergiant star (for recent reviews, see Romano 2015 and Sidoli 2017). Classical HMXBs with a supergiant companion are X-ray sources with a typical X-ray luminosity of ∼10^32–37 erg s^{-1} and moderate variability, which have a flux dynamic range of about ten. In contrast, SFXTs show sporadic X-ray outbursts with a duration of the order of about a day, composed of short (∼10−3−10−2 s) and bright (∼10^33−35 erg s^{-1}) flares. The low luminosity state is characterised by L_{\text{min}} ≈ 10^{32−33} erg s^{-1}, and therefore the flux dynamic range can reach 10^5−10^6. These SFXTs show X-ray spectra reminiscent of those of accreting X-ray pulsars (power law with cut-off in the range 10−30 keV), indicating a likely NS nature for the compact object of the binary system. Several accretion mechanisms have been proposed to explain the X-ray variability of SFXTs. These mechanisms involve the accretion of wind clumps onto the NS (e.g. in’t Zand 2005; Ducci et al. 2009; Chaty 2013, and references therein), gating mechanisms (Grebenev & Sunyaev 2007; Bozzo et al. 2008), subsonic settling accretion regimes (e.g. Shakura et al. 2014), and formation of transient accretion discs (Ducci et al. 2010). IGR J08408–4503 has the lowest duty cycle among the SFXTs, with an activity duty cycle of 0.11% (according to the definition of Paizis & Sidoli 2014 based on INTEGRAL data) or, equivalently, highest inactivity duty cycle of 67.2±5.7% (according to the definition of Romano et al. 2009a, 2014a based on Swift/
Table 1. Bright X-ray flares ($L_X \geq 10^{36}$ erg s$^{-1}$) detected by INTEGRAL, Swift/BAT, MAXI, and long Suzaku and XMM-Newton observations of IGR J08408–4503 at lower luminosities.

<table>
<thead>
<tr>
<th>Time (MJD)</th>
<th>Instrument</th>
<th>Orbital phase</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>55914.029</td>
<td>MAXI</td>
<td>0.077</td>
<td>(a)</td>
</tr>
<tr>
<td>55283.664</td>
<td>Swift/BAT</td>
<td>0.843</td>
<td>(b)</td>
</tr>
<tr>
<td>55071.953</td>
<td>Swift/BAT</td>
<td>0.843</td>
<td>(b)</td>
</tr>
<tr>
<td>55798.035</td>
<td>Swift/BAT</td>
<td>0.923</td>
<td>(b)</td>
</tr>
<tr>
<td>56000.777</td>
<td>Swift/BAT</td>
<td>0.923</td>
<td>(b)</td>
</tr>
<tr>
<td>56475.341</td>
<td>Swift/BAT</td>
<td>0.893</td>
<td>(b)</td>
</tr>
<tr>
<td>55176.746</td>
<td>Suzaku</td>
<td>−0.177 ≤ Φ ≤ +0.112</td>
<td>(c)</td>
</tr>
<tr>
<td>54249.391</td>
<td>XMM-Newton</td>
<td>0.653 ≤ Φ ≤ 0.708</td>
<td>(f)</td>
</tr>
</tbody>
</table>

Notes: (a) Götz et al. (2007); (b) Romano et al. (2014b); (c) Romano et al. (2013); (d) List of the detection of transient sources reported in http://maxi.riken.jp/alert/novae/index.html; (e) Sidoli et al. (2010); (f) Bozzo et al. (2010).

Previously published (Götz et al. 2007; Leyder et al. 2007; Romano et al. 2009b; Sidoli et al. 2009, 2010; Bozzo et al. 2010) and of INTEGRAL data analysed in this work for the first time (Sect. 2). The results are discussed in Sect. 3.

2. Observations of IGR J08408–4503

2.1. Collection of previous X-ray observations

We calculated the orbital phases and the position along the orbit of all the bright flares ($L_X \geq 10^{36}$ erg s$^{-1}$) of IGR J08408–4503 observed since its discovery by Swift/BAT, INTEGRAL, and MAXI. For INTEGRAL, we also searched for previously unreported flares in all the archival data and we found one (see Sect. 2.2). In addition, we considered the long monitoring (about three days) performed by Suzaku, where IGR J08408–4503 was observed accreting at an X-ray luminosity of $10^{32}–10^{33}$ erg s$^{-1}$ (Sidoli et al. 2010), and an XMM-Newton observation where IGR J08408–4503 was caught at a similar low luminosity level (Bozzo et al. 2010). We assumed the orbital parameters derived by Gamen et al. (2015), and we also kept their assumption about the mass of the donor star, $M_d = 33 M_⊙$ (based on the calibration work of Martins et al. 2005) and their derivation for the mass of the NS, $M_{\text{NS}} = 1.61 M_⊙$. The times and orbital phases of these observations are shown in Table 1. The positions of these observations along the orbit are shown in Fig. 1.

2.2. Analysis of INTEGRAL data

We analysed all the available archival data collected by the INTEGRAL Soft Gamma-Ray Imager (ISGRI; Lebrun et al. 2003) detector of the Imager on Board INTEGRAL Satellite (IBIS; Ubertini et al. 2003) on board INTEGRAL (Winkler et al. 2003), from 2003 January 11 to 2019 February 17 (corresponding to 3222 pointings). The IBIS instrument operates in the $\sim 20$ keV–$10$ MeV energy range. We performed the analysis using the Off-line Science Analysis (OSA) software provided by the ISDC Data Center for Astrophysics2. We only considered observations with IGR J08408–4503 within $12^\circ$ from the centre of the IBIS/ISGRI field of view (FOV). In addition, to the previously known flares, IGR J08408–4503 showed a bright flare in 2019 January 6 at 12:11:31.200 UTC (see Fig. 2, top panel). During the flare ($T_{\text{start}} = 58489.508$ MJD; $T_{\text{stop}} = 58489.541$ MJD) the spectrum can be described by a power law with high energy cut-off, with photon index of $2.5 \pm 0.2$, $E_c = 54.0_{-8.5}^{+8.8} \text{keV}$, $E_1 = 34_{-16}^{+31} \text{keV}$ ($\chi^2 = 1.36$, 7 d.o.f.). Uncertainties are given at 68% confidence level. We added systematic uncertainties of 5% to the IBIS/ISGRI spectrum. The peak flux is $2.7 \times 10^{-3}$ erg cm$^{-2}$ s$^{-1}$ ($30–80$ keV), corresponding to a luminosity of $L_X \approx 1.6 \times 10^{36}$ erg s$^{-1}$ (Fig. 2, bottom panel). We searched for periodicities using IBIS/ISGRI data during the flare (i.e. we defined a good time interval with $T_{\text{start}} - T_{\text{stop}}$ defined above) by selecting events with pixel fraction illuminated by IGR J08408–4503 equal to one from the detector shadowgrams obtained before the reconstruction (deconvolution) of the sky image. In addition, we also performed this search using binned light curves (bin = 0.1 s) obtained with the OSA binning tool $ii\_light$. In both cases the Solar System barycentre correction was applied. The search for periodic signals was performed in the range 0.01–1000 s with the event files and 0.2–1000 s with the binned light curve. We used the Z2 and the Lomb-Scargle periodogram techniques (Scargle 1982; Lomb 1976; Buccheri et al. 1983). No statistically significant periodicity was detected. During this flare, IGR J08408–4503 was outside of the JEM-X FOV. We estimated a $2\sigma$ upper limit to the pulsed fraction of 55% and 50% for periods in the ranges 0.2–10 s and 10–1000 s, respectively.

We performed an analysis of all the available photometric data of IGR J08408–4503 collected by the Optical Monitoring Camera (OMC; Mas-Hesse et al. 2003) on board INTEGRAL.

This camera has a much smaller FOV compared to ISGRI (4.979° × 4.979°) and it is equipped with a Johnson V filter. We reduced the data following the prescriptions of the OMC Analysis User Manual3. Since IGR J08408−4503 is bright (V ≈ 7.5), we considered only the observations with integration time of 10 s because they allow a good measurement of the magnitude without pixel saturation. We thus selected 124 “good” observations of IGR J08408−4503. Figure 3 shows the light curve as a function of time (top panel) and folded with the orbital period of the source (bottom panel), where phase zero corresponds to the periastron passage. The OMC light curve presented here is, to the best of our knowledge, the most detailed and long photometric monitoring of this source. It shows irregular variability with amplitudes up to ∼ 0.14.

3. Results and discussion

The bright X-ray flares of IGR J08408−4503 previously observed and the last flare detected by INTEGRAL and reported in this work are clustered around the periastron, within the orbital interval ∼ 0.84−0.14. The long Suzaku observation carried out during the same orbital phases of the flares shows a variable low luminosity state of ∼ 10^{32−33} erg s^{-1} (Sidoli et al. 2010), which implies a luminosity dynamic range of Γ = 10^3−10^6. Based on the calibration of O star parameters provided by Martins et al. (2005), we found that the average radius of the donor star of IGR J08408−4503, $R_d ≈ 22 R_\odot$, is larger than the size of its Roche lobe at the periastron, $R_{l,d} ≈ 14.4 R_\odot$, calculated with the formula provided by Eggleton (1983, Eq. (2)) assuming the stellar and orbital parameters previously adopted in this work (see Fig. 1, where the dotted circle shows the $R_{l,d}$ at periastron). The dot-dashed line of Fig. 1 shows the fraction of the orbit where the system is in Roche lobe overflow (RLO; i.e. when $R_d ≥ R_{l,d}$). We obtained similar results using the calibration of O star parameters provided by Vacca et al. (1996), although in this case the radius of the donor star results to be larger than the periastron distance. The strong tidal interaction that would be caused by the periodic passage of the NS inside the photosphere of the companion star would likely produce a displacement of a significant fraction of the photosphere itself. Consequently, this would lead to a periodic optical luminosity and column density variability. In addition, the high mass accretion rate at $\phi = 0$, where the NS would be inside the companion star, would cause a higher rate of X-ray flares at $\phi = 0$. Since none of these properties has been observed in
IGR J08408–4503, this suggests that the radius of the donor star is likely to be smaller than the periapstron distance. With the information about the visual magnitude measured by the OMC (\(m_V = 7.55 \pm 0.05\)), the distance (\(d = 2.21^{+0.14}_{-0.12}\) kpc), the effective temperature (\(T_{	ext{eff}} = 32,274 \pm 1,800\) K, Martins et al. 2005)\(^4\), the absorption (\(N_{\text{HI}} = 5.5 \pm 0.4 \times 10^{21} \text{cm}^{-2}\))\(^5\), and assuming that the radiation from the donor star is a black body, we found a radius of \(R_D = 23.4^{+0.4}_{-0.3} R_\odot\). Although it is not well constrained, we note that it is consistent with the values of \(R_D\) mentioned above for this type of stars, and thus consistent with the RLO hypothesis. Using the \(B\) and \(R\) magnitudes from the United States Naval Observatory B1 (USNO B1) catalogue (Monet et al. 2003) and the extinction law of Cardelli et al. (1989), we obtained \(R_d = 23.3^{+0.8}_{-1.3} R_\odot\). The larger uncertainty of this estimate is due to the worst photometric accuracy of the USNO B1 catalogue with respect to the OMC measurements.

Regős et al. (2005) studied the mass transfer in eccentric binaries in which RLO is expected to occur. They found that for high eccentricities (\(e \geq 0.6\)), a high mass transfer at periapstron is possible, and matter leaves the donor star through the Lagrangian points \(L_1\) and \(L_2\). A fraction of the matter leaving \(L_2\) falls back to the star, while the other part does not remain bound to the star. Similarly, part of the stream passing through \(L_1\) leaves the system, while most of it forms an accretion disc. Given the orbital parameters, this mechanism might be at work in IGR J08408–4503. The stream of matter lost by the donor star through \(L_2\) could make the environment around the binary system not “cleaned”: slow and denser regions of gas could be crossed by the NS along its orbit, feeding further the NS. In this scenario, the aperiodic optical variability shown by IGR J08408–4503 in the OMC light curve (Fig. 3) might be caused by sporadic absorption of dense clumps of gas lost from \(L_1\) and \(L_2\) crossing the line of sight, or by tidal interactions between the two stars, which disrupts the outer layers of the photosphere of HD 74194. As previously mentioned, another possible peculiarity of IGR J08408–4503 is the short distance between the NS and the surface of the donor star at periapstron, which is just \(\sim 5 \times 10^{10} \text{cm}\), assuming \(R_D = 22 R_\odot\) (the periapstron distance is \(\sim 22.9 R_\odot\)). This would imply that there is likely not enough space for an accretion disc which, once formed during the orbital phases preceding \(\phi \approx 0\), might be disrupted by the tidal interactions with the donor star. A slightly smaller radius for the supergiant would increase the chances of survival of the disc; for example, if \(R_D \approx 19 R_\odot\), i.e. the radius of HD 75211, a O8.5IIb star (Markova et al. 2018).

If the NS of IGR J08408–4503 is fed by an accretion disc, the high X-ray variability could be caused by transitions from inhibition of accretion (during low luminosity states) to the accretion regime (during flares). This would be possible for small variations of the mass rate gravitationally captured by the NS (\(\dot{M}_\ast\)) if the corotation radius

\[
r_{\text{co}} = \left[ \frac{GM_\ast}{\xi \mu \dot{M}_\ast} \right]^{1/3},
\]

defined as the distance from the NS where material in a Keplerian orbit corotates with the NS, is comparable in size to that of the inner radius of the disc; this is defined as the distance from the NS where the magnetic pressure and pressure exerted by the matter in the disc are balanced:

\[
r_{\text{m}} \approx \xi \mu \dot{M}_\ast \left(\frac{GM_\ast M_\ast^2}{c^3}\right)^{1/7}. \tag{2}
\]

In these equations, \(\dot{M}_\ast\) is the mass of the NS and \(\dot{P}_{\text{spin}}\) its spin period, \(\xi \approx 0.4\) in case of accretion from a Keplerian disc or 1 in case of spherical accretion (see Revnivtsev & Mereghetti 2015 and references therein), \(\mu\) is the magnetic dipole moment, \(B = 2\mu |\mathbf{R}_{\text{NS}}|\) is the magnetic field strength at the poles, and \(R_{\text{m}}\) is the radius of the NS.

If \(r_{\text{m}} > r_{\text{co}}\), the centrifugal barrier sets in. During this stage the accretion is expected to be negligible. Once \(r_{\text{m}} \approx r_{\text{co}}\), the centrifugal barrier is overcome and accretion sets in. In this framework, we can consider the following very simplified calculations. We assume that during the accretion state the X-ray luminosity is given by \(L_{\text{acc}} = GM_\ast M_\ast / R_{\text{m}}\). When the magnetic barrier activates (\(r_{\text{m}} = r_{\text{co}}\)) for small variations of \(M_\ast\), which for simplicity can be considered constant in our calculations, this value reduces to \(L_{\text{acc}} \approx GM_\ast M_\ast / r_{\text{co}}\). Therefore, \(r_{\text{co}}\) can be expressed as a function of \(\Gamma = L_{\text{acc}} / L_{\text{gate}}\

\[
r_{\text{co}} \approx R_{\text{m}} \Gamma. \tag{3}
\]

Assuming again \(r_{\text{m}} = r_{\text{co}}\), from Eqs. (2) and (3), we obtain the following relation between \(\mu, L_{\text{acc}}, \text{ and } \Gamma\):

\[
\mu = \frac{e^{-3/4} R_{\text{m}}^{3/4} \Gamma^{7/4} G^{-1/4} M_\ast^{-1/4} L_{\text{acc}}^{1/2}}{\xi^{1/2} \dot{P}_{\text{spin}}^{1/2} \xi^{1/2} \dot{M}_\ast^{1/2}}. \tag{4}
\]

Assuming \(\Gamma = 10^3 - 10^4\), \(L_{\text{acc}} = 10^{36} \text{erg s}^{-1}\), \(R_{\text{m}} = 12 \text{ km}, \) \(M_\ast = 1.61 M_\odot\), and \(\xi = 0.4\), we find \(\mu = 1.1 \times 10^{13} - 6.2 \times 10^{22} \text{ G cm}^3\) and hence \(B = 1.3 \times 10^{13} - 7.2 \times 10^{14} \text{ G}\). From Eq. (1) we then obtain \(\dot{P}_{\text{spin}} = 18 - 570 \text{ s}\), while the corotation radius is \(r_{\text{co}} = 1.2 \times 10^9 - 1.2 \times 10^{10} \text{ cm}\). These calculations indicate a magnetar nature for the compact object of IGR J08408–4503 for a wide range of values of \(\Gamma\). The lack of clear signatures for the presence of an accretion disc in the X-ray spectrum of IGR J08408–4503 in the spectral analyses presented in previous works is in agreement with the high magnetic field and low spin period inferred from the calculations presented above. If \(r_{\text{m}} = r_{\text{co}}\), from the equation of the spectrum emitted by an optically thick accretion disc (e.g. Frank et al. 2002, Eq. (5.43)),

\[
T(r) = \frac{3GMM_c}{8\pi \rho c^2 \sigma} \left( 1 - \sqrt{\frac{R_m}{r}} \right)^{1/4},
\]

where \(\sigma\) is the Stefan-Boltzmann constant, we obtain \(T(r_{\text{m}}) \approx 1 \text{ eV}\), which means that an accretion disc would be too cold to be observed in X-ray.

A possible problem for the accretion disc scenario is that the bright flares (\(L_{\text{m}} > 10^{36} \text{erg s}^{-1}\)) are clustered in an interval of the orbit around the periastron (\(\Delta \phi \approx 0.3\)). We expect a higher mass accretion rate in this interval of the orbit because of RLO and because the stellar wind is denser and slower closer to the donor star. However if the accretion is mediated by a disc, the NS would feel effects of the mass accretion rate variability with a time delay, which is of the order of the viscous timescale (\(\approx \) days; for IGR J08408–4503) and not necessarily in phase with the orbital period. One possibility previously mentioned is that the size of the donor star is so large that the accretion disc is disrupted by tidal interactions at \(\phi \approx 0\). In this case, the accretion is spherically symmetric along the orbit – no delay effects

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\(^4\) The error on \(T_{\text{eff}}\) is a rough estimate obtained by the values in Tables 3 and 6 of Martins et al. (2005).

\(^5\) Obtained from the XMM-Newton observations of IGR J08408–4503 during the low luminosity state and reported in Sidoli et al. (2013). We only considered the absorption affecting the MEKAL (Mewe-Kaasstra-Liedahl) component to exclude the absorption produced around the accreting compact object. The column density is obtained from the weighted mean of the values reported in Table 3 of Sidoli et al. (2013), with uncertainties corrected to \(1\sigma\) confidence level. We converted \(N_{\text{HI}}\) to \(A_V\) using the formula presented in Güver & Özel (2009) and taking into account the uncertainties reported in their paper.
are expected – and the gating mechanism model of Bozzo et al. (2008) can be applied. In this framework, the denser streams of accretion disc by Roche lobe overflow among SFXTs. To the best of our knowledge, there are at least two other cases: IGR J16418−4514 and IGR J16479−4514. Their orbital, stellar, and Roche lobe properties are reported in Table 2. While for reasonable values of the radius, the donor star of IGR J16479−4514 are large compared to its Roche lobe (see Sidoli et al. 2012 and Drave et al. 2013, for further discussions). In particular, we note that with the parameters reported in Table 2, the radius of the donor star of IGR J164618−4532 would be slightly larger than the orbital size, which is obviously not possible. According to Crowther et al. (2006), the radii of B 0.5la stars can be significantly different between different stars. Although on average they are ∼33−34 R⊙, for example another star of similar spectral type, κ Ori, has R⊙ ≈ 22.2 R⊙, which would still imply R⊙ ≳ R⊙, for IGR J164618−4532.

The formation of accretion discs through RLO could therefore be a property common to a group of SFXTs. This hypothesis, however, requires further investigation. Therefore, in-depth optical observations and X-ray studies aimed at determining more precisely the masses and radii of the SFXTs reported in Table 2 and the presence of an accretion disc are of fundamental importance.

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