Dust-scattering Halo and Giant Hard X-Ray Flare from the Supergiant Fast X-Ray Transient IGR J16479−4514 Investigated with XMM-Newton and INTEGRAL

V. Sguera1, A. Tiengo2,3,4, L. Sidoli4, and A. J. Bird5

1 INAF–OAS, Osservatorio di Astrofisica e Scienza dello Spazio, Area della Ricerca del CNR, via Gobetti 101, I-40129 Bologna, Italy; vito.sguera@inaf.it
2 Scuola Universitaria Superiore IUSS Pavia, Piazza della Vittoria 15, I-27100 Pavia, Italy
3 Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Pavia, via A. Bassi 6, I-27100 Pavia, Italy
4 INAF-IASF, Istituto di Astrofisica Spaziale e Fisica Cosmica, Via A. Corti 12, I-20133 Milano, Italy
5 School of Physics and Astronomy, University of Southampton, University Road, Southampton SO17 1BJ, UK

Received 2020 April 20; revised 2020 July 27; accepted 2020 July 27; published 2020 August 27

Abstract

We report results from the analysis of XMM-Newton and INTEGRAL data of IGR J16479−4514. The unpublished XMM-Newton observation, performed in 2012, occurred during the source eclipse. No pointlike X-ray emission was detected from the source; conversely, extended X-ray emission was clearly detected up to a size distance compatible with a dust-scattering halo produced by the source X-ray emission before being eclipsed by its companion donor star. The diffuse emission of the dust-scattering halo could be observed without any contamination from the central point X-ray source, compared to a previous XMM-Newton observation published in 2008. Our comprehensive analysis of the 2012 unpublished spectrum of the diffuse emission, as well as the 2008 reanalyzed spectra extracted from three adjacent time intervals and different extraction regions (optimized for pointlike and extended emission), allowed us to clearly disentangle the scattering halo spectrum from the residual pointlike emission during the 2008 eclipse. Moreover, the pointlike emission detected in 2008 could be separated into two components attributed to the direct emission from the source and scattering in the stellar wind, respectively. From archival unpublished INTEGRAL data, we identified a very strong (~3 × 10^{35} \text{ erg cm}^{-2} \text{ s}^{-1}) and fast (~25 minute duration) flare that was classified as a giant hard X-ray flare, since the measured peak luminosity is ~7 × 10^{37} \text{ erg s}^{-1}. Giant X-ray flares from supergiant fast X-ray transients are very rare; to date, only one has been reported from a different source. We propose a physical scenario to explain the origin in the case of IGR J16479−4514.

Unified Astronomy Thesaurus concepts: Accretion (14); High mass x-ray binary stars (733); X-ray transient sources (1852)

1. Introduction

One of the major outcomes of the INTEGRAL mission, launched in 2002, has been the discovery of a new class of supergiant high-mass X-ray binaries (SGXBs) during systematic scans of the Galactic plane: the supergiant fast X-ray transients (SFXTs; Sguera et al. 2005, 2006). They usually host a neutron star orbiting around an early-type supergiant star (Negueruela et al. 2006). In the X-ray band, they show a rather well-defined set of peculiar characteristics (see Sidoli 2017 for a recent review) that were never seen in previously known classical SGXBs: (i) bright (~10^{36} \text{ erg s}^{-1}) and fast (a few hours to a few days) X-ray transient behavior, (ii) high dynamic ranges of 10^{7}−10^{9}, and (iii) low duty cycles of 0.1%−5% when observed above 20 keV.

One of the very first discovered SFXTs is IGR J16479−4514. It was newly discovered by INTEGRAL in 2003 as an unidentified X-ray transient with no constrained duration (Molkov et al. 2003), and further in-depth studies unveiled its peculiar fast X-ray transient nature (Sguera et al. 2005, 2006). Subsequent near-infrared spectroscopy allowed the identification of its optical counterpart as a supergiant star with a poorly constrained distance (Chatty et al. 2008; Nespoli et al. 2008). Coley et al. (2015) recently reported the best constrained spectral type (O7 and earlier) and distance (in the range 4.4−4.6 kpc) for the companion donor. The X-ray behavior of the source has been investigated with different satellites, e.g., INTEGRAL (Sguera et al. 2008), Swift (Romano et al. 2008; Bozzo et al. 2009), and Suzaku (Sidoli et al. 2013). To date, IGR J16479−4514 is the SFXT with the shortest known orbital period (~3.3 days; Jain et al. 2009); interestingly, a superorbital period of ~11.88 days has been detected as well from Swift and INTEGRAL observations (Corbet & Krimm 2013; Drave et al. 2013). The source duty cycle value is one of the highest among the entire sample of firm SFXTs (~3.3%; Sidoli & Paizis 2018). It is known that IGR J16479−4514 displays X-ray eclipses, as discovered during an XMM-Newton observation that covered part of the eclipse ingress along with part of its total phase (Bozzo et al. 2008).

Here we report new results on IGR J16479−4514 as obtained from an unpublished targeted XMM-Newton observation and archival INTEGRAL data.

2. Data Analysis

Throughout the paper, spectral analysis was performed using XSPEC version 12.9.0, with the photoelectric absorption model based on the Balucinska-Church & McCammon (1992) cross sections and Anders & Grevesse (1989) solar abundances. To properly use the χ^2 statistics in model fitting, all of the spectra were grouped to a minimum of 30 counts per energy bin. Unless stated otherwise, errors are quoted at the 90% confidence level for a single parameter of interest.

2.1. INTEGRAL

For our study, we used data collected with the ISGRI detector (Lebrun et al. 2003), which is the lower-energy layer of the IBIS...
The IBIS/ISGRI public data archive (from revolution 30 to 1500, i.e., from approximately 2003 to 2015 January) has been specifically searched for very powerful hard X-ray flares from IGR J16479–4514 detected at science window (ScW) level (∼2000 s duration). In particular, the data set consists of 9578 ScWs where IGR J16479–4514 was within the total instrument field of view (FoV) of 29° × 29° (down to zero response), i.e., regardless of its off-axis angle. For the sake of completeness, we note that a 12° limit is generally applied because the response of IBIS/ISGRI is not well modeled at large off-axis values, and this may introduce a systematic error in the measurement of the source fluxes. However, our specific aim is to search for exceptionally powerful outbursts (i.e., flux greater than at least 500 mCrab, as explained later in the text) that are likely very rare events. To increase the probability of finding such events, we deliberately did not place any requirement on the off-axis angle of the source; the larger the considered FoV, the greater we deliberately did not place any requirement on the off-axis response of IBIS/ISGRI even when their position is in the partially coded region of the FoV. The IBIS/ISGRI flux maps for each ScW were generated in the 18–60 keV band using the offline scientific analysis software OSA 10.2. Count rates at the position of the source were extracted from individual ScW flux maps. This approach is particularly efficient in unveiling fast transient flares lasting only a very few hours, since the search occurs on the same timescale as the outbursts themselves. In order to specifically search for the most powerful flares, we adopted a conservative source count rate threshold of 80 counts s⁻¹ (18–60 keV) as measured in the single ScW containing the peak of the flare; it translates into an 18–60 keV flux of ~500 mCrab by assuming a Crab-like energy spectrum with a photon index equal to 2.1. Throughout the paper, the conversion from the source count rate to mCrab flux has been obtained by using the most recent Crab observations at the time of writing (revolution 1856, 2017 August), i.e., 1 Crab = 158.13 counts s⁻¹ (18–60 keV). The search was initially performed in the energy band 18–60 keV; then, when a candidate fast flare was found, we also checked the detection in different energy ranges (i.e., 17–30 and 20–40 keV) in order to maximize the source’s best significance detection. After finding a flare, we performed a more detailed timing and spectral analysis. For the latter, we used the standard 13 energy channel response matrix available at the INTEGRAL Science Data Centre (ISDC).

In addition to the investigation of the entire public archive, we have also specifically analyzed an archival targeted INTEGRAL observation of IGR J16479–4514 (revolution 1203, 2012 August), not yet published in other works, that was simultaneous with an unpublished XMM-Newton observation whose results are reported for the first time in Section 3.1.

2.2. XMM-Newton

The XMM-Newton Observatory (Jansen et al. 2001) carries three 1500 cm² X-ray telescopes, each with a European Photon Imaging Camera (EPIC; 0.2–12 keV) at the focus. One of the EPICs uses a pn CCD (Struder et al. 2001), while the other two are equipped with MOS CCDs (Turner et al. 2001).

We discuss here two observations, one performed in 2012 (never reported in the literature) and another done in 2008 (Bozzo et al. 2008), that we have reanalyzed for comparison to obtain a more complete view of the phenomenology during the X-ray eclipse.

On 2012 August 21, IGR J16479–4514 was observed with XMM-Newton from 11:31:03 to 18:04:47 UTC, a net exposure of ~23.9 ks, during an observation simultaneous with part of the abovementioned INTEGRAL observation. The particle background during the XMM-Newton observation was very stable. All three EPIC cameras operated in large-window mode and adopted the medium filter. Data were reprocessed using version 16.0.0 of the Science Analysis Software (SAS) with standard procedures and the appropriate calibration files. The response and ancillary matrices were generated using the SAS metatasks rmfgen and arfgen. Event patterns 0–4 were used when extracting EPIC pn products, and patterns 0–12 were used for both of the MOS cameras.

The XMM-Newton exposure was affected by stray-light contamination produced by a bright source outside the FoV, as it is clearly evident in Figure 1 (top panel). The contaminating source is the LMXB GX 340+0, which is ~35' from IGR J16479–4514. Since GX 340+0 is highly absorbed, its contribution at low energies is negligible (Figure 1, bottom panel).

The source was also observed in 2008, from March 21 14:40 to March 22 01:30, for a net exposure time of about 30 ks, with the EPIC pn in small-window mode and the MOS in full frame. The MOS observations also suffered from stray-light contamination during this observation.

3. Results

3.1. XMM-Newton

The 2012 XMM-Newton observation was also performed during the source eclipse according to the most recent ephemeris reported by Coley et al. (2015): orbital period $P_{orb} = 3.31961$ days, mid-eclipse time $t_{mid} = 55,081.571$ MJD, eclipse duration $\Delta \phi = 0.177$, eclipse at orbital phase $\phi = 0.0$. The EPIC pn exposure covers the time interval 56,160.4995–56,160.75047 (MJD), implying an orbital phase range $\Delta \phi = 0.02–0.09$. The eclipse ingress started on 56,160.15 MJD, 0.35 days before the start of the EPIC pn exposure. At odds with the XMM-Newton observation performed in 2008, which caught the source during the eclipse ingress (Bozzo et al. 2008), IGR J16479–4514 was not detected by XMM-Newton (Figure 1); running the detection SAS metatask edetect_chain on the three EPIC cameras separately, the three final source lists did not include any point source positionally coincident with IGR J16479–4514.

Nevertheless, there is evidence for the presence of diffuse X-ray emission, mainly at low energies, around the source position in the EPIC pn exposure (Figure 1; net exposure of 21.7 ks). This finding is confirmed by the radial distribution of the X-ray emission extracted from within 1' of the Two Micron All Sky Survey (2MASS) source position. We compared this profile with the distribution expected from a pointlike source (Figure 2), resulting in a clearly diffuse emission. Since soft X-rays are efficiently scattered by interstellar dust, this diffuse emission might be the X-ray halo produced by the bright X-ray emission of IGR J16479–4514 before eclipse scattered by a large number of dust grains along the line of sight. Depending on the scattering angle and the distance of the dust, due to the longer path, the scattered emission can reach the observer with a time delay up to several days (see, e.g., Pintore et al. 2017 and references therein).
3.1.1. XMM-Newton Spectroscopy

The EPIC pn, MOS1, and MOS2 spectra of the diffuse X-ray emission observed in 2012 were extracted from an annular region with an inner radius of 20″ and outer radius of 40″ centered at the IGR J16479–4514 position. The background for the three cameras was extracted from two rectangular regions located in the same CCD and not contaminated by stray light, with a total area of 7200 arcsec².

To test the dust-scattering halo hypothesis and search for spectral evolution during eclipse, we compared the background-subtracted spectrum to the corresponding spectra extracted in different time intervals from the 2008 XMM-Newton observation, where the presence of a dust halo was already suggested (Bozzo et al. 2008). In this case, only pn data can be used because the stray light from GX 340+0 in the MOS cameras reached the region where IGR J16479–4514 is located. That observation started at the beginning of the eclipse, and Bozzo et al. (2008) performed a time-resolved spectral analysis by dividing the observation into two time intervals, corresponding to the initial 4 ks of high, rapidly decaying flux and the remaining 28 ks of low, almost constant flux. To better separate the direct and scattered components, which are expected to have different spatial distribution and temporal evolution, we extracted and analyzed spectra from three time intervals (see Figure 3), also sampling the possible evolution during the low flux state, and from two different extraction regions: a 10″ circle to maximize the contribution from the central point source and the same annulus used for the 2012 spectrum to study the evolution of the possible dust-scattering halo.

Similarly to Bozzo et al. (2008), we adopt a spectral model consisting of three power-law, two Gaussian, and two photoelectric absorption components, combined as follows:

$$I(E) = e^{\sigma(E)N_{\text{H}}}[e^{\sigma(E)N_{\text{H}}}I_{1}E^{-\alpha} + I_{2}E^{-\beta} + I_{\text{halo}}e^{-(E-E_{\text{halo}})^2/(2\sigma_{\text{halo}}^2)} + I_{\text{ln}}e^{-(E-E_{\text{ln}})^2/(2\sigma_{\text{ln}}^2)}].$$  \hspace{1cm} (1)

We use this model to simultaneously fit the nine available spectra (extracted from both a 10″ circle and a 20″–40″ annulus in the three time intervals of the 2008 observation and only from a 20″ to 40″ annulus in the 2012 observation), linking together several parameters and forcing to a null normalization all of the spectral components not significantly required to model each spectrum. The width of the two emission lines was fixed to the instrumental spectral resolution. The resulting best-fit parameters are reported in Table 1.

The spectral lines were significantly detected, with consistent parameters, only in the point-source emission. On the other hand, the steepest power-law component, which can be interpreted as the contribution from the dust-scattering halo, was required only in the fit of the spectra of the diffuse component. The other two power-law components have the same slope, but one of them is detected only during the first time interval and requires an additional photoelectric absorption component. These two components can be attributed to direct and small-scale scattered emission from the point source, but, due to the relatively coarse point-spread function of the
3.2. INTEGRAL

3.2.1. Archival Search for Powerful Flares

Our search found a very powerful, fast hard X-ray flare from IGR J16479–4514. Here we report on the collected results. It was detected with a significance of $\sim 9\sigma$ (18–60 keV) during only one ScW (no. 43) in revolution 663, at MJD 54,544.96. Notably, the source off-axis angle was $\sim 17^\circ.5$. The measured average 18–60 keV flux was $630 \pm 70$ mCrab, or $\sim 8.2 \times 10^{-9}$ erg cm$^{-2}$ s$^{-1}$. No detection was obtained in the higher energy band 60–100 keV. The ScW spanned a time range from 2008 March 19 22:37 to 23:30 (UTC).

Figure 5 shows the 18–60 keV IBIS/ISGRI source light curve extracted from the entire ScW with a bin time of 50 s. A single flare is very evident, being characterized by a duration of $\sim 25$ minutes, as well as a remarkable peak count rate of $\sim 330$ counts s$^{-1}$, which translates into a flux of $2.10 \pm 0.26$ Crab (or $\sim 2.7 \times 10^{-8}$ erg cm$^{-2}$ s$^{-1}$). From the light curve, we note that the duration of the flare is a bit shorter than the entire duration of the ScW. Bearing this in mind, we performed an imaging analysis with the good time interval (GTI) by considering only the time interval of the transient activity (i.e., from $\sim 2700$ to $\sim 4300$ s on the x-axis in Figure 5). By doing so, the source was significantly detected at a $13.3\sigma$ level (18–60 keV) despite being located at a large off-axis angle, as can be seen in the significance image in Figure 6.

Unfortunately, the source was out of the IBIS/ISGRI FoV in observations performed immediately before and after the ScW containing the detection of the flare; thus, it is not possible to investigate with IBIS/ISGRI whether further flares took place or not. The BAT hard X-ray transient monitor on board Swift is particularly suited to this aim, since it provides much more continuous coverage thanks to its very large FoV. We retrieved the 15–50 keV Swift/BAT light curve averaged on an orbital timescale (\(\sim 96\) minutes) from the publicly available BAT monitor web page (Krimm et al. 2013). As shown in Figure 7, no additional X-ray activity has been detected immediately before or after the occurrence of the flare. The shadowed area indicates the flaring activity detected by IBIS/ISGRI during the single ScW. We remark that both INTEGRAL/IBIS and Swift/BAT provide complementary information: (i) the continuous coverage by BAT allows us to exclude the occurrence of further X-ray activity before and after the flare, and (ii) the finer IBIS/ISGRI light curve (50 s bin time), with respect to the BAT light curve (95 minute bin time), allows us to unambiguously catch and estimate its exact peak time and flux, respectively.

Figure 8 shows the IBIS/ISGRI light curve of the source (18–60 keV) phase-folded on the orbital period. It is clearly modulated by the deep X-ray eclipse (yellow shaded area in Figure 8), which is consistent with the compact object being totally eclipsed by the supergiant companion. According to the most recent and precise ephemerides of Coley et al. (2015), i.e., the epoch of the mid-eclipse MJD 55,081.57 as $\phi = 0$, the powerful X-ray flare detected by INTEGRAL took place at orbital phase $\phi \sim 0.65$ (thick gray line in Figure 8).

We searched for possible periodicities in the IBIS/ISGRI data of the bright flare, which eventually could be interpreted as the possible pulse period of a neutron star compact object. A very fine bin time (0.1 s) ISGRI light curve (18–60 keV) was extracted from the flare using the ii-light tool in OSA 10.2, and solar system barycenter correction was applied to the photon arrival times. Periodicities were searched in the frequency range from $0.000628$ Hz ($\sim 1590$ s, after which the sensitivity is reduced due to the finite length of the ISGRI light curve) to 5 Hz (0.2 s, corresponding to the Nyquist frequency of the data set). Power spectra were generated using the fast Fourier transform analysis and the Lomb–Scargle periodogram technique, but no statistically significant evidence for coherent modulation was found. We estimated a $3\sigma$ upper limit to the pulsed fraction of $\sim 5\%$ (18–60 keV). Given the exceptionally high flux of the source, we have also performed a timing analysis without the image deconvolution in a nonbinning way (i.e., starting from the single events). This method is particularly suited to search for very fast pulsations, e.g., up to a few milliseconds. To optimize the search, we selected events according to the pixel illuminated factor (PIF), which is the fractional area of each pixel exposed to the source. In particular, only photons from pixels fully illuminated by the source (PIF = 1) were considered. By applying such a PIF filter, it is possible to reduce the background and thus increase the signal-to-noise ratio. After barycentric correction of the photon arrival times in the original event lists, we performed both Lomb–Scargle and fast Fourier transform analysis, searching for periodicities as above; however, no significant evidence for a peak in the power spectra was found.
3.2.2. Targeted Observation

INTEGRAL performed a targeted observation of IGR J16479−4514 during revolution 1203, from 2012 August 21 04:30:00 to 21:25:42 UTC. The source was in the fully coded FoV of IBIS/ISGRI for a total effective on-source exposure of \( \sim 16 \) ks. As shown in Figure 8 (where the orbital phases corresponding to the start and end time of the INTEGRAL observation are indicated by two blue lines), almost the entire observation took place during the eclipse, when the compact object is totally eclipsed by the supergiant companion donor.

The IBIS/ISGRI mosaic was made in the energy band 22–60 keV (to take into account the evolution of the IBIS/ISGRI energy threshold that occurred from revolution number 900 on). The source was not detected in the mosaic or any single ScW. As a result, we inferred a 22–60 keV \( 3\sigma \) upper limit of 4.6 mCrab (\( \sim 5 \times 10^{-11} \) erg cm\(^{-2}\) s\(^{-1}\)). For comparison, we note that the lowest out-of-outburst, as well as out-of-eclipse, hard X-ray emission detected by IBIS/ISGRI is known to be of the order of \( \sim 1.7 \times 10^{-11} \) erg cm\(^{-2}\) s\(^{-1}\) (20–60 keV; Walter & Zurita Heras 2007; Sguera et al. 2008), i.e., only a factor of 3 lower than this upper limit during the eclipse.

4. Discussion

4.1. X-Ray Eclipse

During the XMM-Newton observation performed in 2012, no pointlike X-ray emission was detected from IGR J16479–4514. However, extended X-ray emission was clearly observed up to a distance of at least 40″. As already noted by Bozzo et al. (2008), such a size is compatible with a dust-scattering halo produced by the X-ray emission of IGR J16479–4514 before being eclipsed by its companion. Also, its spectrum, significantly softer than the typical spectrum of this X-ray source out of eclipse, is consistent with that expected from dust scattering, whose efficiency steeply decreases with photon energy (see, e.g., Figure 6 in Draine 2003).

From a time-resolved spectral analysis of the 2008 observation, performed immediately after a bright flare and during earlier phases of the eclipse, we could clearly disentangle the scattering halo component from two distinct components from the central point source. The brightest one is detected only during the initial phases of the eclipse and characterized by a very significant excess of photoelectric absorption and can therefore be attributed to the direct emission from IGR J16479–4514 passing through a dense local environment. The second pointlike component is instead detected throughout the full 2008 observation and declines faster than the dust-scattering halo (see Figure 4); its spectral slope is comparable to the direct component, but its absorption is much smaller and, also considering the large equivalent width of the detected emission lines, can be attributed to scattering in the stellar wind. The largest absorption of the direct component suggests the presence of an absorbing structure in the orbital plane, which does not obscure the scattered emission, emerging more clearly during eclipse. A spatially larger but much less dense structure surrounding IGR J16479–4514 might be responsible for part of the absorption affecting all of the spectral components, since its value of \( N_\text{H} = (6 \pm 2) \times 10^{22} \) cm\(^{-2}\) is significantly larger than the total Galactic absorption column expected in this sky direction (\( N_\text{H} \sim 2 \times 10^{22} \) cm\(^{-2}\); Willingale et al. 2013). However, we note that a similar excess is measured in two nearby bright X-ray...
binaries, GX 340+0 (Miller et al. 2016) and XTE J1652–453 (Hiemstra et al. 2011); therefore, its origin might be the complex structure of the interstellar medium in this Galactic region rather than the local environment of IGR J16479–4514.

The comparison of the fluxes of the different components shows how the contribution from the dust-scattering halo increases at later eclipse phases (see Figure 4). Moreover, the flux of the halo during the 2012 observation is more than three times smaller than that during the 2008 observation, which indicates that the flux of IGR J16479–4514 out of eclipse was significantly smaller in the hours/days preceding the most recent observation. For these reasons, in 2012, the dust-scattering halo could be observed without apparent contamination from the central point source.
55,081.57, according to the most recent and precise ephemerides of Coley et al. (2015). The shaded yellow area indicates the entire duration of the X-ray eclipse. The thick gray line marks the occurrence of the powerful flare detected by IBIS/ISGRI. The two blue lines (green lines) indicate the start and end time of the targeted INTEGRAL (XMM-Newton) observation.

4.2. Giant Hard X-Ray Flare

INTEGRAL detected a fast hard X-ray flare from IGR J16479−4514 (∼25 minute duration) that reached a remarkable peak flux of 2.10 ± 0.26 Crab (18–60 keV). It translates into an X-ray luminosity of $(7.0 \pm 0.9) \times 10^{37} \text{erg s}^{-1}$ if we assume the most constrained value of 4.6 kpc for the distance to date (Coley et al. 2015). This is the most powerful flare ever detected from the source. Moreover, it is one of the most powerful flares ever detected from any SFXT, in this respect being second only to the giant soft X-ray detected from any SFXT, in this respect being second only to the IGR J16479−4514 (Romano et al. 2015), which reached a peak flux (luminosity) of 2.1 Crab $(3 \times 10^{38} \text{erg s}^{-1})$ but in the softer energy band 0.3–10 keV, so a proper comparison between the two events is not possible. Its physical origin was explained in the framework of accretion from a transient disk (Romano et al. 2015).

Previous to our current work, the dynamic range of the source above 20 keV was of the order of ∼350, as reported in the literature (Sguera et al. 2008) by considering the highest measured luminosity level in outburst $(1.5 \times 10^{37} \text{erg s}^{-1}$ at 4.6 kpc distance, 20–60 keV) and the lowest detected hard X-ray emission level outside outburst $(4.3 \times 10^{34} \text{erg s}^{-1}$ at 4.6 kpc distance, 20–60 keV). Our reported giant hard X-ray flare, the strongest ever, allows us to further push the dynamic range up to a value of ∼1630.

For the sake of completeness, we note that this flare from IGR J16479−4514 was previously studied with Swift by Romano et al. (2008). The flare triggered the BAT monitor on board Swift on 2008 March 19 at 22:44:45 UT (Barthelmy et al. 2008). Subsequently, the satellite slewed to the target with the XRT instrument; however, its observation temporally covered the flare only during its rising for about 1000 s (see shaded green area in Figure 5). Romano et al. (2008) mainly performed a Swift broadband X-ray spectral study of this flare. Here we note that, because of the partial Swift temporal coverage of the flare, which was limited only to its rising part, it was not possible to provide an exact measurement of its duration, peak time, and peak flux. Conversely, our newly reported INTEGRAL detection fully covered the entire duration of the flare, allowing such measurements and unveiling its very energetic nature. In this respect, our reported INTEGRAL results are novel and complementary with those previously reported from the Swift observation (Romano et al. 2008).

This exceptionally energetic flare raises questions as to its physical origin. Within the quasi-spherical settling accretion model of Shakura et al. (2012, 2013, 2014), the production of bright X-ray flares from SFXTs (i.e., $L_x > 10^{36} \text{erg s}^{-1}$) is triggered by the sporadic capture of magnetized stellar wind plasma by the magnetized compact object. The consequent magnetic reconnection increases the magnetospheric plasma entry rate; this results in abundant production of X-ray photons, strong Compton cooling, and, ultimately, the unstable accretion of the entire quasi-static shell previously formed above the neutron star magnetosphere. Clearly, the shell can be reformed by new wind capture, so the flare production can be repeated as long as the rapid mass entry rate into the magnetosphere is sustained. In this scenario, a bright flare must be produced on the freefall timescale of the shell (i.e., ∼1000–10,000 s) with a typical energy release of ∼10^{39} \text{erg}, corresponding to a typical mass of the shell of ∼10^{19} g. This view is broadly consistent with the typically measured energy release in known SFXT bright flares detected by INTEGRAL (in the range 10^{38}–10^{40} erg), as well as the corresponding measured mass fallen onto the compact object (10^{15}–10^{16} g; Shakura et al. 2014). As for the specific case of IGR J16479−4514, we took into account the peak luminosity of the giant hard X-ray flare and accordingly calculated the corresponding released energy and accreted mass following Shakura et al. (2014). We derived values of ∼5 × 10^{41} \text{erg} and ∼6 × 10^{41} \text{erg}, respectively. Clearly, this is an exceptional event with respect to the usual flares typically detected, since it released a much greater amount of energy and required a much larger amount of accreted material than usual.

It is known that IGR J16479−4514 undergoes regular flaring activity at a specific orbital phase $\phi \sim 0.65$ (if the epoch MJD 55,081.57 is assumed as $\phi = 0$ according to Coley et al. 2015). This interesting behavior was first reported by Bozzo et al. (2009) using Swift observations and subsequently confirmed by Sidoli et al. (2013) through a nearly complete orbital monitoring with Suzaku. This characteristic likely indicates the presence of a phase-locked large-scale structure in the supergiant wind; consequently, the flares are likely triggered by a higher accretion rate onto the compact object during its passage inside of it. We note that such large-scale structures are believed to be a ubiquitous characteristic of all isolated supergiant stars (Puls et al. 2008; Massa & Prinja 2015). In particular, corotating interaction regions (CIRs) have been suggested as a potential candidate (Mullan 1984; Cranmer & Owocki 1996), being characterized by an overdensity with respect to the unperturbed surrounding stellar wind. Since the giant flare detected by INTEGRAL occurred at orbital phase $\phi = 0.648 \pm 0.002$ (if the epoch MJD 55,081.57 is assumed as $\phi = 0$ and 3.13961 ± 0.00004 days is assumed as the orbital period according to the most recent and precise results of Coley et al. 2015), we propose that the interaction of the compact object with a CIR in the supergiant wind during its passage inside of it has provided the needed very large amount of accreted material.

In order to support our hypothesis, we note that Corbet & Krimm (2013) reported the light curve of IGR J16479−4514 folded on its superorbital period of ∼11.88 days (see their Figure 8); it clearly shows a sharp peak at a superorbital phase in the range $\Phi = 0–0.08$ (if phase $\Phi = 0$ is assumed at MJD 55,996 according to Corbet & Krimm 2013). Recently, Bozzo et al. (2017) proposed that the interaction between the compact object and the CIRs in the wind of its supergiant companion could drive the superorbital periodicities observed in some SFXTs, as well as SGXBs. When the neutron star encounters the CIR, the different
the same orbital phase; this could imply changes of the mass accretion rate related to cycle-to-cycle variations of the arm CIR density (e.g., as in the case of the wind-fed supergiant HMXB IGR J16493–4348; Coley et al. 2019).

5. Summary and Conclusions

In this work, we presented new XMM-Newton and INTEGRAL results on the SFXT IGR J16479–4514. The main results and conclusions from our analysis are as follows.

(i) No point source was detected during the unpublished 2012 XMM-Newton observation performed during eclipse. This allowed us to clearly detect, without any contamination, the diffuse soft X-ray emission discovered in the previously published 2008 XMM-Newton observation during eclipse and tentatively interpreted as a dust-scattering halo (Bozzo et al. 2008). The significantly lower flux observed in the 2012 observation strongly supports the dust halo interpretation.

(ii) A time-resolved reanalysis of the archival 2008 XMM-Newton observation, adopting more time intervals and source extraction regions (optimized for either pointlike or diffuse emission) than in Bozzo et al. (2008), has allowed us to better characterize the pointlike emission during eclipse, disentangling two components with different evolution timescales and power-law spectra with the same slope but significantly different photoelectric absorption.

(iii) INTEGRAL detected an exceptionally energetic (peak luminosity of $\sim 7 \times 10^{37} \text{erg s}^{-1}$, 18–60 keV) and fast (25 minute duration) giant hard X-ray flare. They are very rare from SFXTs; this would be only the second one reported in the literature after that from the SFXT IGR J17544–2619 detected in a much softer energy band (peak luminosity of $\sim 2 \times 10^{38} \text{erg s}^{-1}$, 0.2–10 keV)

(iv) The detected giant hard X-ray flare required an amount of accreted material ($\sim 7 \times 10^{41} \text{g}$) about 2 orders of magnitude greater than usually measured from all previously detected flares from the source. The giant flare occurred at a specific orbital phase that has been previously suggested to be linked to the presence of a stable large-scale structure in the supergiant wind. We invoke CIRs in the wind as a potential candidate, and consecutively, we propose that the interaction of the compact object with such CIRs during its passage inside of it has provided the very large amount of accreted material necessary to produce the exceptionally energetic hard X-ray flare.

We would like to thank the referee for valuable comments that helped us to improve the manuscript. L.S. thanks M. Marelli for interesting discussions. A.T. acknowledges funding in the framework of project ULTRA-ASI–INAF contract No. 2017-14-H.0.

ORCID iDs

V. Sguera @ https://orcid.org/0000-0001-8202-9381
A. Tiengo @ https://orcid.org/0000-0002-6038-1090
L. Sidoli @ https://orcid.org/0000-0001-9705-2883

References

Anders, E., & Grevesse, N. 1989, GeCoA, 53, 197
Balucinska-Church, M., & McCammon, D. 1992, ApJ, 400, 699
Barthelmy, S. D., Baumgartner, W. H., Burrows, D. N., et al. 2008, GCN, 7466, 1
