Tidal disruption of a super-Jupiter by a massive black hole

M. Nikołajuk\textsuperscript{1,2} and R. Walter\textsuperscript{1}

\textsuperscript{1} ISDC Data Centre for Astrophysics, Observatoire de Genève, Université de Genève, Chemin d’Ecogia 16, CH-1290 Versoix, Switzerland
e-mail: m.rik@alpha.uwb.edu.pl
e-mail: Roland.Walter@unige.ch
\textsuperscript{2} Faculty of Physics, University of Białystok, Lipowa 41, 15-424 Białystok, Poland

Received October 30, 2012; accepted February 13, 2013

\section*{1. Introduction}

NGC 4845 is a nearby, high surface brightness spiral galaxy with morphological type Sa(s)ab sp classified as a Seyfert 2 (Vérон-Cetty \& Véront 2006). The distance to NGC 4845 was determined as \( D = 15.6 \) Mpc based on the Tully-Fisher relation (Tully \& Fisher 1988). Corsini et al. (1999) obtained \( D = 13.1 \) Mpc by including the influence of a dark matter to the systematic velocity. We adopt in this paper \( D = 14.5 \) Mpc (\( \mathcal{H}_0 = 75 \) km s\(^{-1}\) Mpc\(^{-1}\)) after Shapley et al. (2003), who performed a thorough literature search to determine the most reliable distance of this galaxy.

The galactic disk inclination is 76\(^{\circ}\) (Pizzella et al. 2005). Coordinates of the galaxy (i.e. \( \alpha_{2000} = 12^{h}58^{m}01^{s}19 \) and \( \delta_{2000} = +01^\circ34'33''02 \), Veron-Cetty \& Véront 2010) set the Galactic neutral hydrogen column density into the direction of the source to \( N_{H}^{Gal} = 1.67 \times 10^{20} \) cm\(^{-2}\) (Dickey \& Lockman 1990, Stark et al. 1992).

NGC 4845 has been observed, so far, in the optical (e.g. by the Sloan Digital Sky Survey – SDSS, the Palomar Optical Sky Survey – POSS and the Hubble Space Telescope – HST), and in the infrared domain (by the Two Micron All Sky Survey – 2MASS and the Infrared Astronomical Satellite – IRAS) (Moshir et al. 1994, Spinoglio et al. 1995, Djorgovski et al. 1998, Sanders et al. 2003, Jarrett et al. 2003, Schneider et al. 2005).

The galaxy has also been observed by the Green Bank Telescope and the Very Large Array in the radio bands 1.4, 4.8, 8.4 GHz (Condon et al. 1998, 2002). The radio emission is dominated by star-forming regions (see Filho et al. 2004, their Fig. 5d) and does not reveal water maser emission (Braatz et al. 2003). Monitoring in the X-ray domain was carried out using the Imaging Proportional Counter onboard the \textit{Einstein} satellite (Fabbiano et al. 1992). The authors estimated only an upper limit in the 0.2-4.0 keV energy band of \( F_X < 2.52 \times 10^{-13} \) erg cm\(^{-2}\) s\(^{-1}\).

\textit{INTEGRAL} discovered a new hard X-ray source IGR J12580+0134 (Walter et al. 2011) during an observation performed in the period January 2-11, 2011, with a position (i.e. \( RA = 194^h52^m12^s \) deg \( DEC = 1^\circ57^\prime38^\prime \) deg, \( \Delta = 0.02 \) arcmin, \( J2000.0 \)) consistent with that of NGC 4845. A few days later, Swift/XRT and \textit{XMM-Newton} observations confirmed the association with the central regions of the Seyfert 2 galaxy. IGR J12580+0134 was detected at a peak flux \( F_{X} = 5 \times 10^{-11} \) erg cm\(^{-2}\) s\(^{-1}\), corresponding to a variability by a factor > 100, which is very unusual for a Seyfert 2 galaxy.

In sect. 2 we report the analysis of the available high-energy observations of IGR J12580+0134 performed with \textit{XMM-Newton}, \textit{Swift}, \textit{MAXI}, and \textit{INTEGRAL}. We analysed these results in sect. 3 and discuss them in sect. 4.

\section*{2. High-energy observations of IGR J12580+0134}

We analysed \textit{INTEGRAL}, \textit{MAXI}, \textit{Swift}, and \textit{XMM-Newton} observations of IGR J12580+0134. A log of the pointed observations is given in Tables 1 and 2. Throughout this section, all uncertainties are given at 1 sigma confidence level.
2.1. INTEGRAL

\textit{INTEGRAL} data were analysed using OSA software (ver. 9). We considered data from IBIS/ISGRI in the 17.3-80 keV. The average fluxes and spectrum were extracted from the mosaic images with mosaic specs.

\textit{INTEGRAL} observations are divided into pointings with duration of \sim 2-3 ks, which are collected during the satellite revolutions. We considered in this paper all available (i.e. 555) pointings from the discovery observation to July 21, 2011, included in revolutions 1004-1070.

Figure 1 shows the IBIS/ISGRI (Lebrun et al. 2003; Ubertini et al. 2003) mosaic obtained around IGR J12580+0134 (17.3-80 keV, significance map) accumulated from January 2 to 11, 2011. During this period the source significance reached 9.7 sigma in the 20-40 keV energy band, corresponding to a flux of $F_{20-40\text{keV}} = (2.5 \pm 0.3) \times 10^{-11} \text{ erg cm}^{-2} \text{s}^{-1}$ for an exposure time of 400 ks. The source was also detected by JEM-X (Lund et al. 2003) (3-20 keV) for an exposure time of 13 ks with a flux of $F_{3-10\text{keV}} = (5.0 \pm 1.4) \times 10^{-11} \text{ erg cm}^{-2} \text{s}^{-1}$.

We also analysed all publicly available IBIS/ISGRI data obtained on the field from the beginning of the mission up to January 27, 2011 using the HEA VENS interface (Walter et al. 2011) with OSA9. The \textit{INTEGRAL} observations performed in previous years (i.e. from 2003 to 2010) did not reveal any hard X-ray activity, and we obtained a five-sigma upper limit of $5.9 \times 10^{-12} \text{ erg cm}^{-2} \text{s}^{-1}$ in the 20-40 keV energy band.

The resulting count rates are listed in Table 3 and plotted in Fig. 2.

2.2. MAXI

NGC 4845 has been observed by the Monitor of All-sky X-ray Image (MAXI), attached to the Japanese Experiment Module onboard the International Space Station. Among the two X-ray instruments onboard MAXI, we analysed only the Gas Slit Camera (GSC) data in the present paper, because of its higher sensitivity (Matsuoka et al. 2009; Mihara et al. 2011).

Table 1. \textit{Swift} and \textit{XMM-Newton} observations of IGR J12580+0134.

| Instrument     | Obs. ID     | Start time (UTC) | Net exp. (ks) |
|----------------|-------------|------------------|---------------|
| \textit{Swift} | 00031911001 | 2011-01-12 23:59:01 | 3.0           |
| \textit{Swift} | 00031911002 | 2011-01-13 03:26:01 | 2.1           |
| \textit{XMM-Newton} | 0658400601 | 2011-01-22 16:23:28 | 14.0          |
| \textit{Swift} | 00031911003 | 2012-06-29 07:56:59 | 3.3           |

Table 2. \textit{INTEGRAL} observations of IGR J12580+0134.

| Revolutions | Start time (UTC) | Stop time (UTC) | EXP (ks) |
|-------------|------------------|-----------------|---------|
| 1004-1006   | 2011-01-02 13:51:14 | 2011-01-11 04:47:40 | 100.0 |
| 1009        | 2011-01-18 19:09:42 | 2011-01-22 01:49:00 | 1.6    |
| 1012        | 2011-01-27 10:55:12 | 2011-01-27 11:21:46 | 1.0    |
| 1052-1055   | 2011-05-28 00:16:37 | 2011-06-06 03:15:17 | 44.2   |
| 1057-1061   | 2011-06-10 03:14:24 | 2011-06-24 03:55:16 | 90.4   |
| 1063        | 2011-06-28 12:02:32 | 2011-06-30 17:10:01 | 29.0   |
| 1067-1068   | 2011-07-10 21:03:15 | 2011-07-15 16:05:07 | 45.0   |
| 1070        | 2011-07-20 08:31:40 | 2011-07-21 16:29:40 | 11.7   |

Notes. EXP indicates the effective exposure time.

Table 3. Intensities of IGR J12580+0134 observed by \textit{INTEGRAL}/ISGRI.

| START TIME (MJD) | END TIME (MJD) | Count rate (count s^{-1}) | Signific. |
|-----------------|----------------|---------------------------|-----------|
| During flare (i.e. Jan 2011) | 55542.63936 - 55563.22030 | 0.192 \pm 0.120 | 1.6 |
| 55563.57725 - 55566.56943 | 55566.22030 | 0.635 \pm 0.139 | 4.6 |
| 55566.22030 - 55569.20899 | 55569.20899 | 1.132 \pm 0.153 | 7.4 |
| 55569.20899 - 55572.19978 | 55572.19978 | 1.157 \pm 0.167 | 6.9 |
| 55572.19978 - 55579.79841 | 55579.79841 | 1.652 \pm 0.674 | 2.4 |
| During flare – total | 55563.57725 - 55579.79841 | 0.944 \pm 0.087 | 10.8 |
| After flare (i.e. Jun-Jul 2011) | 55513.98265 - 55526.153 | 0.341 \pm 0.125 | 2.7 |
| 55526.153 - 55528.78529 | 55528.78529 | 0.304 \pm 0.083 | 3.7 |
| 55528.78529 - 55572.87726 | 55572.87726 | 0.013 \pm 0.111 | 0.1 |
| After flare – total | 55513.98265 - 55572.87726 | 0.269 \pm 0.056 | 4.8 |
| Period < 2011 (Jan 2003-Dec 2010) | 52644.50424 - 55545.30596 | 0.014 \pm 0.026 | 0.5 |
| Period > 2011 (Jan-Jul 2011) | 55563.57724 | 0.470 \pm 0.047 | 9.9 |

Notes. * Data obtained through the HEA VENS interface.
Fig. 2. The light curve of IGR J12580+0134 observed in the 17.3-80 keV energy band by INTEGRAL/ISGRI (red points) and in the 2-20 keV band by MAXI (blue points). The arrow shows an upper limit. Red short-dash line indicates the 5σ upper limit of the source observed by IBIS/ISGRI before 2011. Red long-dash line shows an upper limit observed by EINSTEIN (Fabbiano et al. 1992) and interpolated to 17.3-80 keV. The interpolation is based on the model fitted to the XMM-Newton/INTEGRAL observation. The interpolated EINSTEIN flux is very likely overestimated because of the harder spectrum observed in 2011.

Figure 3 shows the MAXI light curve of NGC 4845 in the 2-20 keV band, obtained from the MAXI/GSC on-demand process interface with the source and background radii of 2 and 3 deg, respectively, centred on the galaxy.

2.3. Swift

The field of view (FOV) around IGR J12580+0134 was observed three times with Swift/XRT on January 12 and 13, 2011 and on June 29, 2012 for a total exposure of 3.1, 2.1, 3.3 ks (observations ID 00031911001, 00031911002, and 00031911003, PI Walter), respectively. We analysed data collected in photon-counting mode (PC) by using standard procedures (Burrows et al. 2005) and the latest calibration files. The Swift/XRT “enhanced” position of the source is $\alpha_{2000} = 194.50492$ deg and $\delta_{2000} = 1.57579$ deg with the error of 2.1 arcsec. To obtain those values we followed the procedure described in Evans et al. (2009) where we used the Swift/XRT-Swift/UVOT alignment and matching UVOT FOV to the USNO-B1 catalogue. We extracted light curves and spectra of IGR J12580+0134 using the Level 2 event file. No pile-up problems were found in either observation. Therefore, we used circle region with radius of 20 pixels (~47 arcsec) around the source coordinates. The background region, which lies in the no visible sources area, was also chosen as a circle with a radius of 50 pixels. There are a number of bad columns on the XRT CCD, and the corresponding pixels were not used to collect the data. To account for them, we used a corrected exposure map created with the xrtpexpomap command and used it to create the ancillary response files with the command xrtmkarf. We maximised the signal-to-noise (S/N) by summing up all the available data obtained in January 2011 (effective exposure time 5116 s). The final extracted spectrum was rebinned to have a minimum of 30 counts in each energy bin. Only 12 source photons were detected in June 2012.

2.4. XMM-Newton

XMM-Newton observed IGR J12580+0134 on January 22, 2011 (obs. ID 0658400601, total exposure time ~ 21 ks, PI Walter) and obtained a source position of $\alpha_{2000} = 194.50427$ deg and $\delta_{2000} = 1.57585$ deg. We maximised the signal-to-noise (S/N) by summing up all the available data obtained in January 2011 (effective exposure time 5116 s). The final extracted spectrum was rebinned to have a minimum of 30 counts in each energy bin. Only 12 source photons were detected in June 2012.

During this observation all the EPIC-pn and EPIC-MOS cameras were operated in full frame mode. The galaxy was observed with both the EPIC-pn and EPIC-MOS; however, in this paper we focus on the data obtained from the first detector.

We processed XMM-Newton observation data files (ODFs) with pipeline eprom (Science Analysis System, SAS, v.10.0) in order to produce a calibrated event list. The event file was filtered to exclude high background time intervals following the recommendations of the SAS analysis thread. We extracted the light curve in the 10-12 keV energy band using all field of view (FOV). We excluded from further analysis time intervals during which the count rate in the 10-12 keV energy band was higher than 14.0 count s$^{-1}$. The resulting effective exposure time was 14.02 ks. We extracted spectra and relevant light curves in the 0.1-2, 2-10, and 0.1-10 keV energy bands. Since the X-ray count rate of IGR J12580+0134 is high, we corrected the product for pile-up extracting the source in an annulus with an inner radius of 1.25 pixels. The background extraction region was chosen at ~ 9.5 arcmin from NGC 4845, far away from any sources but...
still in the same CCD of the EPIC-pn camera. All EPIC images and spectra were corrected for Out-of-Time (OoT) events. EPIC-pn spectra were rebinned before fitting so as to have at least 200 counts per energy bin.

3. Data analysis and results

3.1. Source spectrum

We extracted the XMM-Newton Epic-pn light curves in the 0.1-2 keV (Soft) and 2-10 keV (Hard) energy bands with time bins of 10 s. These two light curves (rebinned to 100 s) and the hardness ratio $HR = (\text{Hard} - \text{Soft})/(\text{Hard} + \text{Soft})$ are shown in Fig. 4, where a short time-scale variability is clearly visible. The variability time scale \( \tau \) between two points characterised by the highest difference in their count rates in 2-10 keV is equal to 90 ± 5 s (\( \Delta \text{Amplitude} = 10.5 \pm 2.0 \) count s\(^{-1}\), found between 17 and 19.5 ks in Fig. 5). The count rate in the 2-10 keV band is 6.33 count s\(^{-1}\), in average, with an observed standard deviation of 2.02 count s\(^{-1}\). It varies between 1.08 ± 0.48 and 15.33 ± 1.77 count s\(^{-1}\).

The hardness ratio does not show any significant variability suggesting that the spectral shape does not vary with flux on short time scales. To check this we extracted two spectra by selecting time intervals in which the count rate in the 2-10 keV energy band is < 6.3 and > 6.3 count s\(^{-1}\). The first spectrum (with the effective exposure time 5.9 ks) could be fitted by an absorbed power law. The resulting spectral parameters are $N_{\text{H}} = (7.43 \pm 0.14) \times 10^{22}$ cm\(^{-2}\) and $\Gamma = 2.32 \pm 0.04$ for a 2-10 keV X-ray flux of $4.95 \times 10^{-11}$ erg cm\(^{-2}\) s\(^{-1}\). The spectrum extracted at a higher count rate (effective exposure time 8.1 ks) could be described using the same model, providing good agreement with the di...
Table 4. The best-fit parameters to the *Swift* and *XMM-Newton* observations in January 2011. The fit to the 1–10 keV energy range.

| Satellite/T<sub>exposure</sub> | Data       | N<sub>HI</sub> (10<sup>22</sup> cm<sup>-2</sup>) | T (10<sup>-2</sup> photons keV<sup>-1</sup> cm<sup>2</sup> s<sup>-1</sup>) | F<sub>2-10 keV</sub> (10<sup>-11</sup> erg cm<sup>-2</sup> s<sup>-1</sup>) | χ<sup>2</sup>/d.o.f. |
|-------------------------------|------------|---------------------------------|------------------|-----------------|------------------|
| Swift/5.1ks                   | All data   | 6.53 ± 0.38                    | 2.36 ± 0.14      | 5.69 ± 1.33     | 4.968 ± 0.130    | 78.8/81          |
| XMM/5.9ks                     | Count rate < 6.3 | 7.43 ± 0.14                    | 2.32 ± 0.04      | 5.50 ± 0.39     | 4.945 ± 0.077    | 90.9/81          |
| XMM/8.1ks                     | Count rate ≥ 6.3 | 7.11 ± 0.10                    | 2.13 ± 0.03      | 5.54 ± 0.28     | 6.937 ± 0.023    | 193.7/150        |
| XMM/14ks                      | All data   | 7.21 ± 0.08                    | 2.19 ± 0.03      | 5.45 ± 0.23     | 6.088 ± 0.020    | 349.5/225        |

3.3. Duration and frequency of the flare

Because the source was still detected significantly in July 2011 by INTEGRAL, the flare probably lasted for 150 days at a level above 2 × 10<sup>−11</sup> erg cm<sup>−2</sup> s<sup>−1</sup>. MAXI observed the source continuously, but at a lower sensitivity. Therefore the flare was just detected by MAXI close to the peak in January 2011.

Such a flare of IGR J12580+0134 with a duration of 150 days has never been detected in the past ten years by INTEGRAL, and it could have been missed only between August 2006 and December 2007 when INTEGRAL did not observe that region of the sky. The flare of NGC 4845 is therefore exceptional, and no such flare was detected for a continuous period of at least 1300 days.

3.4. Black-hole mass

The mass of the central black hole, M<sub>BH</sub>, of NGC 4845 can be estimated using methods based on the X-ray variability time scale.

The upper limit of M<sub>BH</sub> can first be estimated assuming that the shortest time variability τ is related to the innermost stable circular orbit (ISCO). The *XMM-Newton* light curve observed in 2–10 keV band indicates τ < 90 ± 5 s. Additionally, assuming a non-rotating black hole, we can write that cτ = R<sub>sch</sub> = 2GM<sub>BH</sub>/c<sup>2</sup>. The observed variability time scale corresponds to M<sub>BH</sub> < 9.6 × 10<sup>6</sup>M<sub>☉</sub>.

The second technique is based on the X-ray excess variance measurements. This method uses the relationship between the black-hole mass and the X-ray variability M<sub>BH</sub> = C(T − 2σ<sub>x</sub>)/σ<sub>x</sub><sup>2</sup>, where T is the duration of the X-ray light curve and Δt is the bin size, both in seconds, and σ<sub>x</sub><sup>2</sup> = ∑<sub>i</sub>(x<sub>i</sub> − x̄)<sup>2</sup>/N is the normalised excess variance (Nandra et al. 1997; Vaughan et al. 2003; O’Neill et al. 2005). We divided the 2–10 keV *XMM-Newton* light curve into two parts with length T = 4 ks and ~10 ks in order to avoid the gap of 5 ks in the light curve. The estimated mean normalised excess variance, (σ<sub>x</sub><sup>2</sup>)<sub>10keV</sub>, of the 10 s bin light curve is 0.12 ± 0.04. Thus, the calculated central black hole mass in NGC 4845 is M<sub>BH</sub> = 2.3 ± 1.1 × 10<sup>6</sup>M<sub>☉</sub>, where we assumed C = 1.42 (i.e. that the mass of Cyg X-1 is equal to 14.8 ± 1.0 M<sub>☉</sub>; Orosz et al. 2011). The errors on the mass were estimated by performing Monte Carlo simulations (see details in Nikołajuk et al. 2004). The systematic errors, related to the calibration of the excess variance versus mass relationship, are larger and the black-hole mass could range in the interval 10<sup>6</sup>−10<sup>7</sup>M<sub>☉</sub> (O’Neill et al. 2005).

4. Discussion

4.1. Phenomenology

We first consider the possibility that the observed variability is driven by absorption, i.e. that a hole opened on the line of sight in the AGN absorbing torus. The [O III] line intensity in NGC 4845 is 5.40 × 10<sup>−15</sup> erg s<sup>−1</sup> (Ho et al. 1997). According to the X-ray –
also note that the source is not Compton thick, ([O III] have been detected, if present.

times larger (Table 4), the absorption explanation is ruled out. A strong increase in the X-ray flux, by a factor 10^2, is required. We also note that the source is not Compton thick, \( N_H \sim 7 \times 10^{22} \text{ cm}^{-2} \), see Table 4, indicating that it should be bright at hard X-rays, when active.

Supernova explosions and expanding winds may emit hard X-ray flares (Jinnler & Lewin 2003; Chandra et al. 2003; Saxton et al. 2012). Supernova peak X-ray luminosities have been observed up to \( 10^{40} \text{ erg s}^{-1} \) with a decline usually following a \( t^{-0.5-1} \) scaling. The peak X-ray luminosity of IGR J12580+0134 is 100 times brighter, and it declined much faster than observed in supernovae. This, together with the position of IGR J12580+0134 at the very centre of NGC 4845, makes the supernova interpretation of the observed flare very unlikely.

A brightening of the Seyfert nucleus by a factor 10^3 should therefore be explained by a sudden increase in the accretion rate. Tidal disruptions of objects by a massive black hole (see Komossa et al. 2004, Burrows et al. 2011, Cenko et al. 2012; Saxton et al. 2012) have been modelled and simulated by various authors (e.g. Rees 1988, Evans & Kochanek 1989, Ulmer 1999, Alexander & Kumar 2001, Alexander & Livio 2001, Li et al. 2002, Lodato et al. 2009). The induced emission follows a power law decline with a characteristic slope of \(-5/3\), corresponding to our observations.

The peak of the observed 17.3-80 keV luminosity is \( 1.5 \times 10^{42} \text{ erg s}^{-1} \). Most of luminosity of a tidal disruption event is expected to be released in the soft X-rays (and absorbed by the torus in NGC 4845). We can evaluate the maximum soft X-ray emission allowed by the data by adding a soft thermal component to the model and determine for which flux such a component would have been detected. Figure 7 shows the increase in \( \chi^2 \) obtained depending on the soft component luminosity. For a temperature of \( kT = 0.2 \text{ keV} \), which is expected in our case (see eq. 9 in Ulmer 1999), the soft component cannot be more than 10 times brighter than the hard X-ray component. The soft component could of course be brighter if it would peak at lower energies, which is however unexpected, especially for a low-mass black hole.

Assuming that the thermal emission is ten times brighter than the hard X-ray emission, the tidal event luminosity reached the Eddington luminosity at maximum with \( L_{\text{accr}}/L_{\text{Edd}} \approx 0.6 \), as observed in other tidal disruption events (Li et al. 2002). The total energy radiated is then of the order of \( 10^{50} \text{ ergs} \), which corresponds to the energy released by the accretion of 0.5 Jupiter mass (MJ).

We fitted the decline of the IGR J12580+0134 X-ray light curve with the \( (t - t_0)^{-5/3} \) law where \( t_0 \) is the time of the initial tidal disruption (Fig. 8). The peak luminosity of the flare occurred on January 22, 2011 according to \( MAXI \) and \( INTEGRAL \). It turns out from our fit that the beginning of the tidal disruption occurred \( \approx 60-100 \text{ days} \) before the peak of the X-ray flare, marking the heating of the debris at the vicinity of the black hole. A similar delay was mentioned by Li et al. (2002) as the time \( \Delta t_1 \), since the most bounded material returns to the pericentre.
4.2. Comparison with tidal disruption simulations

Detailed hydrodynamic simulations of tidal disruptions were performed by Guillochon & Ramirez-Ruiz (2013) and their results parametrised. The rate of mass falling on the black hole, $\dot{M}(t)$, the time of the peak accretion, $t_{\text{peak}}$, as well as the decay power-law index, $\Gamma$, depend on a few parameters: the structure and mass of the disrupted object and the minimum distance to the black hole.

We compared the simulations to our data assuming that the disrupted object is either a star or a sub-stellar object with polytropic index $\gamma$ of 4/3 or 5/3, respectively. We used the parametrisation included into the Appendix of Guillochon & Ramirez-Ruiz (2013) for different impact parameters $\beta \equiv r_T/r_p$, where $r_T$ and $r_p$ are the tidal and the pericentric radii, respectively. We also assumed $M_\star - R_\star$ relations for the disrupted object valid for sub-stellar objects or stars according to Chabrier & Baraffe (2000).

The observational constraints, $t_{\text{peak}} \approx 0.2$ yr and the peak accretion rate $\dot{M}_{\text{peak}} \approx 2.5 M_\odot/yr$ (under the assumption of a hard X-ray radiation efficiency of 10%), are sufficient to constrain the mass of the disrupted object. For a black-hole mass of 2.3 $\times$ 10$^5$M$\odot$, the mass of the disrupted object turns out to be either 14-16 M$\odot$ (for $\gamma = 5/3$ and $\beta = 0.6 - 1.9$) or 10 - 15 M$\odot$ (for $\gamma = 4/3$ and $\beta = 0.65$). For a black-hole mass increasing to 10$^6$M$\odot$, the mass of the disrupted object would be 25 - 28 M$\odot$ (up to 75M$\odot$ for 10$^7$M$\odot$) for a sub-stellar object or 1 - 3M$\odot$ for a star ($\beta \approx 0.7$). The $\beta$ parameter is not constrained in the case of a sub-stellar object, while a very narrow range is required to disrupt a star. The fraction of the object reaching the black hole would be very small in the case of a stellar disruption.

The hydrodynamic simulations also predict the detailed variability of the accreted mass flow with time. In the case of a star ($\gamma = 4/3$), less centrally condensed than a sub-stellar object, the accreted mass decreases much faster after the peak. This is illustrated in figure 8, where the observed flux behaves similarly to the predictions for the disruption of a sub-stellar object and contrasts with those obtained for a star.

The hydrodynamic simulations indicate, therefore, that the tidally disrupted object was probably a 14 - 30M$\odot$ sub-stellar object and that about 10% of its mass has been accreted on a black-hole weighting no more than 10$^5$M$\odot$. We note that a slightly different equation of state could lead to a mass of the disrupted object as low as several M$\odot$ and that specific simulations of tidal disruption of sub-stellar objects have not yet been done.

The decline in the hard X-ray flux observed in Fig. 8 after 200-500 days can be understood as debris falling back on the remaining object core and decreasing the emission during the late evolution (see fig. 8b in Guillochon & Ramirez-Ruiz 2013). This would indicate that the disruption was not total. Another explanation could be that the corona disappears faster than the debris, possibly indicating a change in the geometry of the accretion flow with time.

4.3. Power spectrum

The power spectrum of the X-ray light curve obtained by XMM-Newton at the flare maximum (see Fig. 9) shows an excess in the range 0.0008-0.004 Hz. This excess could be similar to a quasi-periodic oscillation (QPO) in the accretion flow. The frequency range of the excess corresponds to the innermost stable circular orbit for a black hole of a few $\times 10^5$M$\odot$ (Remillard & McClintock 2006).

![Fig. 9. The 19.1 ks XMM-Newton power spectrum (blue histogram) versus simulated 10 000 powers (red histogram with error bars). The power spectrum of the simulated light curves are power law shaped with a slope of -0.9. 1σ error bars are shown. An excess in the observed power near the log(frequency)= -3 may suggest a presence of the QPO feature.](image-url)

![Fig. 10. Probability multiplied by number of trials ($N_{\text{trials}} = 10000$) against $\chi^2$ for simulated single and broken power-law models. The solid black curve points out expected probability of a perfect model. The best fit by a single power law is obtained with a slope = -1.3. Broken power laws with the low-frequency slope = -0.5, the high-frequency slope between -1.1 and -1.3, and with broken frequency = 0.001 Hz provide a slightly better description of the observed power spectrum.](image-url)
To investigate the significance of this excess, we performed Monte Carlo simulations. We assumed various shapes of the power spectrum of the source and generated 10'000 light curves for each of them (Timmer & Koenig 1995). The spread of the power spectra of all simulated light curves were then compared to the shape of the observed power spectrum, as outlined in Uttley et al. (2002).

We tried single power-law power spectra with slopes between -0.7 and -1.5 and broken power-law models with break frequency frozen to 10\(^{-3}\) Hz, which differ by the low- and high-frequency slopes. Figure 10 shows the \(x^2\) distributions obtained for the best models, together with the expected distribution. The deviation between the simulated and expected distribution indicates that the excess can be obtained by chance at a probability not greater than 5\%. We conclude that a longer XMM observa-
tion would have been very useful and note that an instrument like the Large Observatory For X-ray Timing (LOFT) would have detected several million X-ray photons during one ISCO period for this tidal event, which would have allowed a probe of the geometry of the debris falling towards the black-hole horizon.

4.4. Tidal events frequency

The density of stars in the centre of a well developed galaxy is around 10\(^3\)M\(_\odot\)/pc\(^3\) in a region of 100 pc in radius and is comparable to what is found in globular cluster (Mary & Pfalz 1992). These dense regions allow stellar encounters to create new gravitationally bound systems or ejections (Davies & Benz 1995). Stars in the vicinity of a supermassive black hole may escape to infinity after encounter because their orbits are de-

References

Alexander, T. 2012, in European Physical Journal Web of Conferences, Vol. 39, European Physical Journal Web of Conferences, 5001
Alexander, T. & Kumar, P. 2001, ApJ, 549, 948
Alexander, T. & Livio, M. 2001, ApJL, 560, L143
Bogdán, Á. & Gilfanov, M. 2011, MNRAS, 418, 1901
Braatz, J. A., Wilson, A. S., Henkel, C., Gough, R., & Sinclair, M. 2003, ApJ, 146, 269
Burrows, D. N., Hill, J. E., Nousek, J. A., et al. 2005, Space Sci. Rev., 120, 165
Burrows, D. N., Kennea, J. A., Ghisellini, G., et al. 2011, Nature, 476, 421
Cenko, S. B., Krimm, H. A., Horesh, A., et al. 2012, ApJ, 753, 77
Chabrier, G. & Baraffe, I. 2000, ARA&A, 38, 337
Chandra, P., Dwarkadas, V. V., Ray, A., Immler, S., & Pooley, D. 2009, ApJ, 699, 388
Condon, J. J., Cotton, W. D., & Broderick, J. J. 2002, AJ, 124, 675
Condon, J. J., Cotton, W. D., Gressen, E. W., et al. 1998, AJ, 115, 1693
Corsi, E. M., Pizzella, A., Sarzi, M., et al. 2009, A&A, 542, 671
Davies, M. B. & Benz, W. 1995, MNRAS, 276, 876
Delorme, P., Gagné, J., Malo, L., et al. 2012, A&A, 548, A26
Dickey, J. M. & Lockman, F. J. 1990, ARA&A, 28, 215
Djurković, S. C., de Carvalho, R. R., Gal, R. R., et al. 1998, in IAU Symposium, Vol. 179, New Horizons from Multi-Wavelength Sky Surveys, ed. B. J. Mceean, D. A. Golombek, J. E. Yates, & H. E. Payne, 424
Donley, J. L., Brandt, W. N., Eracleous, M., & Bolter, T. 2002, AJ, 124, 1308
Evans, C. R. & Kochanek, C. S. 1989, ApJ, 346, L13
Evans, P. A., Beadmore, A. P., Page, K. L., et al. 2009, MNRAS, 397, 1177
Fabbiano, G., Kim, D.-W. & Trinchieri, G. 1992, ApJ, 80, 331
Filho, M. E., Barthel, P. D., & Ho, L. C. 2000, ApJS, 129, 93
Guziłochno, J. & Ramirez-Ruiz, E. 2013, ApJ, 767, 25
Ho, L. C., Filippenko, A. V., & Sargent, W. L. W. 1997, ApJ, 112, 315
Immler, S. & Lewin, W. H. G. 2003, in Lecture Notes in Physics, Berlin Springer Verlag, Vol. 598, Supernovae and Gamma-Ray Bursters, ed. K. Weiler, 91–111
Jarrett, T. H., Chester, T., Cutri, R., Schneider, S. E., & Huchra, J. P. 2003, AJ, 125, 525
Jia, J., Ptak, A., Heckman, T. M., Braito, V., & Reeves, J. 2012, ApJ, 759, 41
Komossa, S., Halpern, J. S., Schartel, N., et al. 2004, ApJL, 603, L17
Lebrun, F., Leray, J. P., Lavocat, P., et al. 2003, A&A, 114, L141
Li, X.-L., Narayan, R., & Menou, K. 2002, ApJ, 576, 753
Lodato, G., Kung, A. R., & Pudritz, E. J. 2009, MNRAS, 392, 332
Lund, N., Budtz-Jørgensen, C., Westergaard, N. J., et al. 2003, A&A, 111, 2311
Marx, S. & Pfau, W. 1992, Astrophotography with the Schmidt Telescope
Matsushita, M., Kawasaki, K., Ueno, S., et al. 2009, PASJ, 61, 999
Merritt, D. & Pooley, M. 2004, ApJ, 606, 788
Mihara, T., Nakajima, M., Sugizaki, M., et al. 2011, PASJ, 63, 623
Mikołajuk, M., Czerny, B., Ziolkowski, J., & Gierliński, M. 2006, MNRAS, 370, 1534
Neill, P. M., Nandra, K., Papadakis, I. E., & Turner, J. T. 2005, ApJ, 676, 70
Nikolaev, M., Zerny, B., Ziolkowski, J., & Gierliński, M. 2006, MNRAS, 370, 1405
Olive, F., Bassani, L., Cappi, M., et al. 2006, A&A, 455, 173
Pizzella, A., Corsini, E. M., Dalla Bontà, E., et al. 2005, ApJ, 631, 785
Quanz, S. P., Goldmann, B., Henning, T., et al. 2010, ApJ, 708, 770
Rees, M. J. 1988, Nature, 333, 523
Remillard, R. A. & McClintock, J. E. 2006, ARA&A, 44, 49
Sanders, D. B., Mazzarella, J. M., Kim, D.-C., Surace, J. A., & Soifer, B. T. 2003, AJ, 126, 1607
Saxton, R. D., Read, A. M., Esquej, P., et al. 2012, A&A, 541, A106
Schneider, D. P., Hall, P. B., Richards, G. T., et al. 2005, VizieR Online Data Catalog, 7243, 0
Shapley, A., Fabbianno, G., & Eskridge, P. B. 2001, ApJS, 137, 139
Spinoglio, L., Malkan, M. A., Rush, B., Carrasco, L., & Recillas-Cruz, E. 1995, ApJ, 453, 661
Stark, A. A., Gamme, C. F., Wilson, R. W., et al. 1992, ApJS, 79, 77
Timmer, J. & Koenig, M. 1995, A&A, 300, 707

Acknowledgements. Based on observations with INTEGRAL, an ESA project with instruments and science data centre funded by ESA member states (espe-
cially the PI countries: Denmark, France, Germany, Italy, Switzerland, Spain), and Poland and with the participation of Russia and the USA. We thank Enrico Bozzo, Laetitia Gibaud, and Claudio Ricci for help with Swift and XMM-Newton analyses; Piotr Życki for giving his software template and to Bozena Czerny for discussion about light-curve simulations. MN also thanks the Scientific Exchange Programme (Scix) NMS\(^{26}\) for opportunity of working at ISDC. This research has been supported in part by the Polish NCN grants N N203 581240 and 2012/04(M.ST6)/00780.
Tully, R. B. & Fisher, J. R. 1988, Catalog of Nearby Galaxies
Ubertini, P., Lebrun, F., Di Cocco, G., et al. 2003, A&A, 411, L131
Ulmer, A. 1999, ApJ, 514, 180
Uttley, P., McHardy, I. M., & Papadakis, I. E. 2002, MNRAS, 332, 231
Vaughan, S., Edelson, R., Warwick, R. S., & Uttley, P. 2003, MNRAS, 345, 1271
Véron-Cetty, M.-P. & Véron, P. 2006, A&A, 455, 773
Véron-Cetty, M. P. & Veron, P. 2010, VizieR Online Data Catalog, 7258, 0
Walter, R., Bordas, P., Bozzo, E., et al. 2011, The Astronomer’s Telegram, 3108, 1
Walter, R., Rohlfis, R., Meharga, M. T., et al. 2010, in Eighth Integral Workshop.
The Restless Gamma-ray Universe (INTEGRAL 2010)
Wang, J. & Merritt, D. 2004, ApJ, 600, 149