

# The puzzling source IGR J17361–4441 in NGC 6388: a possible planetary tidal disruption event

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Accepted 2014 July 16. Received 2014 July 16; in original form 2014 March 21

## ABSTRACT

On 2011 August 11, *INTEGRAL* discovered the hard X-ray source IGR J17361–4441 near the centre of the globular cluster NGC 6388. Follow-up observations with *Chandra* showed the position of the transient was inconsistent with the cluster dynamical centre, and thus not related to its possible intermediate mass black hole. The source showed a peculiar hard spectrum ( $\Gamma \approx 0.8$ ) and no evidence of QPOs, pulsations, type-I bursts, or radio emission. Based on its peak luminosity, IGR J17361–4441 was classified as a very faint X-ray transient, and most likely a low-mass X-ray binary. We re-analysed 200 d of *Swift*/XRT observations, covering the whole outburst of IGR J17361–4441 and find a  $t^{-5/3}$  trend evident in the light curve, and a thermal emission component that does not evolve significantly with time. We investigate whether this source could be a tidal disruption event, and for certain assumptions find an accretion efficiency  $\epsilon \approx 3.5 \times 10^{-4} (M_{\text{Ch}}/M)$  consistent with a massive white dwarf, and a disrupted minor body mass  $M_{\text{mb}} \approx 1.9 \times 10^{27} (M/M_{\text{Ch}})$  g in the terrestrial-icy planet regime. These numbers yield an inner disc temperature of the order  $kT_{\text{in}} \approx 0.04$  keV, consistent with the blackbody temperature of  $kT_{\text{in}} \approx 0.08$  keV estimated by spectral fitting. Although the density of white dwarfs and the number of free-floating planets are uncertain, we estimate the rate of planetary tidal disruptions in NGC 6388 to be in the range  $3 \times 10^{-6} - 3 \times 10^{-4} \text{ yr}^{-1}$ . Averaged over the Milky Way globular clusters, the upper limit value corresponds to  $0.05 \text{ yr}^{-1}$ , consistent with the observation of a single event by *INTEGRAL* and *Swift*.

**Key words:** accretion, accretion disc – white dwarfs – globular clusters: individual: NGC 6388 – X-rays: individual: IGR J17361–4441.

## 1 INTRODUCTION

The globular cluster (GC) NGC 6388 is considered one of the best candidates to harbour an intermediate mass black hole (hereafter IMBH; Baumgardt et al. 2005) at its centre. Optical observations allowed a first estimate of the IMBH mass of  $\approx 5700 M_{\odot}$  (Lanzoni et al. 2007). Under the hypothesis that the IMBH is accreting the surrounding matter, it is natural to expect signatures in the X-ray band. *XMM-Newton* and *Chandra* observations towards NGC 6388 showed that several X-ray sources exist in the GC centre (see Nucita

et al. 2008, Cseh et al. 2010) so that a unique identification of the putative IMBH is missing.

Based on the correlation between the X-ray and radio flux from black holes (BH; Merloni et al. 2003), Maccarone (2004) realized that radio observations may be very useful to pinpoint faint objects in GC. Following this suggestion, Cseh et al. (2010) combined radio observations of the central region of NGC 6388 with the *Chandra* X-ray flux of the IMBH candidate, in order to put an upper limit ( $3\sigma$ ) on the BH mass of  $\approx 1500 M_{\odot}$ . A similar result was obtained combining high spatial resolution and wide-field spectroscopy of more than 600 stars in the direction of NGC 6388 (Lanzoni et al. 2013).

A general excitement started on 2011 August 11 when the IBIS telescope (Ubertini et al. 2003) on-board the *INTEGRAL* satellite

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(Winkler et al. 2003) identified a new hard X-ray source, labelled IGR J17361–4441, close to the NGC 6388 centre (Gibaud et al. 2011). The discovery of this transient opened the possibility that we were witnessing the awakening of the IMBH.

In order to explore the nature of IGR J17361–4441, several observing campaigns, in particular in the X and radio domains (Bozzo et al. 2011), have been performed. The X-ray position obtained with *Swift*/XRT was consistent with the centre of NGC 6388 (Ferrigno et al. 2011a). However, *Chandra* follow-up revealed that IGR J17361–4441 was located  $\sim 2.7$  arcsec from the cluster centre and it was not consistent with the position of any known X-ray source (Pooley et al. 2011). The transient source in NGC 6388 was also the target of two *XMM–Newton* slew observations (see for details Nucita et al. 2012) which revealed a spectrum softer than that initially observed by XRT.

Based on the X-ray luminosity of  $6\text{--}9 \times 10^{35}$  erg s $^{-1}$  estimated with XRT, Wijnands et al. (2011) classified IGR J17361–4441 as very faint X-ray transient (VFXT; see Wijnands et al. 2006 for a discussion about VFXTs). Considering the location in a GC, these authors proposed the system being a neutron star (NS) low-mass X-ray binary (LMXB). However, they noted that the observed photon index of  $\Gamma \sim 0.6\text{--}1.0$  is atypical for LMXB transients in this luminosity range, where normally the photon index is around 1.6–2.2 (e.g. Del Santo et al. 2007; Degenaar & Wijnands 2009).

After the discovery, *Swift*/XRT followed the evolution of the IGR J17361–4441 outburst for  $\simeq 200$  d until 2011 November 5 when the source was no longer observable (Bozzo et al. 2012). We have reanalysed these XRT data (obtaining consistent results) and performed a deeper analysis of the light curve and spectral evolution.

We noted that a  $\propto t^{-5/3}$  trend is clearly evident in the light curve and we started to investigate whether this source might be a tidal disruption event (TDE).

TDE have been observed over the years as X-ray (Komossa & Bade 1999; Esquej et al. 2007; Bloom et al. 2011; Cenko et al. 2012) and UV (Gezari et al. 2009, 2012) transients. In most cases, such outbursts follow from the disruption of a star by a supermassive black hole (SMBH), which results in a powerful super-Eddington flare with a duration of several weeks. Recently, it has also been shown that such TDEs can also produce jets, resulting also in radio emission (Bloom et al. 2011; Levan 2011; Zauderer et al. 2011). In a few cases, the luminosity of the outburst appeared to imply that the disrupted object was a relatively low-mass object, such as a planet or brown dwarf. This is the case, for example, of the giant X-Ray flare in NGC 5905 (Li, Narayan & Menou 2002), or, more recently, of IGR J12580+0134, a flare discovered by *INTEGRAL* in 2011 and associated with NGC 4845 (Nikołajuk & Walter 2013).

In both cases, the best fit to the light curve implied the tidal disruption of a giant planet by a SMBH. In one other case, Campana et al. (2011) had interpreted the GRB101225A as a Galactic TDE, where an asteroid had been accreted by an NS. Such interpretation has, however, been ruled out by a redshift measurement of the source (Levan et al. 2014), that demonstrates its extragalactic origin.

Still, the sudden accretion of rocky objects by compact objects in the Galaxy is probably not uncommon. For example, there is substantial evidence for tidal disruption of asteroids by white dwarfs (WDs). To date, there are 30 published cases where debris is seen via thermal emission in the infrared (e.g. Farihi et al. 2010), and sometimes also gaseous metallic emission in the optical (e.g. Gänsicke et al. 2006), and via accreted metals in the stellar atmosphere. These circumstellar discs lie completely within the Roche limit of the stars, approximately  $1 R_{\odot}$ , and are thus consistent with tidally disrupted

planetesimals (Jura 2003). The planetary nature of the disc material is given both by the abundance ratios in the polluted stellar atmospheres (e.g. Gänsicke et al. 2012), and via infrared emission of evolved solids associated with planet formation (Jura, Farihi & Zuckerman 2009).

Among these polluted WDs, there appears to be evidence in support of intense accretion episodes of planetary debris (Farihi, Gänsicke & Koester 2013). Briefly, trace metals in an H-rich WD provide instantaneous measures of accretion rates, which are typically in the range  $10^5\text{--}10^8$  g s $^{-1}$  (Koester & Wilken 2006). On the other hand, atmospheric metals in a comparable He-rich WD give a historical average of accretion over time-scales up to  $10^6$  yr (Farihi, Jura & Zuckerman 2009). Remarkably, while there are examples of stars with time-averaged accretion rates up to  $10^{11}$  g s $^{-1}$ , no instantaneous accretion rate above  $10^9$  g s $^{-1}$  has yet been witnessed among many dozens of metal polluted WDs. Analysis of available data suggest that there are short-lived bursts ( $t_{\text{high}} < 10^3$  yr) of high-rate accretion in these polluted WD systems, such that the product of  $t_{\text{high}} \dot{M}_{\text{high}}$  is around  $10^{24}$  g, or 1/6000 the mass of Earth (Farihi et al. 2012).

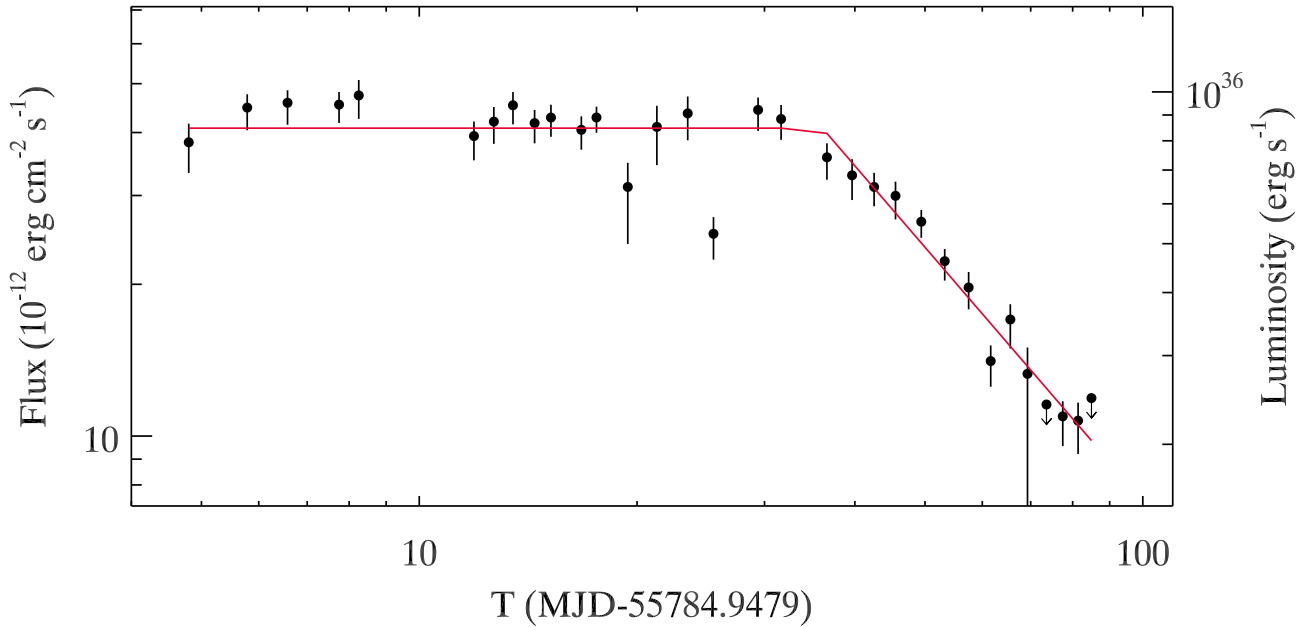
The structure of the paper is as follows. In Section 2, we briefly discuss the *INTEGRAL* and *Swift* data analysis. In Section 3, we analyse the spectral evolution and the light curve of the system, demonstrating a remarkable  $t^{-5/3}$  decline, typical of TDEs. In Section 4, we discuss the possible interpretation of the source: after ruling out a possible X-ray binary scenario, we concentrate on a TDE interpretation, showing that the parameter set that best describe the system indicates the disruption of a rocky object by a WD. We also discuss and rule out a possible interpretation as an extragalactic TDE in a background galaxy. In Section 5, we draw our conclusions.

## 2 OBSERVATION AND DATA ANALYSIS

### 2.1 *Swift*/XRT

We have analysed the *Swift*/XRT observations performed on the target IGR J17361–4441 (Id. numbers from 00032072001 to 00032072038; see also Bozzo et al. 2012) for a total exposure time of  $\simeq 105$  ks. *Swift* data have been analysed by using the standard procedures described in Burrows et al. (2005) and with the latest calibration files.<sup>1</sup> We processed the XRT data with the XRT-PIPELINE (v.0.12.6) task and we applied standard screening criteria by using FTOOLS (HEASOFT v.6.13.0). The source spectra have been extracted from a circular region centred on the target nominal coordinates (with radius of  $\simeq 40$  arcsec) by using the XSELECT routine. The background spectra were obtained from circular regions far enough from the IGR J17361–4441 position. When necessary, we corrected observations affected by pile-up (i.e. with source count rates above  $\simeq 0.5$  ct s $^{-1}$ ). We then used the XRTMKARF task to create the ancillary response files. Of the 38 XRT spectra, we avoided to use the last six because of the low statistics. Each of the 32 spectrum has been rebinned in order to have at minimum 25 counts per channel with GRPPHA. All fits have been performed with XSPEC (Arnaud, Dorman & Gordon 2007) and errors calculated at 90 per cent confidence level.

<sup>1</sup> <http://heasarc.nasa.gov/docs7swift/analysis/>



**Figure 1.** The 1–10 keV *Swift*/XRT light curve corrected for the absorption. The light curve has been fitted with a broken power law, i.e. a constant plus an exponential which results in a  $\propto t^{-5/3}$  law.

## 2.2 INTEGRAL/IBIS

We have analysed all data collected by the low-energy IBIS detector, i.e. ISGRI (Lebrun et al. 2003), when IGR J17361–4441 was present in the total IBIS field of view ( $14^{\circ}.5 \times 14^{\circ}.5$ ). Observations have been performed in the period 2011 August 11–October 22, i.e. *INTEGRAL* revolutions 1078–1101 for a total of 454 science windows (SCW) and  $\simeq 1$  Ms time exposure. Data analysis was carried out with the Off-line Scientific Analysis (OSA) v. 10.0 distributed by the ISDC (Courvoisier et al. 2003). We processed data with the `IBIS_SCIENCE_ANALYSIS` task and extracted images in three energy bands: 18–40, 40–80, 80–150 keV. We did not get any detection at SCW level ( $\sim 2$  ks), so that we mosaicked the 454 images in groups of 38, 39, 61, 63, 130 and 123. A significant signal to noise (above  $5\sigma$ ) has been obtained only in the first energy band (18–40 keV). The errors on the IBIS/ISGRI count rate have been obtained via the significance (signal-to-noise ratio) in output from the OSA software. We extracted an averaged ISGRI spectrum (53 ks) corresponding to the flat part of the XRT light curve (see Section 3.2) by using the OSA task `MOSAIC_SPEC` (useful for faint sources).

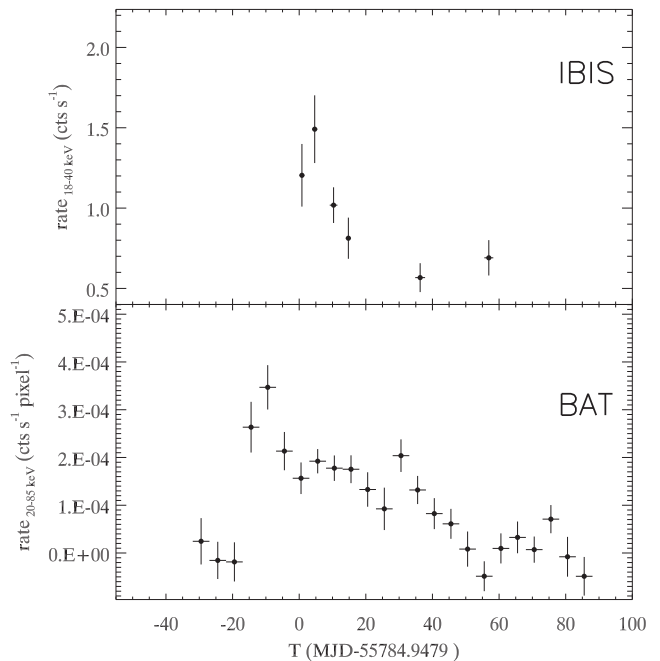
## 2.3 Swift/BAT

The *Swift*/BAT survey data collected from 2004 November up to end of 2013 retrieved from the HEASARC public archive were processed using `BATIMAGER` (Segreto et al. 2010). This code is dedicated to the processing of coded mask instrument data. We found that IGR J17361–4441 is detected in only one time interval, since  $\text{MJD} \sim 55770$  up to  $\text{MJD} \sim 55828$ , with a statistical significance of 15 standard deviations in the 20–85 keV all-sky map. Light curve has been extracted with 5 d temporal bins.

## 3 RESULTS

### 3.1 Temporal analysis

We have estimated the 1–10 keV unabsorbed fluxes by fitting the 32 *Swift*/XRT spectra of IGR J17361–4441 with a simple power law.



**Figure 2.** IBIS (18–40 keV) and BAT (20–85 keV) light curves. The BAT detection occurred 14 d before the IBIS one.

Plotting the flux evolution, we noted that it could be well represented by a broken power law. Thus, we fit the light curve with a constant plus an exponential law (see Fig. 1). It results a plateau flux  $F_{\text{max}} = (4.1 \pm 0.1) \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$  and a knee time of  $t_k = 36 \pm 1$  d from the *INTEGRAL* trigger  $\text{MJD}_{\text{IBIS}} = 55784.9479$ , i.e. roughly 5 d before the first XRT follow-up observation. Then, it was very interesting to observe that after the knee, the data were well fitted with a  $\propto t^{-5/3}$  law ( $\chi^2_{\nu} = 1.14$  with 30 d.o.f.).

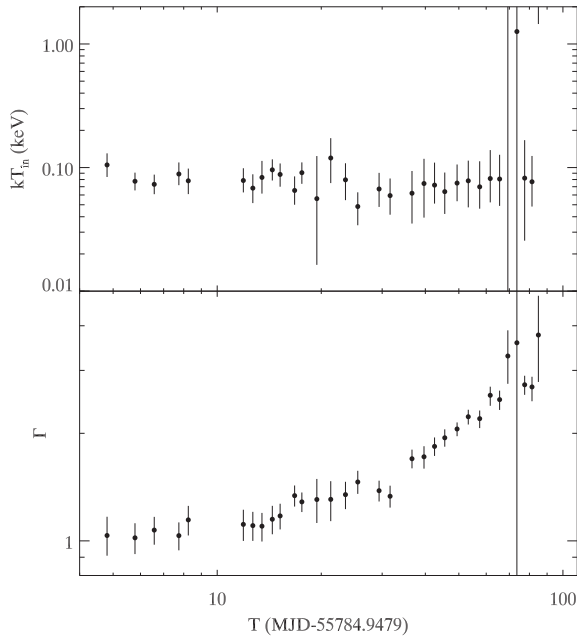
In Fig. 2, the *INTEGRAL*/IBIS (up) and *Swift*/BAT (bottom) hard X-ray light curves are shown. Thanks to BAT, we found that the IGR J17361–4441 outburst was started (in hard X-rays) roughly

14 d ( $\text{MJD}_{\text{BAT}} = 55770.4480$ ) before the *INTEGRAL* trigger, thus implying a total event (observed) duration of 99 d, when the last XRT point ( $\text{MJD}_{\text{stop}} = 55869.8738$  d) is considered as the end.

### 3.2 Spectral analysis

Extending the XRT spectral energy range down to 0.3 keV, an additional disc blackbody component to the power law is requested by the data. Then, the 32 XRT spectra of IGR J17361–4441 have been fit with an absorbed power-law plus DISKBB (in *XSPEC*). The column density is constant at a mean value of  $\simeq 0.8 \times 10^{22} \text{ cm}^{-2}$  (also consistent with Bozzo et al. 2011), so that it has been fixed in our fit procedure. The evolutions of the inner disc temperature ( $kT_{\text{in}}$ ) and power-law slope ( $\Gamma$ ) are shown in Fig. 3. It is interesting to note that in spite of the variation of the power-law component, i.e. an abrupt change of the power-law slope at roughly  $t_{\text{in}} \simeq 30$  d from the *INTEGRAL* trigger is observed, the disc temperature results constant at a value around 0.08 keV (Fig. 3).

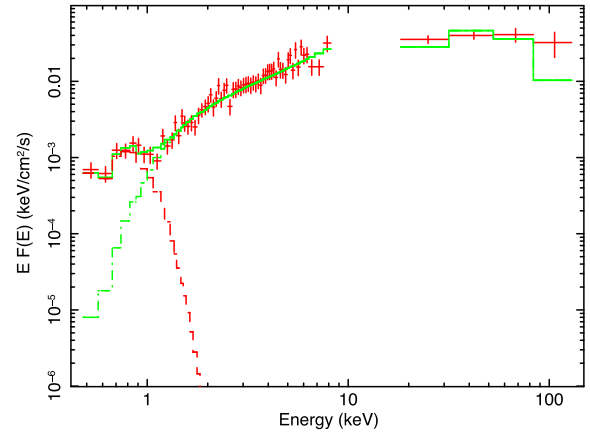
To obtain the hard X-ray spectrum up to  $\simeq 100$  keV, we averaged the IBIS/ISGRI data corresponding to the first four bins of the light curve (Fig. 2, top). These data are simultaneous to the plateau period in the XRT light curve, when IGR J17361–4441 did not show any spectral variation (Fig. 3). Then, we have combined the IBIS/ISGRI spectrum with one of the brighter XRT spectra and fit the broadband spectrum with an absorbed cut-off power-law (CUTOFFPL) plus DISKBB, obtaining parameters (see Table 1) consistent with those reported in Bozzo et al. (2011).



**Figure 3.** *Swift*/XRT spectral evolution of the 0.3–10 keV spectra fit with a disc blackbody component ( $kT_{\text{in}}$ ) plus a simple power law ( $\Gamma$ ).

**Table 1.** XRT plus IBIS broad-band spectrum fit with both an empirical cut-off power law (CUTOFFPL) with  $\Gamma$  as the power-law photon index and  $E_c$  the energy cut-off, and a physical thermal Comptonization model (COMPTT) with  $kT_e$  and  $\tau$  as the temperature of Comptonizing electrons and the Thomson depth, respectively. A multicolour disc blackbody with ( $kT_{\text{in}}$ ) temperature is also requested by the low-energy data, as well as the galactic absorption ( $N_{\text{H}}$ ).

Model	$N_{\text{H}}$ $10^{22} (\text{cm}^{-2})$	$kT_{\text{in}}$ (keV)	$E_c$ (keV)	$\Gamma$	$kT_e$ (keV)	$\tau$	$\chi^2_{\nu}(\text{dof})$	$F_{\text{bol}}$ ( $\text{erg cm}^{-2} \text{ s}^{-1}$ )
DISKBB+CUTOFFPL	$0.7 \pm 0.1$	$0.089^{+0.004}_{-0.005}$	$41^{+18}_{-12}$	$0.8 \pm 0.1$	—	—	0.80(62)	$1.0 \times 10^{-9}$
DISKBB+COMPTT	$0.7 \pm 0.1$	$0.087^{+0.004}_{-0.006}$	—	—	$12 \pm 2$	$8 \pm 1$	1.01(62)	$1.7 \times 10^{-9}$



**Figure 4.** XRT+IBIS spectrum fit with an absorbed disc blackbody plus Comptonization component.

In addition, we fit this spectrum with a physical model (Fig. 4) by using a thermal Comptonization model (COMPTT in *XSPEC*) in place of the cut-off power law obtaining an electron population temperature of roughly 10 keV, an inner disc radius  $R_{\text{in}} \simeq 12600$  km (from the normalization of the DISKBB model; Mitsuda et al. 1984) and a bolometric (0.1–100 keV) flux of about  $2 \times 10^{-9} \text{ erg cm}^{-2} \text{ s}^{-1}$  (see Table 1). Assuming a distance of 13.2 kpc (Dalessandro et al. 2008), we have estimated the bolometric peak luminosity as  $L_{\text{bol}} \simeq 3.5 \times 10^{37} \text{ erg s}^{-1}$ .

It is known that in accreting compact objects  $L_X$  corresponds (as first approximation) to the accretion luminosity  $L_{\text{acc}} = \epsilon \dot{M} c^2$ . Thus, a lower limit to the accreted mass on to the central object can be evaluated.

We have integrated the bolometric luminosity over the time for the whole outburst duration and obtained  $M_{\text{acc}} \simeq 3.4 \times 10^{23} \epsilon^{-1} \text{ g}$ .

## 4 DISCUSSION: WHAT KIND OF SOURCE CAN IT BE?

### 4.1 X-ray binary scenario

Based on the peak luminosity of  $L_{2-10\text{keV}} = 8.5 \times 10^{35} \text{ erg s}^{-1}$ , IGR J17361–4441 has been classified as VFXT (Wijnands et al. 2011). This is a non-homogeneous class of sources characterized by a peak luminosity (in 2–10 keV) within the range  $10^{34-36} \text{ erg s}^{-1}$  (Wijnands et al. 2006). Very faint transients in GC are most likely LMXBs with NS or BH as accreting compact object.

As discussed in details in Kulkarni et al. (1993), Portegies Zwart et al. (2000), and Strader et al. (2012), one expects that even if hundreds of stellar-mass black holes form in a typical globular cluster, only a few of them survive since the others are likely ejected through dynamical interactions. According to Kalogera, King & Rasio (2004), they are likely to have extremely low duty cycles

(below about  $10^{-3}$ ), consistent with the absence of such an object in Galactic GC. Observational support for such picture was provided by the lack of X-ray binaries with BH in Milky Way GC until 2011, when Strader et al. (2012) proposed that two radio sources in the GC M22 are stellar-mass BH.

The possibility that IGR J17361–4441 is a binary system with a BH can be ruled out because of the low radio-to-X-ray flux ratio (see Bozzo et al. 2011; Chomiuk et al. 2013). Ferrigno et al. (2011b) reported on the ATCA non-detection of IGR J17361–4441; they inferred an upper limit of  $19 \mu\text{Jy}$  at 9 GHz which translates into a luminosity at 8.5 GHz of  $4 \times 10^{28} \text{ erg s}^{-1}$ . We note that this value is at least a factor of 100 fainter than the typical radio luminosity observed in BH binaries with  $L_X \simeq 8 \times 10^{35} \text{ erg s}^{-1}$  (see fig. 3 in Migliari & Fender 2006). Moreover, BH transients in the hard state usually show quasi-periodic oscillation (see Homan & Belloni 2005; McClintock & Remillard 2006). These features were also observed in the very faint system *Swift* J1357.2–0933 (Casares et al. 2011; Armas Padilla et al. 2014). However, the power density spectrum constructed after accumulating *RXTE*/PCA light curves of IGR J17361–4441 did not show the presence of any coherent signal (against white noise) in the frequency range  $10^{-3}$ – $10^3$  Hz at  $3\sigma$  confidence level (see fig. 2 in Bozzo et al. 2011).

The other possibility is that IGR J17361–4441 is an LMXB with an NS accreting at very low  $\dot{M}$ , either with low magnetic field (possibly showing suddenly type-I X-ray bursts, i.e. burst-only sources; Cornelisse et al. 2004, Del Santo et al. 2007, Campana 2009) or with high magnetic field, i.e. an accreting millisecond X-ray pulsars (AMSP; Wijnands et al. 2008; Wijnands 2008).

However, the hard X-ray spectrum ( $\Gamma \simeq 0.8$ ; Table 1) observed at the beginning of the outburst of IGR J17361–4441 is not observed in VFXT with low magnetic field NS. Usually, these objects show  $\Gamma \sim 1.5$ – $2.2$  in this luminosity range (see Degenaar & Wijnands 2010 and references therein) and blackbody temperatures (when present) consistently higher than that observed in IGR J17361–4441 (i.e. 0.3–0.5 keV; see Armas Padilla, Degenaar & Wijnands 2013). Moreover, the soft spectra observed at the end of the outburst are typical of the soft spectral state, which is observed in NS burster sources only when in high accretion rate regime (i.e. luminosities; Barret et al. 2000).

The possibility that the system might harbour an AMSP was proposed at the onset of the *Swift* observations, hypothesis which was immediately in contrast with the lack of pulsations in the PCA data (Bozzo et al. 2011). Even considering that pulsation in LMXBs might be transient as observed in Aql X–1 (Casella et al. 2008), we note that AMSPs have similar power-law slopes than the non-pulsating NS and blackbody temperatures even higher, i.e. up to 1 keV (see Papitto et al. 2010; Patruno & Watts 2012). Moreover, they usually do not show variations of the spectral shape at different flux levels (see Falanga et al. 2012 and references therein).

We conclude that the hypothesis either of low magnetic (burster) or high magnetic (AMSP) NS for the compact object of IGR J17361–4441 is unlikely. In addition, this is supported by the fact that NS transients have been observed to show (usually) quiescent luminosities of about  $10^{32-33} \text{ erg s}^{-1}$  (see Rea et al. 2011, and references therein), i.e. higher than the upper limit of few  $10^{31} \text{ erg s}^{-1}$  derived for IGR J17361–4441.

#### 4.2 Hints for a TDE?

Based on the considerations reported in Section 4.1, we suggest IGR J17361–4441 being a TDE. There are two empirical evidences that

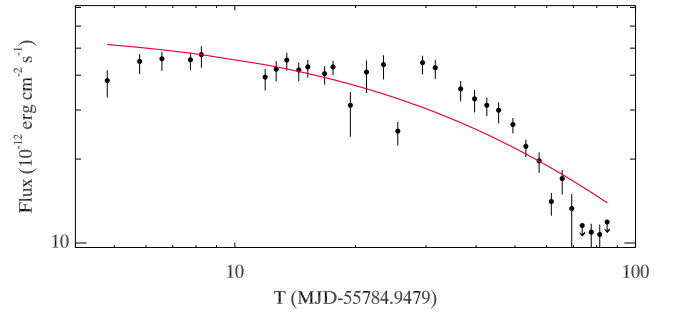


Figure 5. XRT light curve fitted with the model described in equation (1).

point in the direction of interpreting this flare of IGR J17361–4441 as a TDE. First and foremost, the apparent decline of the light curve as  $t^{-5/3}$ , that is typical of such events, even though we can fit the expected decline only to the late light curve, while the early light curve shows a plateau which is generally not expected in TDEs. We tried to fit the light curve with a pure  $t^{-5/3}$  type law and we did not obtain a good fit ( $\chi^2_\nu = 2.3$ , 30 d.o.f., see Fig. 5).

Secondly, several TDEs produced by the disruption of stars by an SMBH appear to be characterized by a thermal emission component that does not evolve significantly with time, as in the present case. Such component has been observed in TDEs discovered in the optical (van Velzen et al. 2011; Gezari et al. 2012; Chornock et al. 2014) and in X-rays (Maksym et al. 2013; Donato et al. 2014). A slow evolution of the thermal component is not expected from theoretical models of TDE, that imply a cooling thermal component (Lodato & Rossi 2011), unless the fallback rate is strongly super-Eddington (Loeb & Ulmer 1997), or unless some reprocessing of the high-energy emission by an opaque shroud of debris is invoked (Guillochon, Manukian & Ramirez-Ruiz 2014, which would only be able to explain the events observed in the optical).

In a TDE, the accreted mass is half of the mass of the disrupted object. According to the numbers quoted above (end of Section 3), we thus estimate that the disrupted minor body would have a mass of  $M_{\text{mb}} \approx 7 \times 10^{23} \epsilon^{-1} \text{ g}$ . Even if the efficiency parameter is low, if the event is caused by accretion on to a compact object it would put the minor body in the asteroid – terrestrial planet mass range, and would thus most likely be of rocky composition.

The standard theory of TDEs (Rees 1988; Evans & Kochanek 1989; Phinney 1989; Lodato, King & Pringle 2009) predicts that the debris of the disrupted object would return to pericentre at a rate given by

$$\dot{M}_{\text{mb}} = \dot{M}_{\text{p}} \left( \frac{t + t_{\text{min}}}{t_{\text{min}}} \right)^{-5/3}, \quad (1)$$

where  $t$  is the time since the beginning of the flare and  $t_{\text{min}}$  is the return time of the most bound debris, given by

$$t_{\text{min}} = \frac{\pi}{2^{1/2}} \left( \frac{r_{\text{t}}}{R_{\text{mb}}} \right)^{3/2} \sqrt{\frac{r_{\text{t}}^3}{GM}}, \quad (2)$$

where  $M$  is the mass of the compact object,  $R_{\text{mb}}$  is the radius of the minor body and  $r_{\text{t}}$  is the tidal radius. Note the strong dependence of  $t_{\text{min}}$  on the tidal radius (Sari et al. 2010; Stone et al. 2013). For an object with a density  $\rho = 3 \text{ g cm}^{-3}$  (appropriate for rocky bodies), the tidal radius is (Davidsson 1999; Jura 2003)

$$r_{\text{t}} = C \left( \frac{3M}{4\pi\rho} \right)^{1/3} \approx 1.8 R_{\odot} C \left( \frac{M}{M_{\text{Ch}}} \right)^{1/3} \left( \frac{\rho}{3 \text{ g cm}^{-3}} \right)^{-1/3}, \quad (3)$$

where  $C$  is a numerical factor dependent on the structure of the body and  $M_{\text{Ch}}$  is the Chandrasekhar mass. For a rocky object,  $C = 1.26$ . Inserting equation (3) into equation (2), we obtain

$$t_{\text{min}} = \frac{C^3 \pi}{2^{1/2}} \left( \frac{M}{M_{\text{mb}}} \right)^{1/2} \sqrt{\frac{3}{4\pi G \rho}} \approx 1.4 \times 10^4 \left( \frac{C}{2} \right)^3 \left( \frac{M}{M_{\text{Ch}}} \right)^{1/2} \epsilon^{1/2} \text{d}, \quad (4)$$

where for the mass of the minor body  $M_{\text{mb}}$  we have used  $M_{\text{mb}} = 2M_{\text{acc}} \approx 7 \times 10^{23} \epsilon^{-1}$ . The peak accretion rate is given by

$$\dot{M}_{\text{p}} = \frac{M_{\text{mb}}}{3t_{\text{min}}}. \quad (5)$$

We can empirically obtain an estimate of the fallback time  $t_{\text{min}}$  by the following argument: if the light curve follows exactly a  $t^{-5/3}$  decline law, then the total energy emitted, the peak luminosity and the fallback time are related by

$$t_{\text{min}} = \frac{2E}{3L_{\text{p}}} \approx 68 \text{ d}, \quad (6)$$

where in the last equality we have used the measured peak luminosity and integrated energy of the event. Note that a fit of the light curve with a function of the form shown in equation (1) would not provide a good fit (since it does not reproduce well the initial plateau, as mentioned above) but would return a best-fitting value for  $t_{\text{min}}$  in the range of 70 d, consistent with the simple estimate above. By imposing that the  $t_{\text{min}}$  estimated from the observations matches the one derived from tidal disruption theory, we obtain an estimate of the accretion efficiency

$$\epsilon \approx 3.5 \times 10^{-4} \left( \frac{M_{\text{Ch}}}{M} \right), \quad (7)$$

which is consistent with the expected accretion efficiency of a WD close to the Chandrasekhar limit. With these estimates for the efficiency, we can obtain an estimate for the mass of the disrupted minor body and for the peak accretion rate as

$$M_{\text{mb}} \approx 1.9 \times 10^{27} \left( \frac{M}{M_{\text{Ch}}} \right) \text{ g}, \quad (8)$$

$$\dot{M}_{\text{p}} \approx 3 \times 10^{20} \left( \frac{M}{M_{\text{Ch}}} \right) \text{ g s}^{-1}. \quad (9)$$

We thus conclude that the disrupted object mass is of the order of a third Earth mass, which is in the terrestrial-icy planetary regime. With such numbers, the inner disc temperature at peak, close to the WD surface, is of the order of  $kT_{\text{in}} \approx 0.04$  keV, consistent with the blackbody temperature estimated by spectral fitting (see Section 3.2).

A critical question to be addressed is whether the disrupted material, that would initially orbit relatively far from the WD surface, would be able to accrete fast enough so that the accretion rate on to the WD matches the fallback rate given in equation (1). For this to happen, we need to require that the viscous time in the disc is much smaller than the fallback time  $t_{\text{min}}$ . Two recent studies have addressed this question. Metzger, Rafikov & Bochkarev (2012) argue that most of the accretion occurs at a late stage after the disc formation, and estimate viscous times of the order of thousands of years. In this case, the WD would accrete at a rate much smaller than the fallback rate and the disc would shine mostly in the infrared. Conversely, Bear & Soker (2013) conclude that the energy

liberated during the formation of the disc is high enough to lead to a rapid accretion of the material, which would lead to an initial spike of intense accretion at rates comparable to the fallback rate. In this case, we do expect to see the system to emit in X-rays. Thus, in order to explain this source as the tidal disruption of a terrestrial planet by a WD, we need to invoke the mechanism suggested by Bear & Soker (2013).

The hard X-ray emission is interpreted to originate from inverse-Compton scattering of lower energy photons ( $kT_{\text{in}} \simeq 0.09$  keV) by high-energy electrons in a hot corona ( $kT_{\text{e}} \simeq 12$  keV; Table 1) forming around the accretion flow (see also Nikořajuk & Walter 2013). This is the same mechanism which is thought to occur in all compact objects accreting matter via an accretion disc. In TDE, we do not have detailed models for the formation and evolution of the corona and the associated time-scales. On the other hand, hard X-ray emission is not uncommon in TDE candidates (Burrows et al. 2011; Cenko et al. 2012; Nikořajuk & Walter 2013), but it is difficult to make a comparison with our IGR J17361–4441 event since they are all thought to have occurred on an SMBH.

### 4.3 Estimating the rate of planetary tidal disruption

In this section, we estimate the rate of tidal disruption of planets by WD in the core of a GC. It should be noted that these estimates rely on a number of assumptions that are either poorly constrained observationally or poorly understood theoretically, so they should be treated with caution.

Numerical simulations have demonstrated that dissolution of planetary systems occurs on time-scales that are shorter than the age of a typical open or GC (Spurzem et al. 2008). We thus expect that the disruption does not follow from the deflection of a planet that is initially bound to the WD.

However, the interacting object may be a free-floating planet (FFP), resulting from the dissolution of planetary systems. The retention of a population of FFP in GC is not obvious. Simple estimates based on equipartition arguments would imply that a planetary population would acquire an extremely large velocity dispersion, well in excess of the escape speed from the cluster, and would thus evaporate within a few relaxation times (note that the relaxation time for NGC 6388 is  $\approx 5.2 \times 10^7$  yr at the core and  $\approx 8 \times 10^8$  yr at the half-mass radius; Harris 1996). However, numerical simulations (Fregeau et al. 2002; Hurlay & Shara 2002) show that a significant population of FFP is retained in relaxed systems. A possible explanation for this behaviour is due to a lack of equipartition. Indeed, again through numerical simulations including a mass spectrum, Trenti & van der Marel (2013) have shown that, as a consequence of Spitzer instability, equipartition does not occur even for relaxed stellar systems, and that the velocity dispersion depends very weakly on mass, such that  $\sigma \propto m^{-0.08}$ . In our particular case, with a mass of a third Earth mass and an average stellar mass of  $0.1 M_{\odot}$ , we estimate that  $\sigma_{\text{pl}} \approx 2.5 \sigma_{\text{star}}$ .

The rate of tidal encounters can be simply evaluated (Soker, Rappaport & Fregeau 2001; Binney & Tremaine 2008):

$$\dot{N}_{\text{TE}} \simeq \frac{4\pi r_{\text{c}}^3}{3} N_{\text{FFP}} N_{\text{WD}} \Sigma \sigma_{\text{pl}}, \quad (10)$$

where  $N_{\text{FFP}}$  is the density of FFPs,  $N_{\text{WD}}$  is the density of WDs,  $r_{\text{c}}$  is the core radius of the cluster and  $\Sigma$  is the cross-section of the interaction,

$$\Sigma = \pi r_{\text{t}}^2 \left( 1 + \frac{2GM}{\sigma_{\text{pl}}^2 r_{\text{t}}} \right), \quad (11)$$

where one has to take into account the effect of gravitational focusing, which is dominant in this case. Note that in equation (10), we assumed that the main contribution comes from the inner part of the GC, within the core radius ( $r_c$ ).

In order to estimate the rate of planetary disruptions, we need to know the number density of FFP and WD in a typical GC, both of which are very uncertain. Here, we provide a pessimistic estimate of the rate of disruptions by considering the lowest values for both parameters, and an optimistic estimate considering the highest values. For the WD number density, we assume either a low value of  $\approx 10^4 \text{ pc}^{-3}$  (Raskin et al. 2009), or a high value – more appropriate for collapsed GC, such as NGC 6388 – of  $10^5 \text{ pc}^{-3}$ , in agreement with simulations performed by Ivanova et al. (2006). Estimating the number density of FFP of rocky composition is even more difficult. It has been estimated that the density of FFP in GC could exceed  $N_{\text{FFP}} = 10^6 \text{ pc}^{-3}$  (Soker et al. 2001), i.e. approximately one per star in NGC 6388 considering the star density reported in Pryor & Meylan (1993). Indeed,  $N$ -body simulations suggested that FFPs could evolve to the current epoch with a population that exceeds the stellar population at the cluster centre by a factor of  $\sim 100$  (Fregeau et al. 2002; Hurley & Shara 2002). This is also supported by  $N$ -body simulation of planet formation performed by Ida, Kokubo & Kominami (2003). We thus assume a low value for  $N_{\text{FFP}} = 10^7 \text{ pc}^{-3}$  (i.e. ten per star) and a high value of  $10^8 \text{ pc}^{-3}$  (i.e. 100 per star).

We take  $r_c = 0.5 \text{ pc}$  for the GC core radius size (Lanzoni et al. 2007) and  $\sigma_{\text{star}} \approx 13 \text{ km s}^{-1}$  (Lanzoni et al. 2013). The tidal radius  $r_t \approx 1.5 \times 10^{11} \text{ cm}$  is estimated from equation (3). We thus obtain a pessimistic estimate of the rate of TDE as

$$\dot{N}_{\text{TE}} \simeq 3.3 \times 10^{-6} \text{ yr}^{-1}, \quad (12)$$

(where we have assumed  $N_{\text{WD}} = 10^4 \text{ pc}^{-3}$  and  $N_{\text{FFP}} = 10^7 \text{ pc}^{-3}$ ) and an optimistic estimate of

$$\dot{N}_{\text{TE}} \simeq 3.3 \times 10^{-4} \text{ yr}^{-1}, \quad (13)$$

(where we have assumed  $N_{\text{WD}} = 10^5 \text{ pc}^{-3}$  and  $N_{\text{FFP}} = 10^8 \text{ pc}^{-3}$ ).

In the *HST*/ACS sources catalogue of NGC 6388 used by Lanzoni et al. (2007), there are 31 point sources within the *Chandra* error box of IGR J17361–4441. No one is a WD (Lanzoni, private communication). A more detailed analysis of the data available in the *HST* archive will be presented in a forthcoming paper. However, it is worth to note that only very bright WDs can be observed by *HST* in the reddened core of NGC 6388.

#### 4.4 Extragalactic TDE

We considered the possibility that IGR J17361–4441 has an extragalactic origin, i.e. it is due by a sudden increase in the accretion rate on an SMBH at the centre of an otherwise quiescent galaxy (see Komossa et al. 2004; Burrows et al. 2011; Saxton et al. 2012; Nikolajuk & Walter 2013).

First of all, we have estimated the number of background AGNs expected towards the target within a circle of radius  $\simeq 0.6 \text{ arcsec}$  through the  $\log N$ – $\log S$  diagram (Hasinger, Miyaji & Schmidt 2005) and by using the *Chandra* flux upper limit  $\simeq 4.8 \times 10^{-16} \text{ erg cm}^{-2} \text{ s}^{-1}$  (Pooley et al. 2011). Assuming a power-law model with  $\Gamma = 1.7$  and an absorption column density  $N_{\text{H}} = 3 \times 10^{21} \text{ cm}^{-2}$  (Dickey & Lockmann 1990), we have obtained an unabsorbed flux in the 0.5–2 keV band of  $2.9 \times 10^{-16} \text{ erg cm}^{-2} \text{ s}^{-1}$  (by using WEBPIMMS v3.9<sup>2</sup>). The expected number of background AGNs is

then  $\simeq 1 \times 10^{-4}$ . Thus, the probability of the existence of a background AGN is unlikely although not negligible.

On the other hand, we have estimated the likelihood that the event is an extragalactic TDE occurring in a background galaxy, either with an AGN activity or not. A decay time-scale of  $\approx 70 \text{ d}$  is in agreement with the expected time-scale for the disruption of a solar-type star by an SMBH. In particular, we can reproduce the observed inner disc temperature at peak of  $kT_{\text{in}} \approx 0.08 \text{ keV}$  and a decay time-scale of 68 d if the disrupted object has a mass  $M_* = 0.48 M_{\odot}$  and the SMBH has a mass of  $M \approx 5.8 \times 10^6 M_{\odot}$ .

The expected observed bolometric flux in this case is given by

$$F_{\text{bol}} = \frac{1}{4\pi D^2} \frac{\epsilon M_* c^2}{3t_{\text{min}}}, \quad (14)$$

where  $M_*$  is the mass of the disrupted star. Now, assuming an SMBH accretion efficiency of  $\epsilon = 0.1$  and  $M_* = 0.48 M_{\odot}$ , we can estimate the distance of the source based on the observed flux  $F_{\text{bol}} \approx 2 \times 10^{-9} \text{ erg cm}^{-2} \text{ s}^{-1}$  and the observed decay time-scale  $t_{\text{min}} \approx 68 \text{ d}$ . We then obtained  $D \approx 160 \text{ Mpc}$ , corresponding to a redshift of  $z \approx 0.04$ .

We can then use the Marconi & Hunt (2003)  $L_{K,\text{bul}} - M_{\text{BH}}$  relation to obtain the  $K$ -band luminosity of the putative host galaxy for the assumed BH mass of  $\sim 5.8 \times 10^6 M_{\odot}$ . At a distance of  $\sim 150 \text{ Mpc}$ , the resulting apparent luminosity magnitude would be of the order of 15. Now, such a bright and relatively nearby galaxy would be seen as extended object by *HST*/ACS. Indeed, the limiting magnitude for bright galaxies (above which they are observed as point sources) is around 23.3 (see Blanton & Moustakas 2009; Bono et al. 2010 and references therein). No extended source has been observed in the field of IGR J17361–4441 by *HST* and we can thus rule out the possibility of an extragalactic TDE.

## 5 CONCLUSION

The nature of the puzzling new *INTEGRAL* source IGR J17361–4441 is still unknown after a number of follow-up observations. We noted two empirical evidences typical of TDEs: a  $\propto t^{-5/3}$  trend of the light curve and a thermal disc blackbody emission almost constant with time. Thus, we started to investigate the possibility that a minor body was tidally disrupted by a compact object. Our observational analysis and theoretical calculations indicate a free-floating terrestrial planet tidally disrupted by a WD. In particular, the mass of the disrupted body is  $M_{\text{mb}} \approx 1.9 \times 10^{27} (M/M_{\text{Ch}}) \text{ g}$ , while the accreting object is consistent with a WD close to the Chandrasekhar limit.

Finally, we have estimated the rate of a planetary disruption event by a WD in the GC NGC 6388: although many of the relevant parameters are highly uncertain, we estimate the rate  $\dot{N}_{\text{TE}}$  to be in the range  $\simeq 10^{-6} - 10^{-4} \text{ yr}^{-1}$ . The lower limit suggests that the detection of such an event in the Milky Way is unlikely. However, if we consider the optimistic estimate for the rate, and considering that the total number of GC in the Galaxy is roughly 150, we obtain a total rate of events of about  $0.05 \text{ yr}^{-1}$ , i.e. one every  $\sim 20 \text{ yr}$ , comparable with the lifetime of *INTEGRAL* and *Swift*.

## ACKNOWLEDGEMENTS

We acknowledge interesting discussions with Giuseppe Bertin, Piergiorgio Casella, Domitilla De Martino, Alessandra De Rosa, Immacolata Donnarumma, Giuliana Fiorentino, Barbara Lanzoni, Cristina Pallanca, Patrizia Romano, Alexander Tschekoskoy, Dimitri Veras, Andrea Tiengo, Alice Zocchi. MDS and GDC

<sup>2</sup> <http://heasarc.gsfc.nasa.gov/Tools/w3pimms.html>

acknowledge financial support from the agreement ASI-INAF I/009/10/0 and from PRIN-INAF 2009 (PI: L. Sidoli). GL acknowledges financial support from PRIN MIUR 2010–2011, ‘*The Chemical and Dynamical Evolution of the Milky Way and Local Group Galaxies*’, prot. 2010LY5N2T. MDS thanks the Mathematics and Physics Department at the University of Salento for hospitality. AN thanks INAF/IAPS for hospitality.

## REFERENCES

- Armas Padilla M., Degenaar N., Wijnands R., 2013, *MNRAS*, 434, 1586
- Armas Padilla M., Wijnands R., Altamirano D., Mendez M., Miller J. M., Degenaar N., 2014, *MNRAS*, 439, 3908
- Arnaud K., Dorman B., Gordon C., 2007, An X-ray Spectral Fitting Package – User Guide for version 12.4.0, Heasarc Astrophysics Science Division, NASA/GSFC (<http://heasarc.gsfc.nasa.gov/docs/xanadu/xspec/>)
- Barret D., Olive J. F., Boirin L., Done C., Skinner G. K., Grindlay J. E., 2000, *ApJ*, 533, 329
- Baumgardt H., Makino J., Hut P., McMillan S., Portegies Zwart S., 2005, *ApJ*, 589, L25
- Bear E., Soker N., 2013, *New Astron.*, 19, 56
- Binney J., Tremaine S., 2008, *Galactic Dynamics*, 2nd edn. Princeton Univ. Press, Princeton, NJ
- Blanton M. R., Moustakas J., 2009, *ARA&A*, 47, 159
- Bloom J. S. et al., 2011, *Science*, 333, 203
- Bono G. et al., 2010, *PASP*, 122, 651
- Bozzo E. et al., 2011, *A&A*, 535, 1
- Bozzo E. et al., 2012, *Astron. Telegrams*, #3958
- Burrows D. N. et al., 2005, *Space Sci. Rev.*, 120, 165
- Burrows D. N. et al., 2011, *Nature*, 476, 421
- Campana S., 2009, *ApJ*, 699, 1144
- Campana S. et al., 2011, *Nature*, 480, 69
- Casares J., Torres M. A. P., Nequeruella I., Gonzalez-Fernandez C., Corral-Santana J. M., Zurita C., Llano S. R., 2011, *Astron. Telegrams*, 3206, 1
- Casella P., Altamirano D., Patruno A., Wijnands R., van der Klis M., 2008, *ApJ*, 674, L41
- cenko S. B. et al., 2012, *ApJ*, 753, 77
- Chomiuk L., Strader J., Maccarone T. J., Miller-Jones J. C. A., Heinke C., Noyola E., Seth A. C., Ransom S., 2013, *ApJ*, 777, 69
- Chornock R. et al., 2014, *ApJ*, 780, 44
- Cornelisse R. et al., 2004, *Nucl. Phys. B*, 132, 518
- Courvoisier T. J.-L. et al., 2003, *A&A*, 411, 53
- Cseh D., Kaaret P., Corbel S., Krđing E., Coriat M., Tzioumis A., Lanzoni B., 2010, *MNRAS*, 406, 1049
- Dalessandro E., Lanzoni B., Ferraro F. R., Rood R. T., Milone A., Piotto G., Valenti E., 2008, *ApJ*, 677, 1069
- Davidsson B. J. R., 1999, *Icarus*, 142, 525
- Degenaar N., Wijnands R., 2009, *A&A*, 495, 547
- Degenaar N., Wijnands R., 2010, *A&A*, 524, 69
- Del Santo M., Sidoli L., Mereghetti S., Bazzano A., Tarana A., Ubertini P., 2007, *A&A*, 468, L17
- Dickey J. M., Lockman F. J., 1990, *ARA&A*, 28, 215
- Donato D. et al., 2014, *ApJ*, 781, 59
- Esquej P., Saxton R. D., Freyberg M. J., Read A. M., Altieri B., Sanchez-Portal M., Hasinger G., 2007, *A&A*, 462, L49
- Evans C. R., Kochanek C. S., 1989, *ApJ*, 346, L13
- Falanga M., Kuiper L., Poutanen J., Galloway D. K., Bozzo E., Goldwurm A., Hermsen W., Stella L., 2012, *A&A*, 545, 26
- Farihi J., Jura M., Zuckerman B., 2009, *ApJ*, 694, 805
- Farihi J., Jura M., Lee J.-E., Zuckerman B., 2010, *ApJ*, 714, 1386
- Farihi J., Gänsicke B. T., Wyatt M. C., Girven J., Pringle J. E., King A. R., 2012, *MNRAS*, 424, 464
- Farihi J., Gänsicke B. T., Koester D., 2013, *Science*, 342, 218
- Ferrigno C., Bozzo E., Gibaud L., Rodriguez J., 2011a, *Astron. Telegrams*, 3566, 1
- Ferrigno C. et al., 2011b, *Astron. Telegrams*, 3617, 1
- Fregeau J. M., Joshi K. J., Portegies Zwart S. F., Rasio F. A., 2002, *ApJ*, 570, 171
- Gänsicke B. T., Marsh T. R., Southworth J., Rebassa-Mansergas A., 2006, *Science*, 314, 1908
- Gänsicke B. T., Koester D., Farihi J., Girven J., Parsons S. G., Breed E., 2012, *MNRAS*, 424, 333
- Gezari S. et al., 2009, *ApJ*, 698, 1367
- Gezari S. et al., 2012, *Nature*, 485, 217
- Gibaud L. et al., 2011, *Astron. Telegrams*, 3565, 1
- Guillochon J., Manukian H., Ramirez-Ruiz E., 2014, *ApJ*, 783, 23
- Harris W. E., 1996, *AJ*, 112, 1487
- Hasinger G., Miyaji T., Schmidt M., 2005, *A&A*, 441, 417
- Homan J., Belloni T., 2005, *Ap&SS*, 300, 107
- Hurley J., Shara M. M., 2002, *ApJ*, 565, 1251
- Ida S., Kokubo E., Kominami J., 2003, in Makino J., Hut P., eds, *Proc. IAU Symp. 208, Astrophysical Supercomputing Using Particle Simulations*. Kluwer, Dordrecht, p. 25
- Ivanova N., Heinke C. O., Rasio F. A., Taam R. E., Belczynski K., Fregeau J., 2006, *MNRAS*, 372, 1043
- Jura M., 2003, *ApJ*, 584, L91
- Jura M., Farihi J., Zuckerman B., 2009, *AJ*, 137, 3191
- Kalogera V., King A. R., Rasio F. A., 2004, *ApJ*, 601, L171
- Koester D., Wilken D., 2006, *A&A*, 453, 1051
- Komossa S., Bade N., 1999, *A&A*, 343, 775
- Komossa S., Halpern J., Schartel N., Hasinger G., Santos-Lleo M., Predehl P., 2004, *ApJ*, 603, L17
- Kulkarni S. R., Hut P., McMillan S., 1993, *Nature*, 364, 421
- Lanzoni B., Dalessandro E., Ferraro F. R., Mocchi P., Valenti E., Rood R. T., 2007, *ApJ*, 668, 139
- Lanzoni B. et al., 2013, *ApJ*, 769, 107
- Lebrun F. et al., 2003, *A&A*, 411, 141
- Levan A. J., 2011, *Science*, 333, 199
- Levan A. J. et al., 2014, *ApJ*, 781, 13
- Li L.-X., Narayan R., Menou K., 2002, *ApJ*, 576, 753
- Lodato G., Rossi E. M., 2011, *MNRAS*, 410, 359
- Lodato G., King A. R., Pringle J. E., 2009, *MNRAS*, 392, 332
- Loeb A., Ulmer A., 1997, *ApJ*, 489, 573
- McClintock J. E., Remillard R. A., 2006, in Lewin W. H. G., van der Klis M., eds, *Compact stellar X-ray sources*. Cambridge Univ. Press, Cambridge, p. 157
- Maccarone T. J., 2004, *MNRAS*, 351, 1049
- Maksym W. P., Ulmer M. P., Eracleous M. C., Guennou L., Ho L. C., 2013, *MNRAS*, 435, 1904
- Marconi A., Hunt L. K., 2003, *ApJ*, 589, L21
- Merloni A., Heinz S., di Matteo T., 2003, *MNRAS*, 345, 1057
- Metzger B. D., Rafikov R. R., Bochkarev K. V., 2012, *MNRAS*, 423, 505
- Migliari S., Fender R., 2006, *MNRAS*, 366, 79
- Mitsuda K. et al., 1984, *PASJ*, 36, 741
- Nikolajuk M., Walter R., 2013, *A&A*, 552, 75
- Nucita A. A., De Paolis F., Ingrassio G., Carpano S., Guainazzi M., 2008, *A&A*, 478, 763
- Nucita A. A., De Paolis F., Saxton R., Read A. M., 2012, *New Astron.*, 17, 589
- Papitto A., Riggio A., Di Salvo T., Burderi L., D’Aí A., Iaria R., Bozzo E., Menna M. T., 2010, *MNRAS*, 407, 2575
- Patruno A., Watts A. L., 2012, in Belloni T., Mendez M., Zhang C. M., eds, *Astrophysics and Space Science Library, Timing neutron stars: pulsations, oscillations and explosions*. Springer-Verlag, Berlin, preprint ([arXiv:1206.2727](https://arxiv.org/abs/1206.2727))
- Phinney E. S., 1989, in Mark M., ed., *Proc. IAU Symp. 136, The Center of the Galaxy*. Kluwer, Dordrecht, p. 543
- Pooley D., Homan J., Heinke C. O., Sivakof G. R., Altamirano D., Maxwell J. E., Cohn H., Luggner P., 2011, *Astron. Telegrams*, 3627
- Portegies Zwart S. F., McMillan S. L. W., 2000, *ApJ*, 528, L17
- Pryor C., Meylan G., 1993, in Djorgovski S. G., Meylan G., eds, *ASP Conf. Ser. Vol. 50, Structure and Dynamics of Globular Clusters*. Astron. Soc. Pac., San Francisco, p. 357



- Raskin C., Timmes F. X., Scannapieco E., Diehl S., Fryer C., 2009, *MNRAS*, 399, 156
- Rea N., Jonker P. G., Nelemans G., Pons J. A., Kasliwal M. M., Kulkarni S. R., Wijnands R., 2011, *ApJ*, 729, L21
- Rees M. J., 1988, *Nature*, 333, 523
- Sari R., Kobayashi S., Rossi E. M., 2010, *ApJ*, 708, 605
- Saxton R. D., Read A. M., Esquej P., Komossa S., Dougherty S., Rodriguez-Pascual P., Barrado D., 2012, *A&A*, 541, 106
- Segreto A., Cusumano G., Ferrigno C., La Parola V., Mangano V., Mineo T., Romano P., 2010, *A&A*, 510, 47
- Soker N., Rappaport S., Fregeau J., 2001, *ApJ*, 87, L10
- Spurzem R., Giersz M., Heggie D. C., Lin D. N. C., 2008, *ApJ*, 697, 458
- Stone N., Sari R., Loeb A., 2013, *MNRAS*, 435, 1809
- Strader J., Chomiuk L., Maccarone T. J., Miller-Jones J. C. A., Seth A. C., 2012, *Nature*, 490, 71
- Trenti M., van der Marel R., 2013, *MNRAS*, 435, 3272
- Ubertini P. et al., 2003, *A&A*, 411, L131
- van Velzen S. et al., 2011, *ApJ*, 741, 73
- Wijnands R., 2008, in Bandyopadhyay R. M., Wachter S., Gelino D., Gelino C. R., eds, *AIP Conf. Proc. Vol. 1010, A POPULATION EXPLOSION: The Nature & Evolution of X-ray Binaries in Diverse Environments*. Am. Inst. Phys., New York, p. 382
- Wijnands R. et al., 2006, *A&A*, 449, 1117
- Wijnands R., Altamirano D., Soleri P., Degenaar N., Rea N., Casella P., Patruno A., Linares M., 2008, in Wijnands R., Altamirano D., Soleri P., Degenaar N., Rea N., Casella P., Patruno A., Linares M., eds, *AIP Conf. Proc. Vol. 1068, A Decade of Accreting Millisecond X-Ray Pulsars*. Springer, Berlin, p. 152
- Wijnands R., Yang Y. J., Degenaar N., Altamirano D., Tudose V., Heinke C. O., 2011, *Astron. Telegrams*, #3595
- Winkler P. et al., 2003, *A&A*, 411, L1
- Zauderer B. A. et al., 2011, *Nature*, 476, 425

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