The XMM-Newton Slew view of IGRJ17361-4441: a transient in the globular cluster NGC 6388

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Abstract

IGRJ17361-4441 is a hard transient recently observed by the INTEGRAL satellite. The source, close to the center of gravity of the globular cluster NGC 6388, quickly became the target of follow-up observations conducted by the Chandra, Swift/XRT and RXTE observatories. Here, we concentrate in particular on a set of observations conducted by the XMM-Newton satellite during two slews, in order to get the spectral information of the source and search for spectral variations. The spectral parameters determined by the recent XMM-Newton slew observations were compared to the previously known results. The maximum unabsorbed X-ray flux in the 0.5-10 keV band as detected by the XMM-Newton slew observations is $\approx 4.5 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$, i.e. consistent with that observed by the Swift/XRT satellite 15 days earlier. The spectrum seems to be marginally consistent ($\Gamma \approx 0.93 - 1.63$) with that derived from the previous high energy observations.

Keywords: (Galaxy:) globular clusters: individual (NGC 6388), X-rays: general

1. Introduction

IGRJ17361-4441 is a hard X-ray transient source first observed by Gibaud et al. (2011) with the IBIS/ISGRI telescope (Ubertini et al., 2003) onboard the INTEGRAL satellite (Winkler et al., 2003) and was quickly recognized to be hosted in the galactic globular cluster NGC 6388 (Ferrigno et al., 2011).
The location of the transient (close to the globular cluster gravitational center, but see later) is of great importance since NGC 6388, among all the globular clusters in our Galaxy, is one of the best candidates (Baumgardt et al., 2005) to host an intermediate mass black hole (hereafter IMBH). In particular, by using high resolution optical observations, Lanzoni et al. (2007) estimated the mass of the IMBH to be \( \simeq 5700 \, M_\odot \). It would be natural for such an IMBH to emit significant radiation in the X-ray band due to the likely accretion of matter from its surroundings. In the context of the earliest observations of globular clusters, Bahcall & Ostriker (1975) and Silk & Arons (1976) were the first to suggest that the X-ray emission detected towards these clusters was due to IMBHs (in the mass range \( 20 \, M_\odot \text{--} 10^{6} \, M_\odot \)) accreting from the intracluster medium. This issue was considered more recently by Grindlay et al. (2001) who provided the census of the compact object and binary population in the globular cluster 47 Tuc and obtained an upper limit to the central IMBH of a few hundred solar masses.

Initial XMM-Newton and Chandra observations in this direction (Nucita et al. 2008 and Cseh et al. 2010) showed that the core of NGC 6388 hosts several X-ray sources. Based on the correlation between the X-ray and radio flux from black holes (Merloni et al. 2003); Maccarone (2004) was the first to point out that the search for radio emission from faint black holes is useful to test the IMBH hypothesis in globular clusters and dwarf spheroidal galaxies (Maccarone et al. 2005). Cseh et al. (2010) observed the central region of NGC 6388 in the radio band using the Australia Telescope Compact Array (ATCA) to search for radio signatures of the IMBH. The radio observation resulted in an upper limit of the IMBH mass of \( \simeq 1500 \, M_\odot \).

The discovery of a transient source close to the NGC 6388 gravitational center could be related to the turning on of the putative globular cluster IMBH. However, as will become clear in the subsequent sections, the nature and spectral properties of the transient IGRJ17361-4441 are difficult to reconcile with the IMBH picture and rather favour an interpretation as a high mass X-ray binary (HMXB) or a low mass X-ray binary (LMXB). Several observational campaigns (in the X-rays as well as in the radio band) were organized in order to pinpoint IGRJ17361-4441 and draw firm conclusions on the NGC 6388 IMBH paradigm.

In this paper we briefly discuss (see section 2) the past X-ray observations of the NGC 6388 globular cluster (see Nucita et al. 2008 and Cseh et al. 2010) and the discovery of the hard transient IGRJ17361-4441 by INTEGRAL (Gibaud et al. 2011) as well as the follow-up observations conducted.
by Chandra (Pooley et al. 2011), Swift/XRT and RXTE observatories (Ferrigno et al. 2011 and Bozzo et al. 2011). Then we concentrate (see section 3) on the analysis of two XMM-Newton slew observations of NGC 6388 conducted 15 days after the INTEGRAL discovery of the source. The two slew observations had $\simeq 7.6$ seconds and $\simeq 7.7$ seconds on source exposure time. Finally our conclusions are presented in section 4.

2. Previous observations of NGC 6388

2.1. XMM-Newton and Chandra observations of NGC 6388

By studying a combination of high resolution (HST ACS-HRC, ACS-WFC, and WFPC2) and wide field (ESO-WFI) observations of the globular cluster NGC 6388, Lanzoni et al. (2007) claimed the existence of a central IMBH. Such a compact object of mass $\simeq 5700 \, M_\odot$ should reside in the globular cluster center of gravity localized at the coordinates (J2000) $RA = 17^h 36^m 17.23^s$, $Dec = -44^0 44' 7.1''$. An uncertainty of 0.3'' is associated with both coordinates.

Nucita et al. (2008) suggested that this IMBH should emit radiation in the X-ray band due to accretion from the surrounding matter. A 48 ks XMM-Newton observation was made on 21 March 2003. It resulted in a spectrum which was well fit by an absorbed power-law model. The resulting best fit parameters were $N_H = (2.7 \pm 0.3) \times 10^{21} \, \text{cm}^{-2}$ for the hydrogen column density and $\Gamma = 2.4 \pm 0.1$ for the power law index. The unabsorbed flux in the 0.5–7 keV band was $F_{0.5-7} = (4.0 \pm 0.2) \times 10^{-13} \, \text{erg cm}^{-2} \, \text{s}^{-1}$ which, for a distance of 13.2 kpc corresponds to a luminosity of $L_{0.5-7} \simeq (7.2 \pm 0.4) \times 10^{33} \, \text{erg s}^{-1}$. Note that the hydrogen column density is consistent with the average one found in the direction of the target (Dickey & Lockman 1990).

Note however that, as first pointed out by Bahcall & Wolf (1976), a black hole in a stellar cluster will experience a Brownian motion due to gravitational interactions with the surrounding objects. Thus, the black hole is not necessarily at the dynamical center of the host cluster, but may move with mean square velocity given by (Merritt et al. 2007)

$$\frac{1}{2} M \langle v_{rms}^2 \rangle \simeq \frac{3}{2} m \sigma^2$$

(1)

where $M$, $m$ and $\sigma$ represent the black hole mass, the perturber average mass and the stellar velocity dispersion within $\sim 0.6 r_i$, respectively. Here $r_i$ is the influence radius of the black hole (for details see Merritt et al. 2007 and references therein).
The Chandra satellite, with a much better angular resolution than that of XMM-Newton, observed towards NGC 6388 for \( \sim 45 \) ks on 21 April 2005 (id 5505). Nucita et al. (2008) identified 16 discrete sources within the half mass radius (\( \sim 40'' \), see Lanzoni et al. 2007) of the cluster. The 3 sources close to the gravitational center were not spatially resolved by the authors, so that they were considered virtually as a single source (labeled as \#14\(^*\)). The unabsorbed flux in the 0.5-7 keV band of the \#14\(^*\) is \( F_{0.5-7} \sim 1.7 \times 10^{-13} \) erg cm\(^{-2}\) s\(^{-1}\), corresponding to a luminosity of \( L_{0.5-7} \sim 3 \times 10^{33} \) erg s\(^{-1}\).

A more detailed analysis on the same Chandra data set was conducted by Cseh et al. (2010). After removing the pixel randomization, these authors were able to spatially resolve the source \#14\(^*\) into three separate sources labeled as \#12, \#7 and \#3. In particular, the source \#12, which is consistent with the position of the center of gravity of NGC 6388, is characterized by an unabsorbed flux of \( F_{0.3-8} \sim 4.0 \times 10^{-14} \) erg cm\(^{-2}\) s\(^{-1}\) corresponding to an intrinsic luminosiy of \( L_{0.3-8} \sim 8.3 \times 10^{32} \) erg s\(^{-1}\).

Cseh et al. (2010) searched for a radio counterpart of the putative IMBH in NGC 6388 using the ATCA facility. Unfortunately, this search only resulted in an upper limit to the radio flux at 5 GHz of \( \sim 81 \) \( \mu \)Jy/beam. Therefore, it was only possible to determine an upper limit to the IMBH radio luminosity of \( L_R < 8.4 \times 10^{28} \) erg s\(^{-1}\).

Based on the fundamental plane of black hole accretion (Merloni et al. 2003 and Koerding et al. 2006) and using the observed X-ray and radio luminosities, it was then possible to put a 3\( \sigma \) upper limit of \( \sim 1500 \) M\(_\odot\) on the mass of the IMBH in NGC 6388 (Cseh et al. 2010). The estimated mass value has to be treated with caution for two reasons: i) the identification of the X-ray counterpart of such a black hole is not trivial since several sources are close to the NGC 6388 center of gravity. If none of them are associated with the IMBH, then one can not use the fundamental plane relation to get an estimate of the mass; ii) the fundamental plane relation (as derived by Merloni et al. 2003 and Koerding et al. 2006) is not tested for black hole masses in the range of interest for IMBHs, i.e. \( 10^3 \) M\(_\odot\) – \( 10^4 \) M\(_\odot\). Note however that Maccarone et al. (2005) and Maccarone & Servillat (2008) showed that the non-detection of a radio source, in combination with the estimate of the globular cluster ISM density\(^2\) and the expected value of the accre-

\(^2\)The amount of gas contained in globular clusters is an issue of debate. The intracluster medium density can be estimated by using the dispersion measures of the pulsars observed
tion rate, can be used to get information (at least as an order of magnitude estimate) of the IMBH mass.

2.2. INTEGRAL discovery of IGRJ17361-4441 and subsequent X-ray follow-up observations

On 11 August 2011, Gibaud et al. (2011) reported the discovery of a new hard X-ray transient (IGRJ17361-4441) by the IBIS/ISGRI telescope (Ubertini et al. 2003) onboard the INTEGRAL satellite (Winkler et al. 2003). The spectrum of the source, associated with the globular cluster NGC 6388, was described by a power law with photon index $\Gamma = 2.6^{+1.0}_{-0.7}$ and characterized by a flux in the 20-100 keV of $F_{20-100} \simeq 9.7 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$.

Since this newly discovered transient is possibly associated with the IMBH in NGC 6388, IGRJ17361-4441 became the target of several X-ray follow-up observations aimed at obtaining accurate position and flux measurements to test if this association is correct.

Wijnands et al. (2011) (but see also Ferrigno et al. 2011) reported a Swift/XRT observation (1.9 Ks on 16 August 2011) in which the astrometrically corrected position of IGRJ17361-4441 was $RA = 17^{h} 36^{m} 17.5^{s}$, $Dec = -44^{\circ} 44^{\prime} 7.1^{\prime\prime}$. A more detailed analysis on the XRT data conducted by Bozzo et al. (2011) determined the new transient position to be $RA = 17^{h} 36^{m} 17.27^{s}$, $Dec = -44^{\circ} 44^{\prime} 7.0^{\prime\prime}$ with an associated error (on both coordinates) of 1.9$^\prime$. Thus, the distance of the transient from the center of gravity of NGC 6388 is $0.4^\prime\prime \pm 1.4^\prime\prime$. Hence, the source position is consistent (according to the Swift/XRT data) with the center of gravity of the cluster and (possibly) associated with the IMBH. Note also that a 2.5 Ks Chandra observation was made on 29 August 2011 (Wijnands et al. 2011) in order to improve the accuracy of the location of the transient. IGRJ17361-4441 is located at the coordinates $RA = 17^{h} 36^{m} 17.418^{s}$, $Dec = -44^{\circ} 44^{\prime} 5.98^{\prime\prime}$ (the nominal Chandra positional accuracy is 0.6$^\prime$ on both coordinates). In this case, the estimated distance of the transient to the cluster center of gravity is $2.3^\prime\prime \pm 0.5^\prime\prime$.

Based on the Swift/XRT astrometry only, one could conclude that the position of IGRJ17361-4441 is formally consistent with the center of gravity within the cluster (see e.g. Freire et al. 2001, 2003) or inferred by the empirical knowledge about the stellar mass loss (Pfahl & Rappaport 2001).

3We note that the distances between the sources and the center of gravity of the globular cluster NGC 6388 are calculated by using the well known Haversine formula. Distance uncertainties are calculated by correctly propagating the errors on both $\alpha$ and $\delta$ coordinates.
of NGC 6388 and possibly related to the putative IMBH in the globular cluster. An updated radio observation conducted at ATCA by Bozzo et al. (2011) put a more stringent upper limit to the radio luminosity of $L_R < 5 \times 10^{28}$ erg s$^{-1}$ so that, following the same procedure as in Cseh et al. (2010) and the 2005 Chandra X-ray flux estimate, the new IMBH upper limit turns out to be $\simeq 600$ M$\odot$ (Bozzo et al. 2011).

However, a caveat on this conclusion is necessary. The new Chandra refined source coordinates (even if formally consistent with the source position determined by Swift/XRT) indicate that the transient could be a new X-ray source (see later) not associated with the IMBH. In this case, and for the reasons explained above, one should not use the black hole fundamental plane relation in order to estimate the IMBH mass. If one believes that the transient is associated with the NGC 6388 center of gravity, then it should also be noted that at least three sources (those labeled as #12, #7 and #3 in Cseh et al. 2010) are within the error box of Swift/XRT. In particular, sources #12 and #7 have fluxes $\simeq 4.0 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ and $\simeq 6.9 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$, respectively. If source 7 is associated with the IMBH, the X-ray and radio observations together with the fundamental plane relation give an upper limit of $\simeq 1200$ M$\odot$.

The Swift/XRT spectrum of the transient source was fitted (Bozzo et al. 2011) with an absorbed power law with photon index $\Gamma \sim 0.5 - 0.9$ and hydrogen column density $N_H \simeq (0.5 - 0.9) \times 10^{22}$ cm$^{-2}$, i.e. consistent with that derived from the previous XMM-Newton data.

The flux in the $1.0 - 10$ keV band is $F_{1-10} = (4.5 - 4.8) \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$, a factor 100 more luminous than the source #12 possibly associated with the NGC 6388 IMBH (Cseh et al. 2010). When the broad band spectrum (obtained by using Swift/XRT and INTEGRAL/ISGRI) was analysed (and fit with a broken power law), Bozzo et al. (2011) obtained a flux of $F_{1-10} = (4.6^{+0.1}_{-0.5}) \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$ in the $1.0 - 10$ kev band and a flux of $F_{20-100} = (7.8^{+0.8}_{-3.8}) \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$ in the $20 - 100$ kev band.

These results are consistent with those obtained by using the XRTE/PCA follow-up observation made on 17 August 2011. In particular, it was found that $F_{3-15} = (6.7^{+0.1}_{-3.4}) \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$ in the $3-15$ keV band (Bozzo et al. 2011).
3. The XMM-Newton slew observations

The large collecting area of the nested mirrors together with the high quantum efficiency of the EPIC/PN camera make the XMM-Newton satellite the most sensitive X-ray observatory available at present (Jansen et al. 2001). The XMM-Newton satellite was recognized to be a good instrument to collect data during slewing manoeuvres and is performing an X-ray survey of the sky (Saxton et al. 2008). Note that the XMM-Newton slew observations are moderately deep with a detection limit of $1.2 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ in the 0.2 – 12.0 keV band.

Due to the scheduled observation program, the XMM-Newton satellite twice observed the region of the sky around NGC 6388. The observations were taken on September 1st 2011 at 13:10:34 (hereafter S1 observation) and 19:00:17 (UT) (hereafter S2 observation), i.e. 15 days after the first Swift/XRT follow-up observation of IGRJ17361-4441. The transient source was then observed serendipitously for $\simeq 7.6$ s and $\simeq 7.7$ s in the two slew observations with the EPIC/PN instrument (see Fig. 1).

We decided to analyze the data sets separately in order to study a possible spectral variation on time-scales of hours.

The source spectrum has been extracted from a circle of radius 60″ about the source with the background being extracted from an annulus of inner radius 90″ and outer radius 120″ about the source. The detector matrices are calculated taking into account the transit of the source across the detector and using the method described in Read et al. (2008). Hence, the source and background spectra (as well as the response matrices) were imported in the XSPEC package (version 12.4.0) for the spectral analysis and fitting procedure. The adopted model is an absorbed power law (wabs*power) with the hydrogen column density fixed to the average value found by ROSAT in the direction of the target, i.e. $2.5 \times 10^{21}$ cm$^{-2}$. Note that this value is consistent with that derived by Nucita et al. (2008) when analyzing the 2005 XMM-Newton observation of NGC 6388 and also similar to the column density found by Bozzo et al. (2011) (see also Ferrigno et al. 2011) while studying the Swift/XRT follow-up observation of IGRJ17361-4441. The adopted model

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4The exposure times were estimated by calculating the distance travelled by the source on the detector with the typical XMM-Newton slew speed of 90 deg h$^{-1}$. The resulting exposure times were also corrected for chip gaps and bad pixels (for details see Read et al. 2008).
Figure 1: Contours (increasing by factors of 2) of lightly-smoothed 0.2-12 keV XMM-Newton slew emission (EPIC-pn camera, the two 01/09/11 observations combined), superimposed on a SAO-DSS image of NGC6388.

Figure 2: The XMM-Newton spectrum of IGRJ17361-4441 (data points) collected during the first slew observation on September 1st 2011. The solid line represents the best fit model (see text for details).
The fitting procedure to the S1 spectrum resulted in the best fit parameters \( \chi^2/\nu = 1.4 \) for 11 d.o.f.) \( \Gamma = 1.16 \pm 0.20 \) and \( N = (1.7 \pm 0.7) \times 10^{-3} \). The absorbed fluxes in the 0.5–2.0 keV, 2.0–10 keV, and 0.5–10.0 keV bands are \( F_{0.5-2} = (5.4^{+2.8}_{-3.2}) \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1} \), \( F_{2-10} = (3.6^{+1.4}_{-1.7}) \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1} \), and \( F_{0.5-10} = (4.1^{+1.6}_{-1.9}) \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1} \), respectively.

Fitting the S2 spectrum with the same model gives the best fit parameters \( \chi^2/\nu = 0.4 \) for 10 d.o.f.) \( \Gamma = 1.28 \pm 0.35 \) and \( N = (1.2 \pm 0.6) \times 10^{-3} \). The absorbed fluxes in the same bands as above are \( F_{0.5-2} = (3.4^{+2.3}_{-2.3}) \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1} \), \( F_{2-10} = (1.9^{+1.1}_{-1.4}) \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1} \), and \( F_{0.5-10} = (2.1^{+1.2}_{-1.8}) \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1} \), respectively.

The maximum unabsorbed flux of the source in the 0.5-10 keV band is \( \approx 4.5 \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1} \) corresponding to an intrinsic luminosity of \( \approx 9.3 \times 10^{35} \text{ erg s}^{-1} \).

In Figure 3, the unabsorbed X-ray fluxes of NGC 6388 in the 0.5 – 10 keV band (from 2003 to 2011) are shown. In the insert, we give the data points corresponding to the IGRJ17361-4441 flare observed and monitored by
several instruments (Swift/XRT, RXTE/PCA and XMM-Newton) in 2011 only. Note that for the XMM-Newton observation in 2003, the Chandra observation in 2005, and the Swift and RXTE in 2011 the 0.5 – 10 keV band fluxes were obtained by extrapolating (to this energy band) the best fit models available in the literature (see e.g. Bozzo et al. 2011).

What can be easily observed from the results reported here, is that the X-ray flux in the 0.5-10 keV band as detected by the XMM-Newton slew observations, i.e. $\simeq 4.5 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$, is consistent with that observed by Swift/XRT 15 days earlier. Note also that the spectrum power-law seems to be marginally consistent ($\Gamma \simeq 0.93 - 1.63$) with that derived from the previous high energy observations ($\Gamma \simeq 0.5 - 0.9$, see Bozzo et al. 2011), a point that could help in a classification of the transient nature (see the subsequent discussion).

Figure 4: The data points from the left to the right correspond to the NGC 6388 flux in the 0.5 – 10 keV band from 2003 to 2011. In the insert, we give the data points corresponding to the flare observed and monitored in 2011 only (see text for details).

4. Results and discussion

IGRJ17361-4441 is a hard transient recently observed by the INTEGRAL satellite. X-ray follow-up observations have shown that the source is within the globular cluster NGC 6388. Based only on the astrometry of the Swift/XRT
satellite, the transient position is consistent with the center of gravity of the globular cluster and this opens the possibility that IGRJ17361-4441 is associated with an IMBH which is turning on.

However, if one believes that the transient is associated with the IMBH in NGC 6388, then it should be noted that at least three X-ray sources (those labeled as #12, #7 and #3 in Cseh et al. 2010) are within the error box of Swift/XRT. In particular, the sources #12 and #7 have fluxes which differ at least by a factor 2 between them. If source #7 is associated with the IMBH, then the observed Chandra X-ray flux (see Nucita et al. 2008 and Cseh et al. 2010) and the updated radio observation of Bozzo et al. (2011) together with the fundamental plane relation give an upper limit of $\simeq 1200\, M_\odot$.

In the IMBH hypothesis, the intrinsic luminosity of the source as determined by using the XMM-Newton slew data (i.e. $\simeq 9.3 \times 10^{35}\, \text{erg s}^{-1}$) should be compared with that derived by using the 2005 Chandra data (and in particular for the source #12 in Cseh et al. 2010) when the putative IMBH was in quiescent state. In this case, one finds that the source luminosity increased by at least a factor $\simeq 1000$. Moreover, the spectrum seems to follow a power law with photon index $\Gamma \simeq 0.96 - 1.63$.

Nevertheless, the refined source position given by the Chandra satellite (even if still in agreement with the Swift/XRT result) argues against the IMBH hypothesis in favor of a newly discovered source. In this case, the XMM-Newton intrinsic source luminosity should be compared with the upper limit for the quiescent state of the source, Pooley et al. (2011), based on the non-detection of the source in the 2005 Chandra observation, estimated this limit to be $\simeq 10^{31}\, \text{erg s}^{-1}$. Thus, in this case the transient source has increased its luminosity by a factor close to $10^5$.

Two more possibilities for the nature of the transient source are that it is either a HMXB or a LMXB. The first possibility is actually unlikely since these systems involve companion stars with mass larger than $\simeq 10\, M_\odot$ (Lewin & van der Klis 2006), i.e. O/B stars which are not expected to exist in globular clusters. Note also that NGC 6388 was extensively observed by the HST instruments (see e.g. Catelan et al. 2006) and the collected data did not show the presence of any O or B star in the globular cluster.

Hence, among the IMBH alternatives, the LMXB option is the most favorable. This is supported by the X-ray luminosity ($\simeq 9.3 \times 10^{35}\, \text{erg s}^{-1}$) and by the soft spectrum ($\Gamma \simeq 0.93 - 1.63$) observed in the XMM-Newton slew observation which seems to be consistent with the typical characteristics

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of the LMXB class of objects. A long X-ray observation (sufficient to allow a
detailed timing and spectral analysis) may help in understanding the physics
underlying this transient source.

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