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Chandra provides new X-ray positions for IGR J16393−4643 and IGR J17091−3624

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Using the High Resolution Camera on *Chandra*, we have obtained the most accurate X-ray positions known for IGR J16393−4643 and for IGR J17091−3624. The obscured X-ray pulsar IGR J16393−4643 lies at R.A. (J2000) = $16^{\mathrm{h}}\ 39^{\mathrm{m}}\ 05\overset{\mathrm{s}}{.}47$, and Dec. = $-46^\circ\ 42'\ 13\overset{''}{.}0$ (error radius of $0\overset{''}{.}6$ at 90% confidence). This position is incompatible with the previously-proposed counterpart 2MASS J16390535−4642137, and it points instead to a new counterpart candidate that is possibly blended with the 2MASS star. The black hole candidate IGR J17091−3624 was observed during its 2011 outburst providing coordinates of R.A. = $17^{\mathrm{h}}\ 09^{\mathrm{m}}\ 07\overset{\mathrm{s}}{.}59$, and Dec. = $-36^\circ\ 24'\ 25\overset{''}{.}4$. This position is compatible with those of the proposed optical/IR and radio counterparts, solidifying the source's status as a microquasar. The other three targets of our observations, IGR J14043−6148, IGR J16358−4726, and IGR J17597−2201, were not detected with 3σ upper limits of, respectively, 1.7, 1.8, and 1.5 (in 10^{-12} erg cm^{-2} s^{-1}) on their observed X-ray fluxes (2–10 keV).

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1. Introduction

Surveys by *INTEGRAL* have enabled the discovery of hundreds of new high-energy sources [1, 2]. While the soft γ-ray imager has proven adept at finding new sources dubbed *INTEGRAL* Gamma-Ray sources or IGRs[1], the position error radii are on the order of a few arcminutes. These are clearly too large to permit the identification of a single counterpart in the optical and infrared (IR) bands. A sub-arcsecond X-ray position obtained with *Chandra* will help localize the correct counterpart enabling follow-up spectral studies to be performed in the optical/IR, which will eventually help lead to a source classification.

Here, we present the results from *Chandra* snapshot observations of five IGRs located along the Galactic Plane: IGR J14043−6148, IGR J16358−4726, IGR J16393−4643, IGR J17091−3624, and IGR J17597−2201. These objects were previously observed with *RXTE*, *Swift*, or *XMM-Newton*, and so some of their spectral and timing behavior is known. They share a common trait in that the identity of the optical/IR counterpart was not firmly established when the *Chandra* observations were proposed.

The fields of these sources were observed for $\sim$1 ks each by the High Resolution Camera (HRC) aboard *Chandra*. These observations were scheduled between 2010 December and 2011 March. In addition to these X-ray observations, on 2011 July 19, we observed IGR J14043−6148 with the National Optical Astronomy Observatory (NOAO) Extremely Wide Field Infrared Imager (NEWFIRM) in the J, H, and K_s broadband filters.

2. Detected sources

2.1 IGR J16393−4643

Our *Chandra* observation of IGR J16393−4643 [3, 4] provides the most precise position for this absorbed X-ray pulsar: R.A. (J2000) $= 16^{\mathrm{h}}\ 39^{\mathrm{m}}\ 05^{\mathrm{s}}.47$ and Dec. $= -46^\circ\ 42'\ 13''.0$ with an error radius of $0''.6$ (90% confidence). The HRC position is consistent with those obtained with *XMM-Newton* and with *INTEGRAL* [5]. However, this position is incompatible with the position of 2MASS J16390535−4642137 which is located $1''.4$ away and which has an error radius of $0''.12$ (at 90% confidence). Thus, we conclude that the 2MASS source, whose optical/IR analysis led to diverging conclusions about its spectral class [6, 7], is unlikely to be the counterpart to IGR J16393−4643. None of the four candidate counterparts proposed in [6] are consistent with the *Chandra* position.

This suggests that the true counterpart to IGR J16393−4643 might be a distant (and reddened) star that is blended with the bright 2MASS star. We combined deep near-IR images of the field of IGR J16393−4643 with the NOAO/NEWFIRM telescope with those of archival *Spitzer*-IRAC observations from the GLIMPSE campaign in the mid-IR [8]. These images are presented in Fig. 1. What appears as a single object in the J band is revealed as two distinct peaks in the counts map of the 5.8 μm band: one corresponds to the 2MASS object, and the other could be a deeply-reddened star situated on the wings of the PSF of the 2MASS star. At 8 μm (not displayed), neither source candidate can be disentangled from the tail of a cloud-like region of diffuse emission.

[1] a comprehensive list can be found at http://irfu.cea.fr/Sap/IGR-Sources

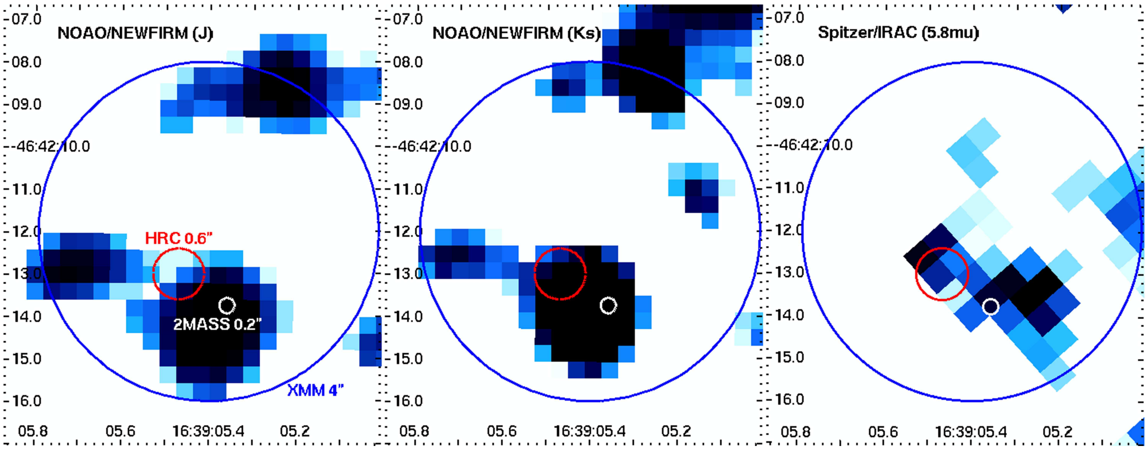

Figure 1: Image of the field of IGR J16393−4643 as captured by the NOAO/NEWFIRM telescope in the J and K_s bands (left and middle panels), and at 5.8 μm (right panel) from *Spitzer*-IRAC [8]. Coordinates are given as equatorial R.A. and Dec. (J2000) where North is up and East is left. The 90%-confidence error circles corresponding to the HRC position from this work, the *XMM-Newton* position [5], and that of the previously-proposed infrared counterpart 2MASS J16390535−4642137 are indicated.

If this candidate is real, and if it represents the true counterpart to IGR J16393−4643, then it has been effectively isolated at 5.8 μm. There are no objects listed in the GLIMPSE catalog [8] consistent with the *Chandra* position. The sensitivity limit of the GLIMPSE survey would place an undetected supergiant O9 star ($T_{\rm eff} \sim 30,000$ K, and $R \sim 20\,R_\odot$) with $A_V \sim 20$ at a minimum distance of 25 kpc, which is probably too far to be plausible. On the other hand, for an undetected main-sequence B star ($T_{\rm eff} \sim 24,000$ K, and $R \sim 10\,R_\odot$), the sensitivity limit implies a large, but reasonable distance ($\sim$12 kpc away). We point out that IGR J16393−4643 is positionally coincident with the edge of an active, massive star-forming (H II) region situated at a distance of 12.0±0.3 kpc [9]. If the blended counterpart to IGR J16393−4643 is a main-sequence B star that originated from this H II region, then this would suggest a distance of $\sim$12 kpc to the X-ray source, consistent with our estimate from the sensitivity limit.

2.2 IGR J17091−3624

Our *Chandra* observation of the microquasar IGR J17091−3624 [10, 11] coincided with the 2011 outburst so we were able to detect the source at a position of R.A. (J2000) = $17^{\rm h}\,09^{\rm m}\,07\overset{\rm s}{.}59$ and Dec. = $-36^\circ\,24'\,25\overset{''}{.}4$ with an error radius of $0\overset{''}{.}6$ (90% confidence). This is the most accurate X-ray position known for this object and it is $0\overset{''}{.}5$ away from, and is consistent with, the XRT position which has an uncertainty of $3\overset{''}{.}5$ [12].

As illustrated in Fig. 2, the IR [13] and radio [14] positions are only marginally compatible with each other at the 90% confidence limit. Nevertheless, they are both inside the HRC error circle so the coordinates from the three energy bands (radio, IR, and X-rays) can be considered to be consistent which further solidifies the source's status as a microquasar.

Adopting an absorbed power law model with spectral parameters fixed to those of the XRT observation ($N_{\rm H} = 7.8 \times 10^{21}$ cm^{-2}, and $\Gamma = 1.6$) [12], the HRC count rate of 37 count s^{-1} (0.3–10 keV) converts to an absorbed flux of 2.1×10^{-9} erg cm^{-2} s^{-1} (2–10 keV). This is a factor 35

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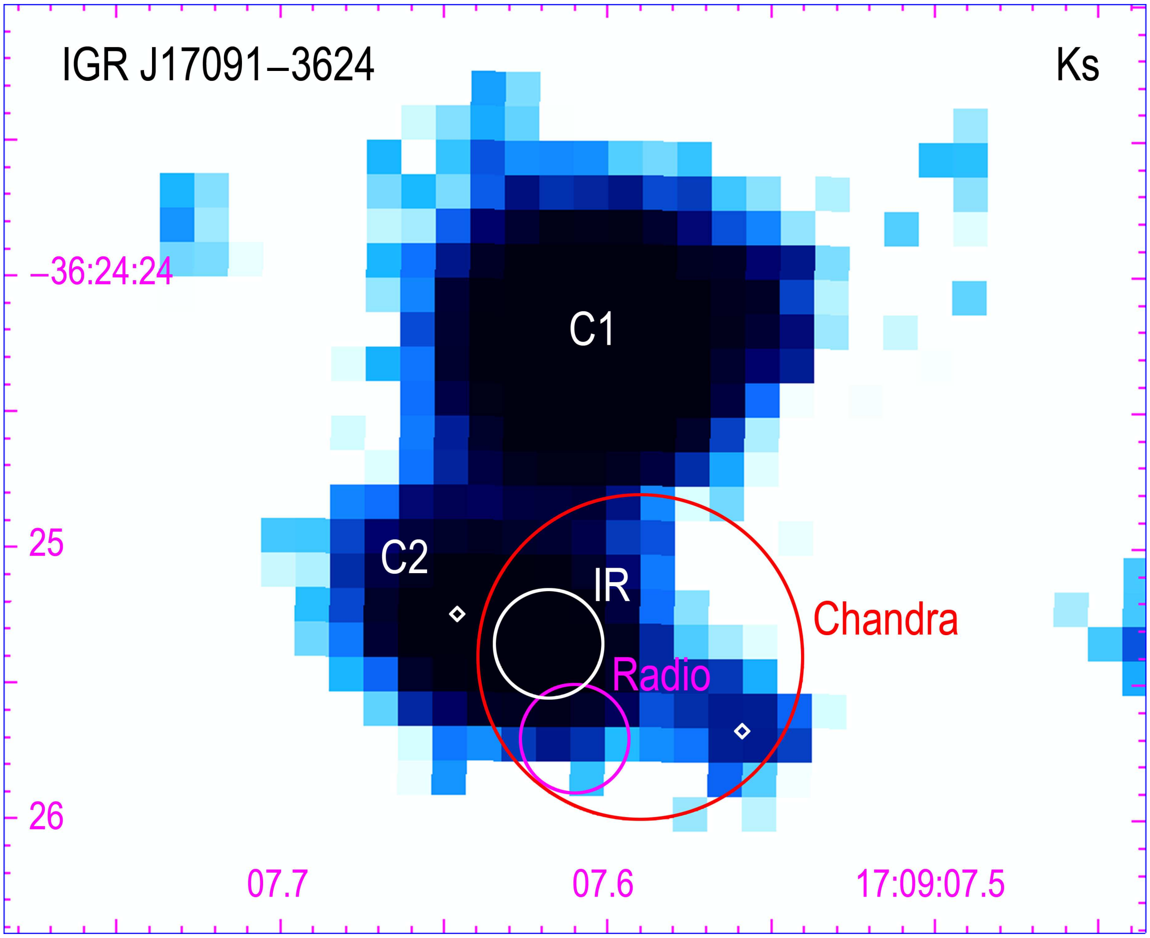

Figure 2: The field of IGR J17091−3624 in the *I* band as captured by the IMACS imaging spectrograph on the 6.5-m Magellan Baade Telescope at the Las Campanas Observatory during 2011 Feb. 6 [13]. Coordinates are given as equatorial R.A. and Dec. (J2000) where North is up and East is left. The error circles corresponding to the *Chandra*-HRC position (this work), and that of the proposed infrared [13] and radio [14] counterparts are indicated. The *Swift*-XRT error circle of [12] is larger than the image. Also indicated are the general locations of the two counterpart candidates ("C1" and "C2") from [6], and the locations (represented by diamonds) of nearby infrared sources.

times the 2–10-keV flux recorded by XRT (6×10^{-11} erg cm^{-2} s^{-1}) [12], and nearly two orders of magnitude larger than the average flux measured by IBIS/ISGRI when translated to the 2–10-keV band (3.5×10^{-11} erg cm^{-2} s^{-1}) [1]. The peak intensity measured by *Swift*-BAT[2] on 2011 Feb. 15 (MJD 55607) is 2.5×10^{-9} erg cm^{-2} s^{-1} (2–10 keV). The HRC count rate converts to an observed luminosity of $1.0\times10^{38}\left[\frac{d}{20\,\mathrm{kpc}}\right]^2$ erg s^{-1}.

3. Undetected sources

3.1 IGR J14043−6148

We did not detect IGR J14043−6148 [1] during our observation, nor were any other sources

[2] http://heasarc.nasa.gov/docs/swift/results/transients

detected inside the IBIS/ISGRI error circle of 4′.5 radius. The 3σ upper-limit on the source count rate is 0.008 counts s^{-1} in the 0.3–10 keV band. A power law whose parameters are fixed to those derived from the XRT observation ($N_H = 7 \times 10^{22}$ cm^{-2}, and $\Gamma = 1.8$) [15] yields an absorbed 2–10-keV flux $\leq 1.7 \times 10^{-12}$ erg cm^{-2} s^{-1} which is less than the flux measured with XRT (2.9×10^{-12} erg cm^{-2} s^{-1}) [15] or with IBIS/ISGRI (4.6×10^{-12} erg cm^{-2} s^{-1}) [1] when translated to the same energy range (2–10 keV). This suggests that the source is variable in the X-rays which rules out a SNR, and points instead towards the AGN scenario proposed originally by [1] and by [15].

3.2 IGR J16358−4726

Unfortunately, IGR J16358−4726 [16] was not active (or it was very faint) during our 1-ks observation and so it was not detected. No other sources were detected in the field. The non-detection is not surprising given that monitoring observations with *RXTE* [3] show few periods of activity in the last 7–8 years. We set a 3σ upper limit of 0.005 counts s^{-1} on the 0.3–10-keV flux from IGR J16358−4726. An absorbed power law with parameters fixed to those from an *XMM-Newton* observation in which the source was detected ($N_H = 2 \times 10^{23}$ cm^{-2} and $\Gamma = 1.5$) [17] gives an observed flux $\leq 1.8 \times 10^{-12}$ erg cm^{-2} s^{-1} in the 2–10-keV band. This upper limit from *Chandra* is less than the average flux observed with IBIS/ISGRI when translated to the 2–10-keV band (3.9×10^{-12} erg cm^{-2} s^{-1}) [1]. For comparison, [17] used *XMM-Newton* to measure a flux of $(3.1 \pm 0.6) \times 10^{-13}$ erg cm^{-2} s^{-1} during detections, with 3σ upper limits of 4×10^{-14} erg cm^{-2} s^{-1} during non-detections.

3.3 IGR J17597−2201

IGR J17597−2201 [18] was not active during our 1-ks observation, and so it was not detected. The 3σ upper limit on the X-ray flux (0.3–10 keV) at the [19] source position is 0.009 counts s^{-1}. For comparison, *Chandra* recorded 0.19 counts s^{-1} in 2007 when the source was active [19]. Adopting the spectral parameters from the *XMM-Newton* observation of [20], i.e., $N_H = 4.5 \times 10^{22}$ cm^{-2} and $\Gamma = 1.7$, the upper limit converts to an absorbed flux (2–10 keV) of $\leq 1.5 \times 10^{-12}$ erg cm^{-2} s^{-1}. This is well below the average flux (2–10 keV) extrapolated from IBIS/ISGRI (3.5×10^{-11} erg cm^{-2} s^{-1}) [1]. The long-term light curve of IGR J17597−2201 from *RXTE* monitoring shows that the source was active during 2001–2008 (mostly concurrent with the IBIS/ISGRI observations), and has been dormant since then. Therefore, this *Chandra* upper limit represents a boundary on the quiescent flux for this source. The distance to the source is not known, but [21] propose a distance of between 5 and 10 kpc, while [22] suggest an upper limit of 16 kpc from the X-ray bursts. The *Chandra* upper limit corresponds to an observed quiescent X-ray luminosity of $\leq 1.8 \times 10^{34} \left[\frac{d}{10\,\mathrm{kpc}}\right]^2$ erg s^{-1}.

4. Summary & Conclusions

Our *Chandra* observations enabled us to derive sub-arcsecond X-ray coordinates for IGR J16393−4643 and IGR J17091−3624. The refined X-ray coordinates that we obtained for IGR J16393−4643 excludes the 2MASS star that we had previously proposed as the optical/IR counterpart (whose spectral class was the subject of disagreement), and points instead to a new (and probably distant) counterpart candidate in the mid-IR that is blended with the bright 2MASS star. For IGR J17091−3624,

[3] http://asd.gsfc.nasa.gov/Craig.Markwardt/galscan

we provide a precise X-ray position that is consistent with the reported optical/infrared and radio counterparts, cementing its status as a microquasar. Three of our targets were not detected: IGR J14043−6148, IGR J16358−4726, and IGR J17597−2201. Nevertheless, the upper limits that we derived for their fluxes helps to establish the range of dynamic variability, which can prove useful for clarifying their nature. The non-detection of IGR J14043−6148 suggests an active galactic nucleus rather than a supernova remnant. The upper limit for IGR J17597−2201 sets the boundary on the quiescent flux from a probable low-mass X-ray binary that has been dormant since 2008. These results were published as Bodaghee et al. (2012), ApJ, 751, 113 [23].

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