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ON THE NEAR-INFRARED IDENTIFICATION OF THE *INTEGRAL* SOURCE IGR J16328–4726P. PERSI¹, M. FIOCCHI¹, M. TAPIA², M. ROTH³, A. BAZZANO¹, P. UBERTINI¹, AND P. PARISI¹¹INAF/IAPS-Roma, Via fosso del cavaliere, 100, I-00133 Roma, Italy; paolo.persi@iaps.inaf.it²Instituto de Astronomía, Universidad Nacional Autónoma de México, Ensenada, B.C., Mexico³Las Campanas Observatory, Carnegie Institution of Washington, La Serena, Chile

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ABSTRACT

The aim of this work is to identify the infrared (IR) counterpart of the Galactic high-mass X-ray binary IGR J16328–4726 discovered by the *INTEGRAL* satellite, and to derive the extinction and distance to the system. We present new deep sub-arcsecond *JHK_s* imaging and low-resolution near-IR spectroscopy in the 1.5 and 2.4 μm range of IGR J16328–4726. We report the presence of two near-IR stellar sources separated by about 1".8 at the location of the unresolved 2MASS source J16323791–4723409, previously considered to be the near-IR counterpart of the X-ray source. From the analysis of their near-IR colors and spectra as well as accurate positions, we uniquely identify the true IR counterpart of IGR J16328–4726. Our 1.5–2.4 μm spectrum of this star is consistent with the published classification O8Iafpe. Assuming this, and in combination with new *JHK_s* photometry, a reddening $A_V = 23.6 \pm 0.7$ and a distance of 7.2 ± 0.3 kpc from the Sun are derived.

Key words: stars: imaging – supergiants – X-rays: individual (IGR J16328–4726)

1. INTRODUCTION

The phenomenology of supergiant fast X-ray transients (SFXTs) has been one of the most discussed topics in high-energy astrophysics in the last decade. Recognized as a new class of high-mass X-ray binaries (HMXBs) thanks to the discoveries obtained by the *INTEGRAL* satellite (Sguera et al. 2005; Negueruela et al. 2006), SFXTs are massive binaries that are composed of a compact object (most likely a neutron star as many show also X-ray pulsations) accreting matter from the wind of an OB supergiant donor. Their transient X-ray emission, characterized by flares on timescales from hours to days, shows a dynamic range spanning up to five orders of magnitude in the hard X-ray region from quiescence ($10^{32} \text{ erg s}^{-1}$) to the flare peaks (10^{36} – $10^{37} \text{ erg s}^{-1}$) and represents the most extreme case of X-ray variability among HMXBs. The accretion mechanism producing this puzzling behavior is highly debated, since SFXTs display X-ray spin or orbital periodicities, X-ray and optical spectra very similar to those shown by classical persistent HMXBs hosting supergiant donors, but very different transient X-ray behavior. Furthermore, the impossibility of having wind instability from the supergiant companion (i.e., spanning over a dynamic range up to 10^5) implies a more complex mechanism in place of the wind standard theory. The discovery of these transients is important because they might be a dominant population of hidden HMXBs, which are good tracers of recent star formation. They are crucial to the investigation of accretion mechanisms, studies of massive star formation, the chemical enrichment of our Galaxy, and the evolutionary path of massive binaries, and for making a significant contribution to studying the neutron star equation of state.

IGR J16328–4726 is an X-ray source in the Galactic Plane, reported by Bird et al. (2007), and Bodaghee et al. (2007) as a transient unidentified source. The Galactic position suggests that the source could be in the Norma spiral arm where a lot of HMXBs have been first detected by the *INTEGRAL* satellite (Bodaghee et al. 2007). It was listed as a variable source in the 4th IBIS/ISGRI Catalog (Bird et al. 2010), in the *Swift* BAT 70 month all-sky survey (Baumgartner et al. 2013), and in the

BAT 100 month of SFXTs (Romano et al. 2014). Grupe et al. (2009) reported the detection of an outburst observed with *Swift*/BAT (at 07:54:27 UT on 2009 June 10) which was followed up by a *Swift*/XRT observation. They determined the best source position at $\alpha(2000) = 16^{\text{h}}32^{\text{m}}37^{\text{s}}.88$, $\delta(2000) = -47^{\circ}23'42''.4$ with an uncertainty of 1".7 (90% confidence). At this position no optical counterpart was identified. In addition an orbital period of about 10 days has been reported by Corbet et al. (2010) and Fiocchi et al. (2010).

Grupe et al. (2009) proposed the star 2MASS J16323791–4723409 as the possible infrared (IR) counterpart. Hard X-ray studies (Fiocchi et al. 2010) suggested that the source is a SFXT candidate. From the analysis of the IR energy distribution obtained by combining the 2MASS and mid-IR data, Fiocchi et al. (2013) suggested that the stellar companion in the system is an OB-type star. From their *K*-band spectrum, Coleiro et al. (2013) classified IGR J16328–4726 as a probable O8Iafpe supergiant star.

As the X-ray source is located in a very crowded field, and no optical counterpart has been identified, we have obtained sub-arcsec resolution *JHK_s* images, supported by new low-resolution 1–2.5 μm spectra, in order to uniquely identify the near-IR counterpart of IGR J16328–4726. The observations are described in Section 2, while the discussion on the spectrum and the near-IR images is given in Section 3. Finally in Section 4 we report our conclusions.

2. OBSERVATIONS

2.1. Near-IR Images

Broad-band *JHK_s* images centered on the nominal position of IGR J16328–4726 were obtained on 2014 March 20 using FourStar attached to the Magellan Baade 6.5 m telescope. This IR camera uses four Rockwell 2048 × 2048 HAWAII-2RG arrays providing a scale of 0".16/pix. The final image in each band was constructed with 15 exposures at neighboring telescope positions, each with 1 s integration. The images have been calibrated in position and photometrically using 292 stars from the 2MASS Point Source

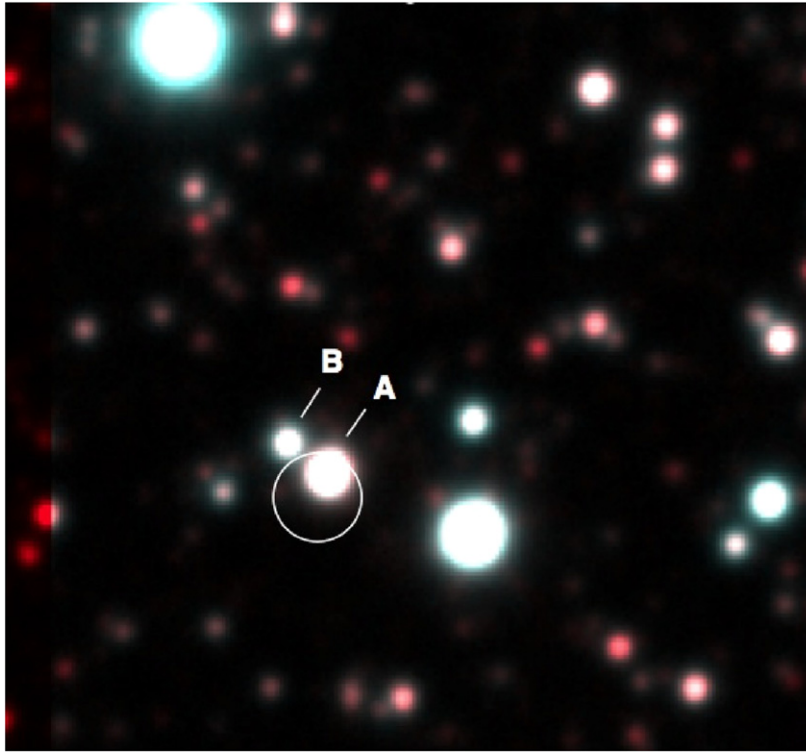


Figure 1. JHK_s color-coded image of an area of $30'' \times 30''$ taken with FourStar on the Magellan Baade telescope on 2013 March 20. IGR J16328–4726 is the star marked A. The *Swift* position with the relative uncertainty is marked with a circle.



Figure 2. Left panel: K_s image obtained with the Magellan Baade telescope. The continuous line represents the center of the $0''.8$ wide slit position. Sources A (IGR J16328–4726) and B, discussed in the text, are labelled. Right panel: the 2MASS K_s image of the same field and scale is shown for comparison. Note that stars A and B are unresolved in the latter and, thus, in the corresponding entry in the 2MASS Point Source Catalog.

Catalog (2MPSC) in the $11' \times 11'$ field covered by our observation. Figure 1 illustrates the color image obtained by combining the J (blue), H (green), and K_s (red) images in a region of approximately $30'' \times 30''$ around the transient X-ray source.

Comparing our K_s image with the corresponding one from 2MASS (Figure 2), it is clear that source 2MASS J16323791–4723409 is actually composed of two clearly separated (by about $1''.8$) stars, which we named A and B, and which are unresolved by 2MASS. We measured

Table 1
Coordinates and Near-infrared Magnitudes of the Sources A and B
inside the 2MASS Source

ID	$\alpha(2000)$ (h m s)	$\delta(2000)$ ($^{\circ}$ ' ")	J (mag)	H (mag)	K_s (mag)
A	16 32 37.85	-47 23 41.45	15.11 (0.02)	12.66 (0.02)	11.41 (0.02)
B	16 32 37.99	-47 23 40.38	15.17 (0.03)	14.07 (0.04)	13.35 (0.03)

accurate positions of these two sources and obtained individual JHK_s photometry using the PSF-fitting procedure within IRAF.⁴ The zero points were determined using the 2MASS photometry of more than 200 2MASS sources in our field with reliable photometric values in the 2MPSC. The uncertainty in the resulting photometry is than 0.02 mag, while the rms error in the astrometry is $0''.07$ in both R.A. and decl. This was determined by comparison of 2MASS positions with those measured on our final images, for the non-blended stars in common.

Table 1 reports the measured positions and photometry of each of the two stars. Given the uncertainty of $1''.7$ estimated by Grupe et al. (2009) for the X-ray position, we have identified source A as the true IR counterpart of IGR J16328–4726, as the disagreement between the nominal X-ray position and that of source A is $1''.01$, while for source B it is $2''.30$. This is well illustrated in Figure 1, in which is reported the error of the *Swift* satellite (open circle). In addition, the identification is further confirmed when analyzing the individual spectra of the stars (see next section).

At the position of source A we have found the GLIMPSE source (G336.7492+00.4223) detected in the four IRAC bands, and the *WISE* source (J163237.83–472341.4) detected at 3.4 and $4.6 \mu\text{m}$. The angular separations between the GLIMPSE and *WISE* sources and source A are respectively $0''.32$ and $0''.17$.

2.2. Near-IR Spectroscopy

Low-resolution long-slit spectroscopy was performed on 2012 May 31 with the Folded-port IR Echelle Spectrograph (FIRE) mounted on the 6.5 m Magellan Baade telescope of Las Campanas Observatory in its high throughput prism mode. This configuration provides simultaneous spectra from 0.82 to $2.51 \mu\text{m}$ with the spectral resolutions $R_H = 450$ and $R_K = 300$ in the H and K atmospheric windows, respectively. The instrument is described in detail by Simcoe et al. (2013). The fixed slit length is $50''$ and its width was set to $0''.8$, which is larger than the typical seeing encountered during our run. The spatial scale is $0''.17/\text{pixel}$. The slit was placed so that it includes both stellar sources, A and B, oriented with a position angle of approximately 40° , as shown in Figure 2. We performed five 30 s integrations in each of two positions along the slit (the so-called A–B mode), resulting in a total on-chip integration time of 300 s. Immediately after, we gathered spectra of the A0V star HD172951, with a similar air mass. This was used for telluric absorption correction and flux calibration, using the 2MPSC photometry for HD172951

($H = 9.77$, $K = 9.71$). The wavelength calibration was done with contemporaneous Ne–Ar comparison lamp integrations.

The spectra were reduced for wavelength calibration, sky subtraction, extraction, combination of individual spectra, correction for telluric absorption, and flux calibration, using the standard FIRE pipeline reduction described in http://web.mit.edu/~rsimcoe/www/FIRE/ob_data.html. Final filtering for spurious spikes, selected extraction and flux measurements (with Gaussian fitting) was performed with the IRAF ONEDSPEC package. Examination of the spectrum of star B of the close pair revealed that it corresponds to a late-type star, unrelated to IGR J16328–4726. On the other hand, the spectrum of star A shows strong $\text{Br}\gamma$ emission, strengthening the identification with the X-ray binary. The measured signal-to-noise ratio of the spectrum of IGR J16328–4726 is approximately 8 in the H -band range and 15 in the K -band range. The magnitudes derived from the flux-calibrated spectrum agree within 20% in K and 10% in H with the photometry from direct images taken 20 months later (see Section 2.1).

3. DISCUSSION

3.1. Spectral Classification of the IR Counterpart of IGR J16328–4726.

The spectrum of source A matched the characteristics expected for the companion star of the collapsed object in the binary system IGR J16328–4726. The 1.5 – $1.8 \mu\text{m}$ and 2.04 – $2.41 \mu\text{m}$ sections of this spectrum are shown in Figure 3. The applied telluric corrections are also illustrated in the bottom panels. Although the only bright emission line in this spectrum is $\text{Br}\gamma$, we considered other fainter lines, detected above the 2σ level, worth identifying and measuring. These are indicated above the spectral plots and their fluxes and equivalent widths are listed in Table 2. Due to the low spectral resolution of this spectrum, many expected atomic lines are heavily blended.

A 2.05 – $2.30 \mu\text{m}$ spectrum of this object has recently been published by Coleiro et al. (2013) with a spectral resolution three times higher than that presented here. Based on their spectrum, these authors classified the IR counterpart of IGR J16328–4726 as an O8Iaf star, basically because of the observed $\text{Br}\gamma$ and $\text{C III}/\text{N III}/\text{O III}$ emission lines together with some He I absorption. Comparing the present spectrum with Coleiro et al.’s is not straightforward as the spectral resolution is very different. The most striking difference is the absence of the strong $\text{N III}+\text{C III}$ emission and nearby He I absorption lines at $2.11 \mu\text{m}$ in our spectrum, but this is expected as these emission and absorption features strongly blended, as their central wavelengths differ by only $0.002 \mu\text{m}$, thus canceling each other at low resolution. More enigmatic is the C IV triplet in emission, at $2.08 \mu\text{m}$, which is strong in our spectrum but very weak in Coleiro et al.’s. Whether this is due to real variations or caused by imperfect telluric feature cancellation at that wavelength in one of the spectra, is impossible to determine. The faint emission line at $2.21 \mu\text{m}$ present in both spectra was identified as due to Na I, while we tentatively propose it to be an [Fe I] line. In conclusion, the present K -band spectrum is consistent with Coleiro et al.’s spectral classification of the IR component of this high-mass X-ray binary (sgHMXB/SFXT), IGR J16328–4726.

⁴ IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc. under contract to the National Science Foundation.

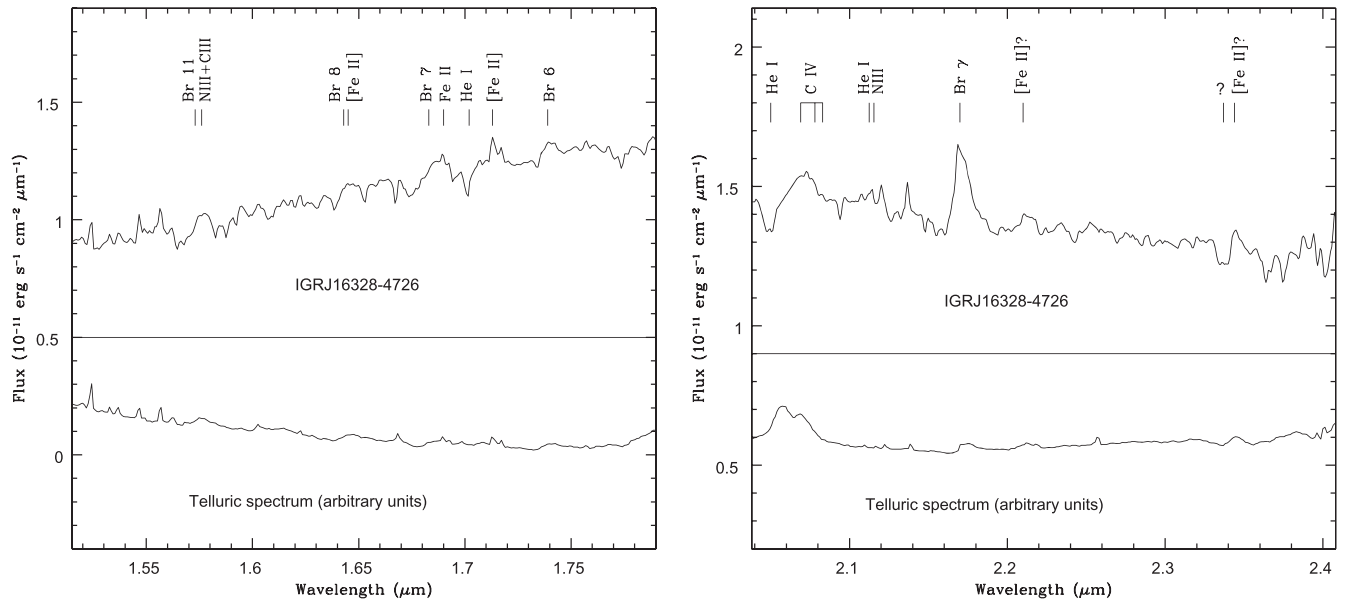


Figure 3. FIRE low-resolution spectrum of IGR J16328–4726 in the H (left panel) and K (right panel) bands. The wavelengths of some spectral lines present or expected are indicated. The telluric corrections are also shown.

Table 2
Identification of the Main Lines in the Spectrum of IGR J16328–4726

Identification	λ (μm)	Flux ($10^{-15} \text{ erg cm}^{-2} \text{ s}^{-1}$)	EW ($\text{\AA}$)
Br11 (15–4)	1.571	...	...
+ N III + C III	1.575	7.1	–3.2
Br8 (12–4)	1.641	...	...
+ [Fe II]	1.643	3.9	–3.5
Br7 (11–4)	1.681	...	...
+Fe II	1.688	2.6	–6.0
He I	1.700	–4.5	3.7
Fe II	1.712	4.9	–4.3
Br6 (10–4)	1.737	3.9	–3.5
He I	2.058	–9.2	5.2
C IV	2.069–2.083	13.4	–11.8
Br γ (7–4)	2.166	26.4	–19.8
[Fe II]	2.211	3.8	–2.9
[Fe II]	2.341	4.8	–3.8

3.2. Reddening and Distance to IGR J16328–4726

Knowledge of the X-ray luminosity is important, as it represents one of the fundamental parameters for the study of these transient hard X-ray sources. The main uncertainty in deriving such X-ray luminosity is the distance to the source. Very recently, Paizis & Sidoli (2014) presented the cumulative luminosity distributions of a sample of SFXTs and concluded that a power-law model is a plausible representation for these sources.

From the present photometry and the adopted spectral classification, the extinction toward IGR J16328–4726 and its distance from the Sun are derived. For a normal extinction law (Rieke & Lebofsky 1985), $A_V = 9.4E(J - H)$ and $A_V = 5.9E(J - K)$. Comparing our observed $(J - H) = 2.454 \pm 0.03$ and $(J - K_s) = 3.70 \pm 0.03$ color indices with those of an unreddened O8I star, $(J - H)_0 = -0.11$, $(J - K)_0 = -0.21$, and $M_K = -5.52$ (Martins & Plez 2006), we derive the color excess values $E(J - H) = 2.56$ and $E(J - K) = 3.91$. Therefore, averaging these extinctions,

$A_V = 23.6 \pm 0.7$ or $A_K = 2.64 \pm 0.08$ (Rieke & Lebofsky 1985). These values imply $d = 7.2 \pm 0.3$ kpc. The estimated uncertainties of A_V and d are derived mainly from our photometric errors. In fact, according to Martins & Plez (2006), M_K varies between -5.53 and -5.52 in the range of O7I and O9I stars, while the colors remain unchanged. In addition, the fact that the filter used was K_s instead of K may contribute to the uncertainties in the determination of A_V and d , but these should be quite small compared with those of the intrinsic colors. From our value of A_V we obtain a value of column density $n_H = 5.1 \times 10^{22} \text{ cm}^{-2}$ that is consistent with being due to interstellar material at the distance of the source (Marshall et al. 2006).

In addition, the derived distance of the X-ray binary IGR J16328–4726 agrees with those reported for the known SFXTs (see Paizis & Sidoli 2014) and suggests that this source is in the Norma spiral arm. In fact, along our source direction ($l = 336^\circ 75'$) the Norma spiral arm extends from ~ 4 to 10 kpc (Vallée 2008).

Finally, the distance to IGR J16328–4726 is a significant contribution toward characterizing the luminosity distribution of SFXTs and verifying their power-law shape, which is flatter than that of classical HMXBs (i.e., Paizis & Sidoli 2014). This study is very important in helping to understand the physical processes producing their sporadic transient X-ray emission, to place SFXTs in the larger context of HMXBs, and to study their evolutionary path.

4. CONCLUSIONS

We obtained a near-IR spectrum from 1.5–2.4 μm and broadband JHK_s images with sub-arcsec resolution of the *INTEGRAL* source IGR J16328–4726. From the analysis of these observations we derived the following conclusions.

1. At the position of the 2MASS J16323791–4723409 source, previously identified as the IR counterpart of the transient X-ray source, we resolved two stars separated by $1''.8$. We measured an accurate position and photometry of each of the two stars, which are unresolved in the 2MASS image, and identified the IR counterpart of IGR J16328–4726.

2. The near-IR spectrum of the brighter source (here named A) is dominated by hydrogen emission lines. Our spectrum is consistent with the spectral classification O8Iafpe proposed by Coleiro et al. (2013).

3. From the spectral classification and JHK_s photometry, we derived the extinction to IGR J16328–4726 to be $A_V = 23.6 \pm 0.7$ and that the system is at a distance of 7.2 ± 0.3 kpc from the Sun.

4. Our results indicate that for a correct identification of X-ray sources belonging to the Galactic plane, and in particular to determine very accurate physical parameters such as visual extinction and distance, the spatial resolution of the 2MASS survey is not sufficient.

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