On the near Infrared identification of the INTEGRAL source IGR J16328-4726.

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ABSTRACT

The aim of this work is to identify the infrared 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-arcsec JHK_s imaging and low-resolution near-IR spectroscopy in the 1.5 and 2.4 range of IGR J16328-4726. We report the presence of two near-infrared 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 infrared counterpart of IGR J16328-4726. Our 1.5 to 2.4 μm spectrum of this star is consistent with the published classification O8Iafpe. Assuming this and in combination with new $JHKs$ photometry, a reddening $A_V = 23.6 \pm 0.7$ and a distance of 7.2 $\pm$0.3kpc from the Sun is derived.

Subject headings: X-rays: individual (IGR J16328-4726) – stars: supergiants – infrared: spectroscopy – infrared:near-IR images

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 a.l 2006), SFXTs are massive binaries which 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 time scales from hours to days, shows a dynamic range spanning up to five orders of magnitude in the hard X-ray from quiescence (10^{32} erg/s) to the flare peaks (10^{36}-10^{37} erg/s) 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 to have 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 the recent star formation. They are crucial to the investigation of accretion mechanisms, studies of the massive star formation, the chemical enrichment of our Galaxy, the evolutionary path of massive binaries and to give a significant contribution in 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 suggest that the source could be in the Norma spiral arm where a lot of HMXBs have been firstly detected by INTEGRAL satellite (i.e. Bodaghee et al. 2007). It was listed as a variable source in the 4th IBIS/ISGRI Catalog (Bird et al. 2010) and in the Swift BAT 70 month all-sky survey (Baumgartner et al. 2013), and 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 α (2000) = $16^h32^m37.88^s$, δ (2000)= -47°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 infrared 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 crowed field, and no optical counterpart have 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-infrared 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-infrared 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 6.5m telescope. This infrared camera uses 4 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 Catalog (2MPSC) in the 11′ × 11′ field covered by our observation. Fig. 1 illustrates the color image obtained by combining the J (blue), H (green), and K_s (red) images in a region of approximately 30″ × 30″ around the transient X-ray source.

Comparing our K_s image with the corresponding one from 2MASS (Fig. 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 accurate positions of these two sources and obtained individual JHK_s photometry using the PSF-fitting procedure within IRAF[1]. 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, RA. and Dec. This was determined by comparison between 2MASS positions with those measured on our final images, for the non-blended stars in common.

[1]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.

Table 1 reports the measured positions and photometry of each of the two stars. Given the uncertainty of 1.7″ estimated by Groupe et al. (2009) for the X-ray position, we have identify source A as the true infrared 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, this is 2.30″. This is well illustrated in Fig.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 subsection).

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 μm. **The angular separations between the GLIMPSE and WISE sources with source A are respectively 0.32″, and 0.17″.**

2.2. Near-Infrared Spectroscopy

Low-resolution long-slit spectroscopy was performed on 2012 May 31 with the Folded-port Infrared Echellette Spectropraph (FIRE) mounted on Las Campanas Observatory 6.5-m Magellan/Baade telescope in its high throughput prism mode. This configuration provides simultaneous spectra from 0.82 to 2.51 μm with spectral resolutions 450 and 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 ″/pixel. The slit was placed so that it includes both stellar sources, A and B, oriented with a position angle of approximately 40^o, as shown in Fig. 2. We performed 5 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 star 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 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 Brγ emission, strengthening the identification with the X-ray binary. The measured signal to noise ratio (S/N) 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 infrared 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 to 1.8 μm and 2.04 to 2.41 μm sections of this spectrum are shown in Fig. 3. The applied telluric corrections are also illustrated in the bottom panels. Although the only bright emission line in this spectrum is Bracketγ, we considered other fainter lines, detected above the 2-σ level, worth identifying and measuring. These are indicated above the spectral plots and their fluxes and equivalent widths 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 μm spectrum of this object has recently been published by Coleiro et al. (2013) with a spectral resolution three times higher than the one presented here. Based on their spectrum, these authors classified the infrared counterpart of IGR J16328-4726 as an O8Iaf star, basically because of the observed Brγ and CIII/NIII/OIII emission lines together with some He I absorption . Comparing the present spectrum with Coleiro et al.'s is not straight forward as the spectral resolution is very different. The most striking difference is the absence of the strong NIII+CIII emission and nearby He I absorption lines at 2.11μm in our spectrum, but this is expected as these emission and absorption features strongly blended, as their central wavelengths differ by only 0.002 μm, and thus, canceling each other at low resolution. More enigmatic is the CIV triplet in emission, at 2.08 μm, 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 μm present in both spectra was identified as due to Na I, while we tentatively propose to be an [Fe I] line. In conclusion, the present K-band spectrum is consistent with Coleiro et al's spectral classification of the infrared component of this high-mass X-ray binary (sgHMXB/SFXT), IGR J16328-4726.

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 conclude that a power-law model is a plausible representation for these sources.

From the present photometry and the adopted spectral classification, the extinction towards 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±0.03 and (J-K_s) = 3.70±0.03 color indices with those of an unreddened O8I star, $(J-H)_o = -0.11$ and $(J-K)_o = -0.21$ 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±0.7, or A_K = 2.64±0.08 (Rieke & Lebofsky 1985). These values imply d = 7.2±0.3 kpc. The estimated uncertainty 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 a O7I and O9I stars, while the colors remain unchanged**. In addition ,the fact that the filter that we 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 10^{22} 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 suggest that this source is in the Norma spiral arm.

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

4. Conclusions

We obtained a near-IR spectrum from $1.5 - 2.4\mu$m and broad-band 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 infrared counterpart of the transient X-ray source, we resolved two stellar stars separated by $1.8''$. We measured accurate position and photometry of each of the two stars which are unresolved in the 2MASS image and identify the infrared 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±0.7 and that the system is at a distance of 7.2 ±0.3kpc from the Sun.

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

Based on observations made with the BAADE telescope located at Las Campanas Observatory (Chile) .We thank Dr. Andrew Monson for obtaining the JHK_s images at our request. M. Tapia acknowledges DGAPA/UNAM grant No. IN-101813.

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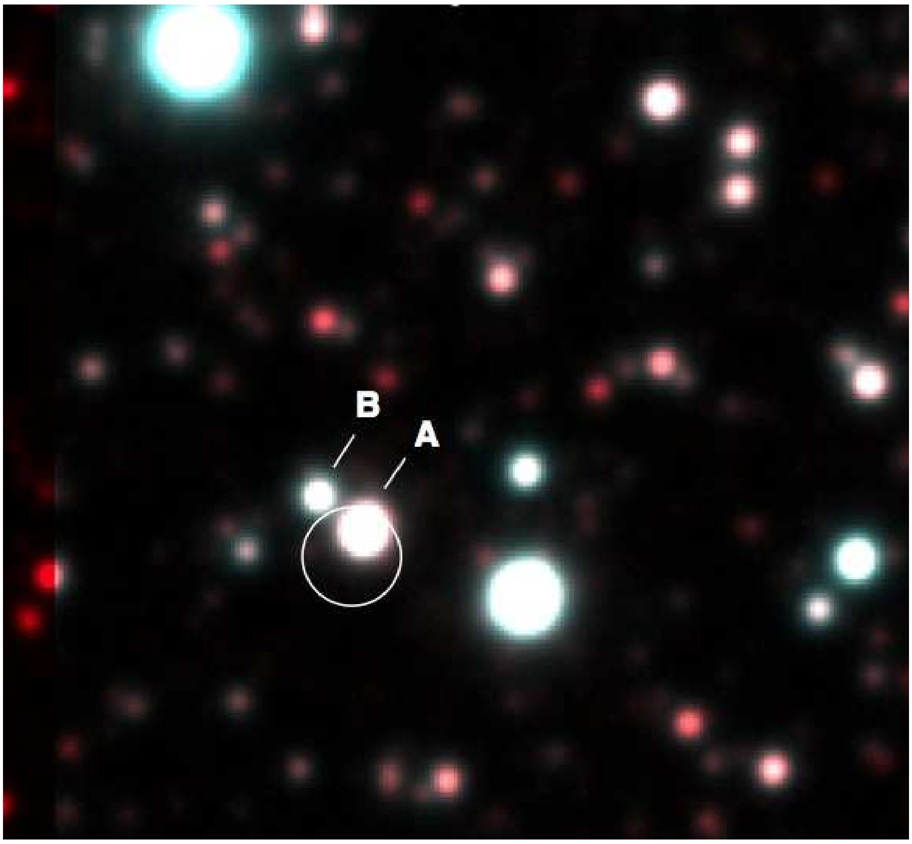

Fig. 1.— JHK_s color-coded image of an area of $30'' \times 30''$ taken with FourStar on the Magellan Baade telescope on 20 March 2013. IGR J16328-4726 is the star marked A. The Swift position with the relative uncertainty is marked with a circle.

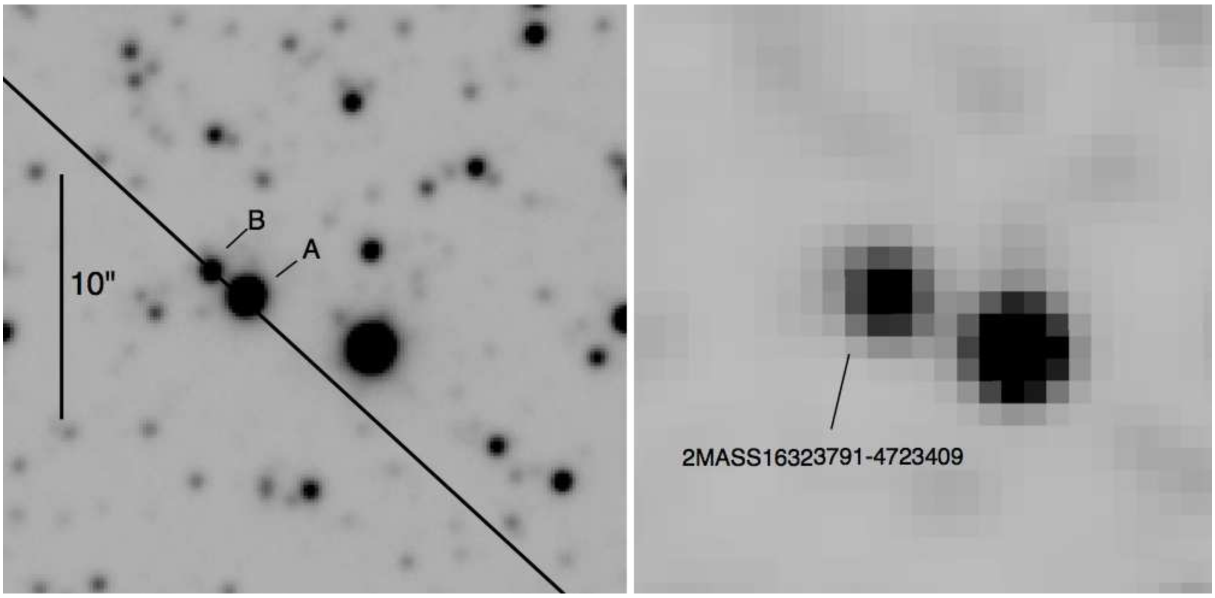

Fig. 2.— *Left panel:* K_s image obtained with the Magellan BAADE telescope. The continuos line represents the centre of the $0.8''$-wide slit position. Sources A (IGR J16328-4726) and B, discussed in the text, are labelled. *Right panel:* 2MASS K_s image of the same field and scale is shown for comparison. Note that stars A and B are unresolved in the latter and, thus, in the corresponding entry in the 2MASS Point Source Catalog.

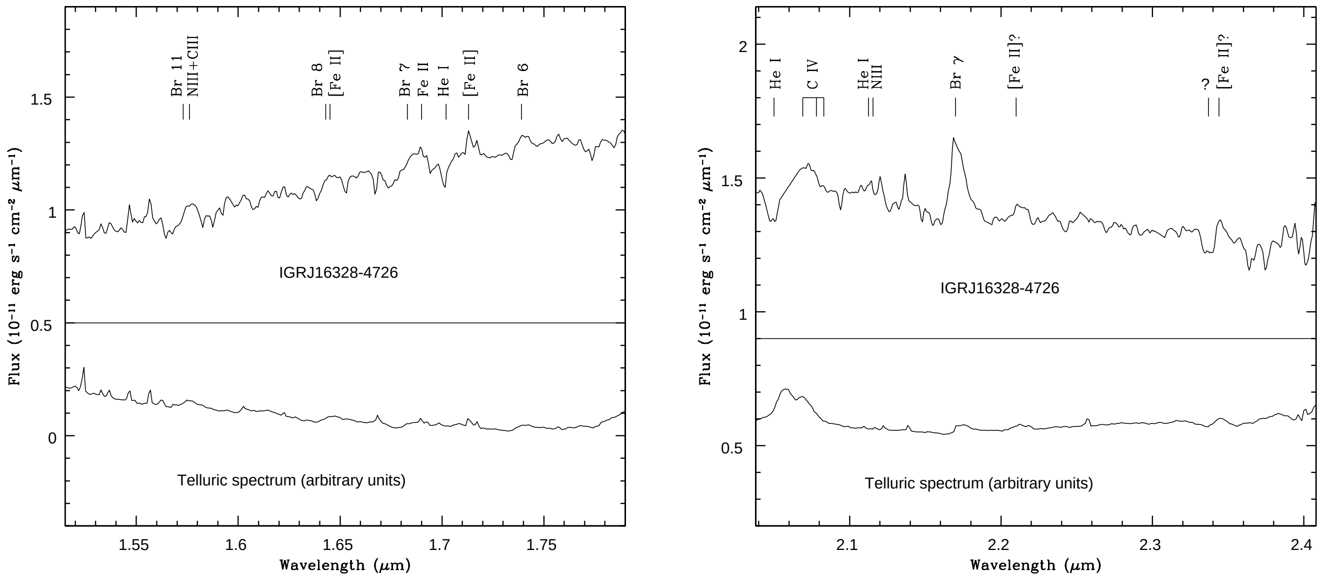

Fig. 3.— FIRE low-resolution spectrum of IGR J16328-4726 in the *H* (left panel) and *K* (right panel) bands. The wavelength of some spectral lines present or expected are indicated. The telluric corrections are also shown

Table 1: Coordinates and near-infrared magnitudes of the sources A and B inside the 2MASS source

ID	$\alpha(2000)$	$\delta(2000)$	J	H	K_s
	h m s	$\circ$ $'$ $''$	mag	mag	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)

Table 2: Identification of the main lines in the spectrum of IGR J16328-4726

Identification	λ (μm)	Flux 10^{-15} erg cm^{-2} s $^{-1}$	EW (A)
Br11 (15-4)	1.571		
+ NIII + CIII	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
HeI	2.058	-9.2	5.2
CIV	2.069-2.083	13.4	-11.8
Brγ (7-4)	2.166	26.4	-19.8
[Fe II]	2.211	3.8	-2.9
[Fe II]	2.341	4.8	-3.8