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Letter to the Editor

Search for the optical and infrared counterpart of GRS 1758−258

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Abstract. We report the results of a deep search for the optical and near infrared counterpart of the microquasar source GRS 1758−258. At least two possible candidate counterparts of the binary star companion have been recognized on the basis of astrometric coincidence to within $1''$. Our photometric study shows that the brightest of them would be consistent with a K-type giant star, while the weakest one would be a main sequence F companion. Follow up spectroscopic observations in the near infrared H and K-bands have failed so far to provide evidence for emission lines that may support an unambiguous identification. However, the proximity of these two sources to the sub-arcsec VLA radio position of GRS 1758−258 makes them deserving further attention in the future.

Key words: stars: individual: GRS 1758−258 – X-rays: stars – radio continuum: stars

1. Introduction

GRS 1758−258 is one of the two persistent hard X-ray (≥ 30 keV) emitters in the Galactic Center region together with 1E 1740.7−2942 (Sunyaev et al. 1991; Goldwurm et al. 1994). The two sources are known to exhibit radio counterparts with double-sided jets emanating from a central compact source (Mirabel et al. 1992a; Rodríguez, Mirabel & Martí 1992). This morphological analogy with extragalactic AGNs and quasars is part of the motivation for considering both GRS 1758−258 and 1E 1740.7−2942 to be members of the microquasar class of black hole galactic X-ray binaries (see e.g. Mirabel & Rodríguez 1998 for a recent review). However, the galactic origin of GRS 1758−258 and 1E 1740.7−2942 has not been verified yet by means of classical photometric or spectroscopic studies of their optical/infrared counterpart, provided of course that we could actually detect it.

For a successful counterpart search in the crowded fields of the Galactic Center region, it is almost imperative to have a very accurate X-ray or radio position. This information is today available, with sub-arcsec accuracy, through observations at radio wavelengths for both 1E 1740.7−2942 (Mirabel et al. 1992) and GRS 1758−258 (Mirabel & Rodríguez 1993). On the other hand, it is also required that the interstellar extinction does not completely prevent the observations. In the 1E 1740.7−2942 case, there is little hope that an optical counterpart may be ever found, given the strong absorption towards this source ($N_H \geq 8 \times 10^{22}$ cm^{-2}, Mirabel 1994). On the contrary, the absorption towards GRS 1758−258 is estimated to be significantly lower, i.e, $N_H = (1.5 \pm 0.1) \times 10^{22}$ cm^{-2} (Mereghetti et al. 1997a). This corresponds to an extinction of $A_V \simeq 8.4$ magnitudes in the optical and to only $A_K \simeq 0.9$ magnitudes in the near infrared (Rieke & Lebofsky 1985; Predehl & Schmitt 1995). Thus, the search for an optical and near infrared counterpart to GRS 1758−258 should be regarded as a feasible project. Indeed, several observers have undertaken such a search (Mereghetti et al. 1992; Mirabel & Duc 1992), but the initial lack of a sub-arcsec accurate radio position did not facilitate a successful result in this very crowded region. As a consequence, most of the subsequent discussions on the nature of GRS 1758−258 have been based on the bona fide assumption that only magnitude upper limits were available (Chen et al. 1994; Mirabel 1994).

In this paper, we address again the issue of the GRS 1758−258 counterpart by re-analyzing old images of the field as well as obtaining new deep ones. The astrometry has been also revised and improved, with our attention being focused on the Mirabel & Rodríguez (1993) precise radio position, namely R.A.(J2000)=$18^h01^m12\overset{s}{.}395$ and DEC.(J2000)=$-25^\circ44'35\overset{''}{.}90$, that is accurate to $\pm0\overset{''}{.}1$. As a result, we think now that there are a minimum of two possible candidate counterparts for this microquasar source contrary to early beliefs. The identification is mainly based at present on astrometric coincidence, and further observations would be necessary to confirm, or to rule out, the proposed candidates. It is important to mention that one of them is the same stellar-like object with $I \sim 19$ originally pointed out by Mereghetti et al.

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Table 1. Magnitudes of the candidate counterparts

Filter	Date of observation	1st VLA-C Candidate	2nd VLA-C Candidate	VLA-D Candidate
B	1998 Mar 26	> 24.2	> 24.2	> 24.2
V	1998 Mar 26	23.9 ± 0.4	> 24.9	21.9 ± 0.2
R	1998 Mar 26	21.0 ± 0.2	22.6 ± 0.3	19.3 ± 0.2
I	1998 Mar 26	19.0 ± 0.2	21.1 ± 0.3	17.4 ± 0.1
J	1994-97	16.2 ± 0.1	–	14.3 ± 0.1
H	1994-97	14.8 ± 0.1	–	13.0 ± 0.1
K	1994-97	14.0 ± 0.1	–	12.3 ± 0.1

(1994a). The rest of the paper is devoted to discuss the possible stellar types and luminosities of the normal companion of GRS 1758−258 that would be consistent with the candidate counterparts. Further details may be found in Chaty (1998).

2. Observations and results

Our observations were carried out using different telescopes at the European Southern Observatory[1] (ESO) in La Silla (Chile). On several epochs between 1992 and 1997, we obtained J, H and K-band images with the IRAC2b camera at the ESO 2.2 m telescope. For the epoch 1998 March 26, $UBVRI$ optical images of the region were similarly acquired using the ESO New Technology Telescope (NTT) with the EMMI CCD. On 1998 May 18, NTT spectroscopy was also obtained in the H and K-bands with the SOFI infrared spectrograph and imaging camera. All frames were reduced using standard procedures based on the IRAF image processing system.

2.1. Astrometry and photometry

The astrometry on these images was obtained in two steps involving the use of the Palomar Observatory Sky Survey (POSS) digitized plates (Lasker et al. 1990). First, we selected ten POSS stars in the GRS 1758−258 field being included in the Hipparcos and Tycho catalogues (ESA, 1997). These objects were used as primary reference stars in order to establish a precise astrometric grid. This allowed us to measure the positions of six fainter stars in the ESO frames being well distributed very close to the suspected position of GRS 1758−258. Afterwards, these fainter objects were adopted as secondary reference stars from which the final astrometry could be determined. We estimate that our total combined error is such that the $\pm0\farcs1$ radio positions can be located with a 90% confidence radius of about $0\farcs8$ in the NTT and $0\farcs9$ in the 2.2 m frames, respectively.

In Fig. 1 we show a wide field NTT image of the GRS 1758−258 region in the optical I-band. The 90% confidence error circles representing the SIGMA and ROSAT PSPC positions are plotted on it (Goldwurm et al. 1994; Mereghetti et al. 1994b). For illustration purposes, we have also overlayed

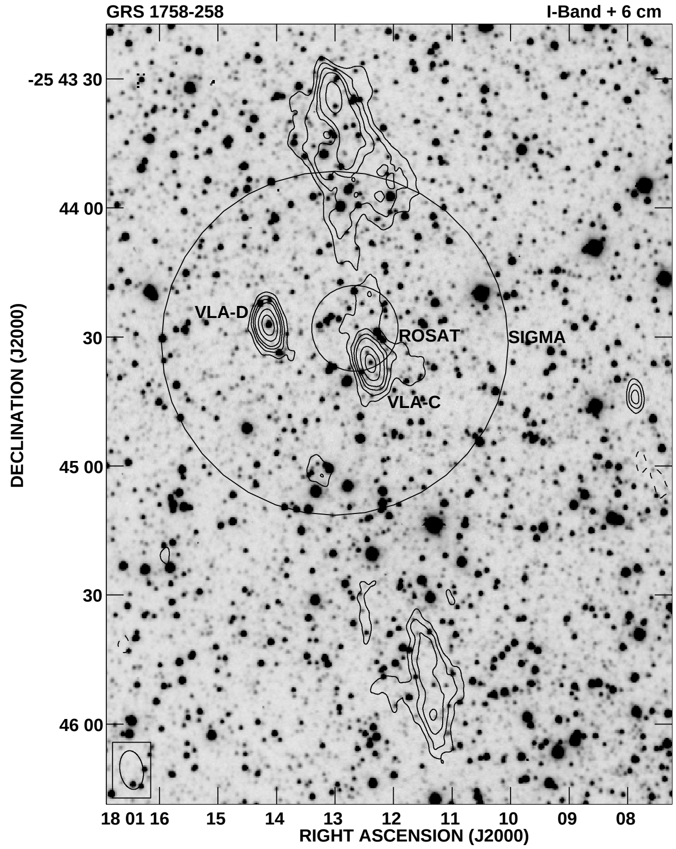

Fig. 1. I-band NTT image of the GRS 1758−258 field with VLA radio contours at 6 cm overlayed. The SIGMA and ROSAT 90% confidence error circles are also shown. Their radii are of $40''$ and $10''$, respectively (Goldwurm et al. 1994; Mereghetti et al. 1994b). Radio contours are -3, 3, 4, 5, 6, 8 and 10 times 0.012 mJy beam^{-1}, the VLA map rms noise. The corresponding synthesized beam is $9\farcs1\times6\farcs4$, with position angle of $9\fdg5$.

the radio contours showing the extent of the microquasar jets. These contours correspond to a deep radio image obtained with the NRAO[2] Very Large Array (VLA), to be discussed in more detail in a future paper. In addition to the jet extended emission, the GRS 1758−258 central component and another compact source to the east are clearly detected. We will refer to them as sources VLA-C and VLA-D as in Rodríguez et al. (1992).

In Fig. 2 we present an enlarged view of the target position at optical (I-band) and near infrared (K-band) wavelengths, in the form of contour maps. The location of radio sources VLA-C and VLA-D is indicated on these images by means of their 90% confidence circle. It is clear that at least two optical objects (perhaps three) may be consistent with being the central source of the GRS 1758−258 radio counterpart or VLA-C. They are well detected individually only in the NTT frames. In the infrared, the IRAC2b resolution is not good enough to resolve them. A likely counterpart candidate to the radio source VLA-D (R.A.(J2000)=$18^h01^m14\fs142$ and

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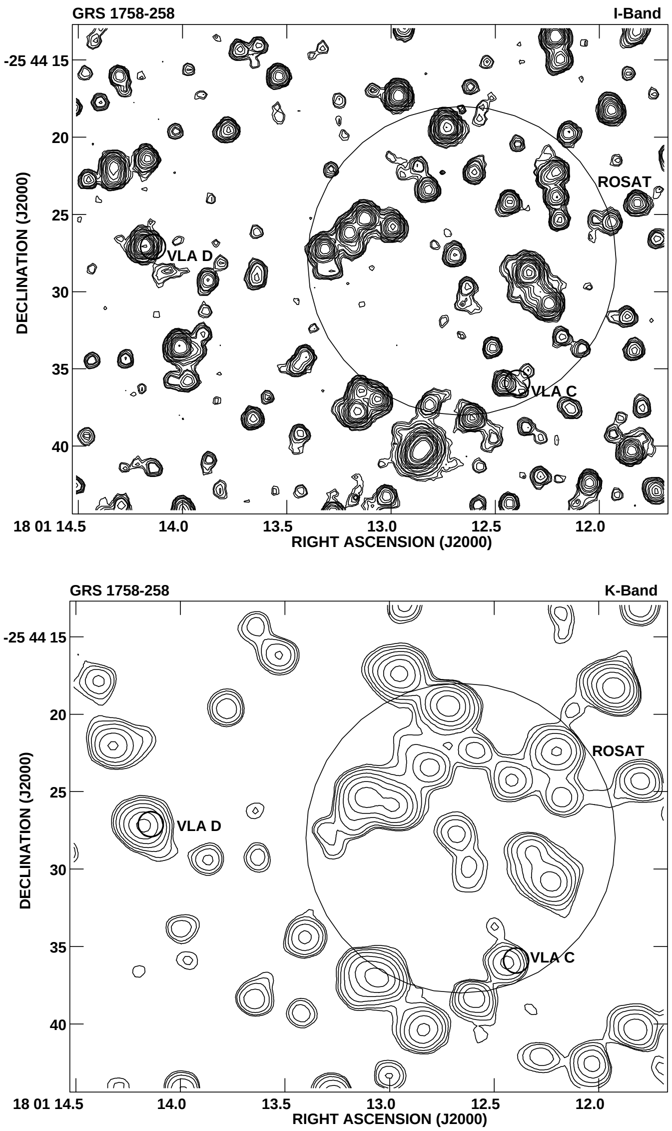

Fig. 2. Contour maps showing in detail the location of the GRS 1758−258 central source at optical (NTT, I-band) and near infrared (2.2m, K-band) wavelengths. The 90% confidence error circle of the ROSAT position and that of the radio positions for VLA-C and VLA-D are also marked.

DEC.(J2000)=$-25°44'27.''08$; $\pm0.''1$ uncertainty) is obvious in all ESO frames. The apparent Johnson magnitudes of all the optical and infrared sources relevant to the following discussion are listed in Table 1. Those of the second VLA-C candidate may be partially contaminated by the proximity of the first brighter one. No significant photometric variations $\gtrsim$ 0.1 magnitudes have been detected on time scales of weeks during follow-up infrared observations (Chaty 1998).

Note that in some previous works optical and infrared magnitudes and upper limits were reported erroneously, and seem to imply long term variability when compared with Table 1. The VLA-C candidate counterpart observed in May 1991 had I ∼19 (Mereghetti et al. 1997a, 1997b; the value I ∼17 was previously reported owing to a typing error in Mereghetti et al. 1994a). The upper limits of K ∼17 and or I ∼21 often quoted (e.g., Mirabel & Rodríguez 1993; Mirabel 1994; Chen et al. 1994) resulted from preliminary radio positions and astrometry solutions and/or from misinterpretation of previously published results that unfortunately propagated through the literature. In conclusion, there is no evidence that any of the objects considered as possible counterparts has varied.

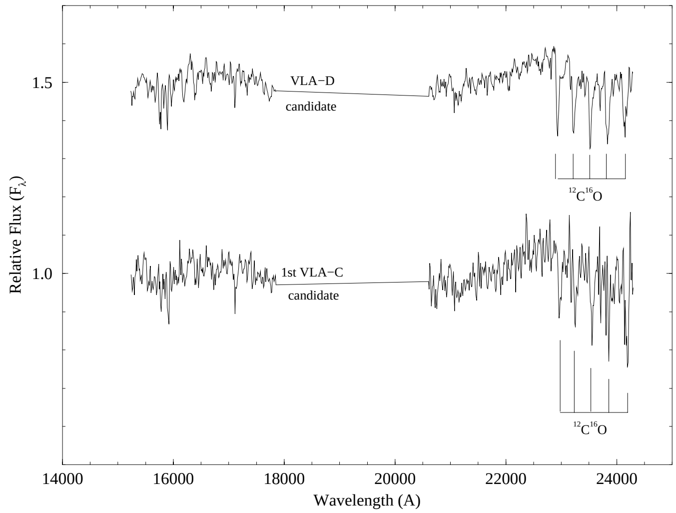

Fig. 3. Near infrared spectrum of the VLA-C and VLA-D candidate counterparts obtained with the SOFI instrument at the NTT on 1998 May 18. The continuum has been rectified and normalized for better display.$^{12}C^{16}O$ absorption band are the only identified spectral features. The huge gap between 1.8 and 2.1 μm is due to the very strong atmospheric opacity.

2.2. Infrared spectroscopy

The SOFI slit was aligned with a position angle allowing to observe the VLA-C and VLA-D candidates simultaneously. The integration time amounted to one hour and consisted of short exposures with the targets at different slit positions, thus allowing an accurate sky cancellation during the processing. Atmospheric transmission was corrected using the Maiolino et al. (1996) procedure. This involves division of the target spectrum by that of a solar type standard, observed at the same air mass, plus a correction for the standard star absorption lines by means of a synthetic solar spectrum. The final result is shown in Fig. 3, where the main interesting features are the clear $^{12}C^{16}O$ bands in both the VLA-C first candidate and in the VLA-D candidate as well. Feature identifications and equivalent widths are listed in Table 2. All the observed wavelengths appear close to the rest frame value, implying radial velocities of at most $\lesssim$ 300 km s^{-1}, i.e., as expected for a common stellar object inside the Galaxy. The spectrum of the VLA-C second candidate is only very marginally detected with SOFI and does not contaminate that of the first one.

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Table 2. Equivalent widths of absorption features[a]

Feature Identification	Wavelength (μm)	1st VLA-C Candidate (Å)	VLA-D Candidate (Å)
$^{12}C^{16}O(2,0)$	2.294	8	9
$^{12}C^{16}O(3,1)$	2.323	8	11
$^{12}C^{16}O(4,2)$	2.354	10	10
$^{12}C^{16}O(5,3)$	2.383	5	11
$^{12}C^{16}O(6,4)$	2.414	12	9

[a] Typical errors in the wavelength calibration are ±0.001 μm and ±1 Å in the equivalent width estimates.

3. Discussion

The fact that candidate counterparts are available now for GRS 1758−258 opens the possibility to investigate the true nature of this microquasar source, as well as to extrapolate the preliminary results to its Galactic Center twin 1E 1740.7−2942. In the following, we will always assume that only VLA-C is associated with GRS 1758−258 and that VLA-D, being undetectable in X-rays and misaligned with the jets, is most likely an unrelated source.

The observed magnitudes in Table 1, together with the recent column density estimate $N_H = (1.5 \pm 0.1) \times 10^{22}$ cm^{-2} by Mereghetti et al. (1997a), yield the following dereddened absolute magnitudes assuming a 8.5 kpc distance. For the brighter VLA-C candidate, we find: $B > -1.5$, $V = +0.9 \pm 1.1$, $R = +0.1 \pm 0.6$, $I = +0.3 \pm 0.5$, $J = -0.8 \pm 0.3$, $H = -1.3 \pm 0.2$ and $K = -1.6 \pm 0.2$. The corresponding dereddened colors are, e.g., $V - R = +0.8 \pm 1.7$, $V - I = +0.6 \pm 1.6$, $V - J = +1.7 \pm 1.4$, $V - H = +2.2 \pm 1.3$, $V - K = +2.5 \pm 1.3$, $J - H = +0.5 \pm 0.5$, $J - K = +0.8 \pm 0.5$ and $H - K = +0.3 \pm 0.4$. From these values, the most consistent spectral type would be an early K giant star (Johnson 1966; Ruelas-Mayorga 1991). The agreement with an early K III companion is specially good for the absolute magnitudes. The colors are less constraining due to errors, but nevertheless consistent with this determination. On the other hand, the presence of $^{12}C^{16}O$ absorption bands is very typical of evolved late type stars (Kleinmann & Hall 1986) thus giving further support to our classification.

If the association of this candidate with VLA-C is correct, GRS 1758−258 would be an X-ray binary system of low/intermediate mass. This suggests an interesting similarity of GRS 1758−258 with other persistent Galactic Bulge X-ray sources with weak radio emission, such as for instance GX 13+1 (Grindlay & Seaquist 1986). The infrared spectrum of GX 13+1 also contains $^{12}C^{16}O$ absorption bands believed to be the signature of a late type giant companion (Bandyopadhyay et al. 1997). However, the main problem with this interpretation is the absence of observed emission lines. Emission lines should be normally expected from the accretion disk of the system and they are not evident in the spectrum of Fig. 3. In particular, we do not see any clearly detectable Brackett-γ emission, while other Galactic Bulge sources (e.g. Sco X-1, GX 13+1, GX 1+4) do display it (Bandyopadhyay et al. 1997). Therefore, we cannot strictly rule out at present that this counterpart candidate is a mere line-of-sight coincidence in the crowded regions of the Galactic Bulge. From the images in Fig. 2, we find ~ 120 I-band and ~ 50 K-band sources in a solid angle of 1000 arc sec^2. Then, the a priori probability of finding an object in our astrometric error circle is non negligible and amounts to $\sim 20\%$ and $\sim 10\%$ in the optical and infrared, respectively.

Alternatively, for the weaker VLA-C counterpart candidate the approximate absolute magnitudes that we estimate are $R = +1.7 \pm 0.9$ and $I = 2.4 \pm 0.8$. With the same caution as above for line-of-sight coincidences, these values would point towards a main sequence F star as the most likely interpretation, thus implying a low-mass X-ray binary system. No reliable spectroscopic information is available for this source given its weakness.

The two VLA-C candidates reported here certainly exclude the possibility of a high mass companion for GRS 1758−258. It is also worth mentioning that, if we could see them through the same huge absorption as in 1E 1740.7−2942, then their apparent magnitudes would be consistent with the present 1E 1740.7−2942 limits. This fact is reassuring that both microquasars are likely to have similar companions. Moreover, if the VLA-C first candidate is indeed GRS 1758−258, its extrapolated apparent magnitude at L'-band (3.8 μ) assuming the 1E 1740.7−2942 absorption is found to be $L' \gtrsim 14$. This value is interestingly not far from the possible marginal detection of 1E 1740.7−2942 by Djorgovski et al. (1992) long ago ($L' = 13 \pm 1$). In any case, we conclude this work by stressing the need for further sensitive observations to confirm or to rule out the proposed identifications.

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