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Radio images of the microquasar GRS 1758−258

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Abstract. We present sensitive images of the microquasar GRS 1758−258 at two different radio wavelengths. The positions, flux densities and spectral indices of the central source and the extended radio lobes are reported. Our results confirm the synchrotron nature of the radio lobes. We also present a very deep radio image of the jet flow at arcminute scales. The source VLA-C, previously proposed as the exciting source of the system, is found to coincide with the *Chandra* position.

Key words. stars: individual: GRS 1758−258 – stars: winds, outflows

1. Introduction

GRS 1758−258 is one of the two brightest persistent hard X-ray sources in the Galactic Center region and belongs to the class of galactic microquasars. The reader is referred to the review by Mirabel & Rodríguez (1999) and the proceedings book by Castro-Tirado et al. (2001) for both a comprehensive discussion and recent findings on microquasar properties.

GRS 1758−258 was originally discovered in hard X-rays ($\geq$30 keV) using the SIGMA coded mask telescope on board the satellite GRANAT (Sunyaev et al. 1991; Goldwurm et al. 1994). The nature of the donor star in GRS 1758−258 remains a matter of discussion (Martí et al. 1998; Eikenberry et al. 2001). A possible X-ray orbital period of 18.45 ± 0.03 d has been recently reported, suggesting the companion is a giant filling the Roche lobe (Smith et al. 2000). A galactic compact X-ray source is usually classified as a microquasar system when relativistic radio jets are detected emanating from it. In the case of GRS 1758−258, the radio jets were detected by Rodríguez et al. (1992) using the Very Large Array (VLA) interferometer of the National Radio Astronomy Observatory (NRAO) in New Mexico, USA. The jets clearly appear to be bipolar, extending over nearly one arcminute, and ending with the formation of two radio lobes. The relativistic nature of the jets, although likely, has not been confirmed yet by proper motion measurements. At an assumed distance of 8.5 kpc to the Galactic Center, each radio lobe would be $\gtrsim$2.5 pc long. Using the notation of Rodríguez et al. (1992), the southern/northern radio lobes and the central core from which the jets emanate will be designated as sources VLA A, B and C, respectively. There is another radio source in the field (VLA-D) which appears to be unrelated to the microquasar. In this note we report deep radio maps of GRS 1758−258 that provide a significant improvement over the original work presented by Rodríguez et al. (1992).

2. Observations and data processing

The radio maps presented here are the result of combining and reanalyzing several observing runs from the VLA data

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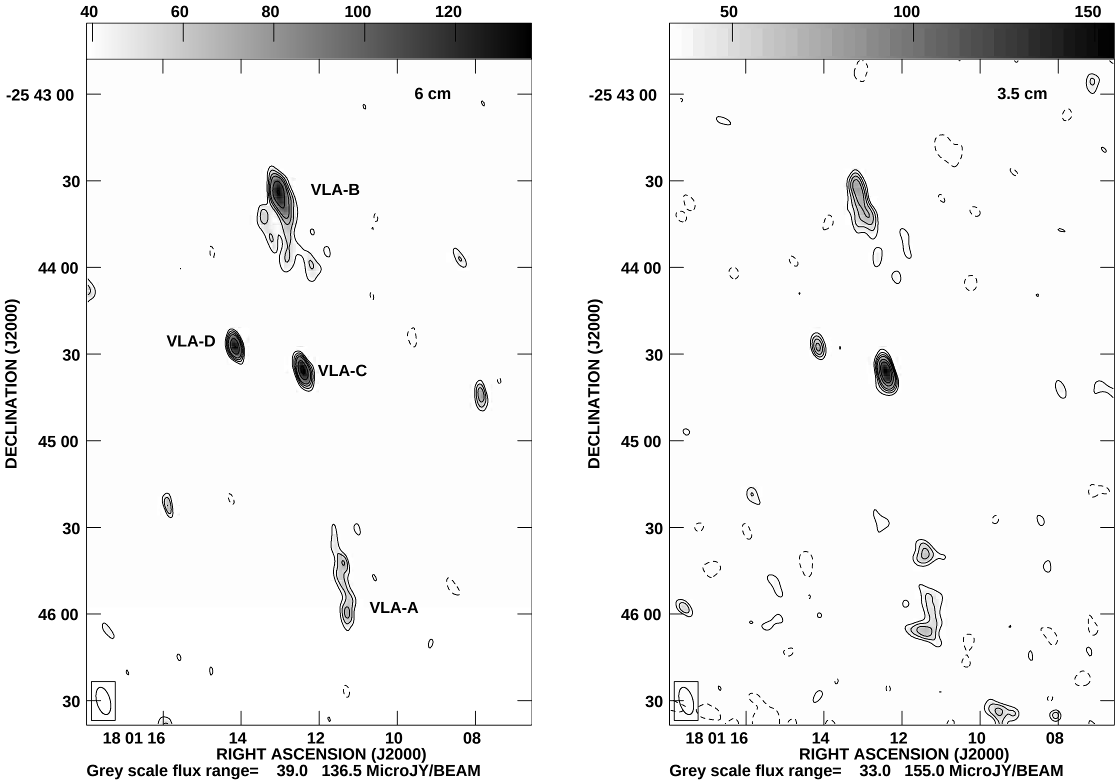

Fig. 1. VLA maps of GRS 1758−258 at 6 cm (left) and 3.5 cm (right) corrected for the attenuation of the primary beam. They have been computed with natural weight and using only the uv data of 1997 August. The contours shown are −3, 3, 4, 5, 6, 8 and 10 times the rms noise at the phase center, which is estimated to be 0.013 and 0.011 mJy beam^{-1} at 6 and 3.5 cm, respectively. The 3.5 cm map has been restored using the same synthesized beam as the 6 cm data, corresponding to $9\farcs7\times4\farcs7$ with a position angle of $14\fdg9$.

archives. Most of them were originally intended to provide a radio monitoring of GRS 1758−258 during multifrequency campaigns that took place in 1997; see Lin et al. (2000) for full details. In addition to this primary goal, good quality maps of the source can be obtained by concatenating different VLA runs into a single data set and this is the main purpose of the present note. The complete log of the VLA epochs, configurations and wavelengths selected for our mapping purposes is listed in Table 1.

The primary data set presented here uses the VLA observations taken in 1997 in CS and B configurations. These observations were carried out at two different wavelengths (6 and 3.5 cm). The scans at the two wavelengths were acquired one after the other, with a repetitive interval of about half an hour. Therefore, they can be considered to be practically simultaneous in time and thus used for spectral index studies. Here, the spectral index α is defined in such a way that $S_\nu \propto \nu^\alpha$, where S_ν is the flux density at a given frequency ν. We have also retrieved the C-type configuration data of 1992, which covers a time interval of a few months. These were the first VLA observations of GRS 1758−258.

The calibration and data processing was performed using the AIPS package of NRAO. Both in 1992 and 1997, the source 1331+305 was observed for amplitude calibration while the phase calibrator was always 1751−253, which is located $2\fdg1$ away.

Table 1. Log of VLA observations used in this work.

Epoch Date	Modified Julian Day	VLA Configuration	Wavelength (cm)
1992 Jan. 28	48649	CnB	6
Feb. 20	48672	B=>C	6
Mar. 21	48702	C	6
Apr. 09	48721	C	6
Apr. 11	48723	C	6
1997 Apr. 10	50548	B	6
Aug. 03	50663	CS	6, 3.5
05	50665	CS	6, 3.5
08	50668	CS	6, 3.5
11	50671	CS	6, 3.5
14	50674	CS	6, 3.5
15	50675	CS	6, 3.5
18	50678	CS	6, 3.5
20	50680	CS	6, 3.5
24	50684	CS	6, 3.5

Table 2. Observational data for the sources in the GRS 1758−258 field.

VLA Source	$\alpha_{\rm J2000}$	$\delta_{\rm J2000}$	$S_{6\,\rm cm}$ (mJy)	$S_{3.5\,\rm cm}$ (mJy)	Spectral Index	Notes
A	$18^{\rm h}01^{\rm m}11\overset{\rm s}{.}27 \pm 0\overset{\rm s}{.}04$	$-25°45'58\overset{''}{.}3 \pm 1\overset{''}{.}5$	0.25 ± 0.04	0.24 ± 0.03	-0.1 ± 0.4	Southern Lobe
B	$18^{\rm h}01^{\rm m}13\overset{\rm s}{.}00 \pm 0\overset{\rm s}{.}03$	$-25°43'35\overset{''}{.}7 \pm 0\overset{''}{.}9$	0.65 ± 0.06	0.40 ± 0.05	-0.9 ± 0.3	Northern Lobe
C	$18^{\rm h}01^{\rm m}12\overset{\rm s}{.}40 \pm 0\overset{\rm s}{.}01$	$-25°44'36\overset{''}{.}1 \pm 0\overset{''}{.}2$	0.14 ± 0.02	0.15 ± 0.02	$+0.1 \pm 0.4$	Central Source
D	$18^{\rm h}01^{\rm m}14\overset{\rm s}{.}16 \pm 0\overset{\rm s}{.}01$	$-25°44'27\overset{''}{.}4 \pm 0\overset{''}{.}3$	0.14 ± 0.02	0.07 ± 0.02	-1.3 ± 0.6	Unrelated Source

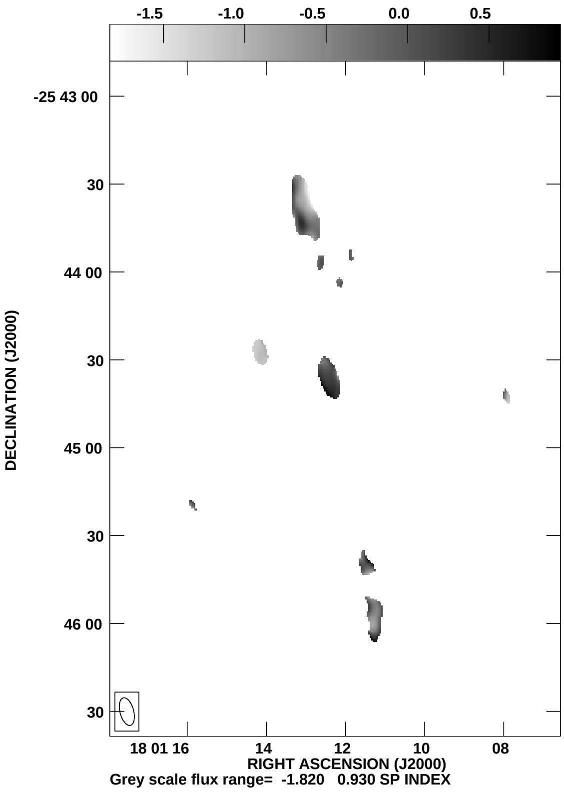

Fig. 2. Spectral index map of GRS 1758−258 computed using the 6 and 3.5 cm maps of Fig. 1.

The independently calibrated uv data sets were finally concatenated with the AIPS task DBCON. The total on-source integration time is ∼12 and 6 h at 6 and 3.5 cm, respectively. The final synthesis maps were generated using the AIPS tasks MX and IMAGR with full natural weight in order to emphasize the extended emission of the jets.

3. The radio maps at 6 and 3.5 cm

The VLA runs in 1997 August provided us with an excellent opportunity to image GRS 1758−258 simultaneously at two different wavelengths with sensitivity to extended emission at arcminute angular scales. The maps resulting from concatenating the 1997 August data are presented in the two panels of Fig. 1. The two maps only include visibility data within a uv range of projected baselines longer than 2 kλ. This value has been chosen after some experimentation in order to emphasize the arcminute-sized radio jets while still avoiding extended emission from the galactic plane. The 3.5 cm map was computed with a uv taper of 30 kλ and restored using the same clean beam as in the 6 cm map. We did this in an attempt to produce matching beam maps at both wavelengths. Both maps in Fig. 1 have been corrected by the response of the primary beam using the PBCOR task of AIPS. This correction is particularly important at 3.5 cm.

We list in Table 2 the observed parameters for the main sources in the GRS 1758−258 field. The positions given for the extended radio lobes correspond to the peaks of the radio emission. The position of the central core (VLA-C) is consistent with previously published values (e.g. Mirabel & Rodríguez 1993). The values in this table are averages of all the 1997 August data. Their sensitivity to the uv range parameter does not exceed 10–20% for compact sources. The effects are more dramatic for the lobes because if the minimum baseline is too large, the interferometer would begin to be blind to such extended features.

The spectral index information is presented in Fig. 2. Here, the matching beam maps of Fig. 1 have been combined into a spectral index map. Pixels with a signal-to-noise ratio (SNR) lower than 4 have been blanked prior to combination. The resulting spectral index error is in the range ±0.2 to ±0.6.

By inspecting this figure, together with the averaged values in Table 2, we believe that the radio lobes appear to be mostly non-thermal emitters. This is clear for the brighter northern lobe (VLA-B), thus confirming optically-thin synchrotron radiation as the most likely emission mechanism. The fainter southern lobe (VLA-A) has a flatter average spectral index, but the larger associated error means it is still consistent with a synchrotron origin, as expected by analogy with VLA-B. The lobe spectral indices are not uniform on the sky and spectral gradients are likely to exist. It should also be noted that the indices are more uncertain close to the edges of the sources, where the SNR is lower. The pixels with better SNR are clearly non-thermal for both lobes.

The central core (VLA-C) is consistent with a flat or rising spectrum, as reported in Lin et al. (2000). A flat radio spectral index appears to be characteristic of black hole systems in the low/hard spectral state, such as Cygnus X-1, GRS 1915+105, GX 339−4, SgrA*, etc. (see e.g. Fender 2001; Falcke et al. 2001). This is usually interpreted as being due to a continual outflow from the

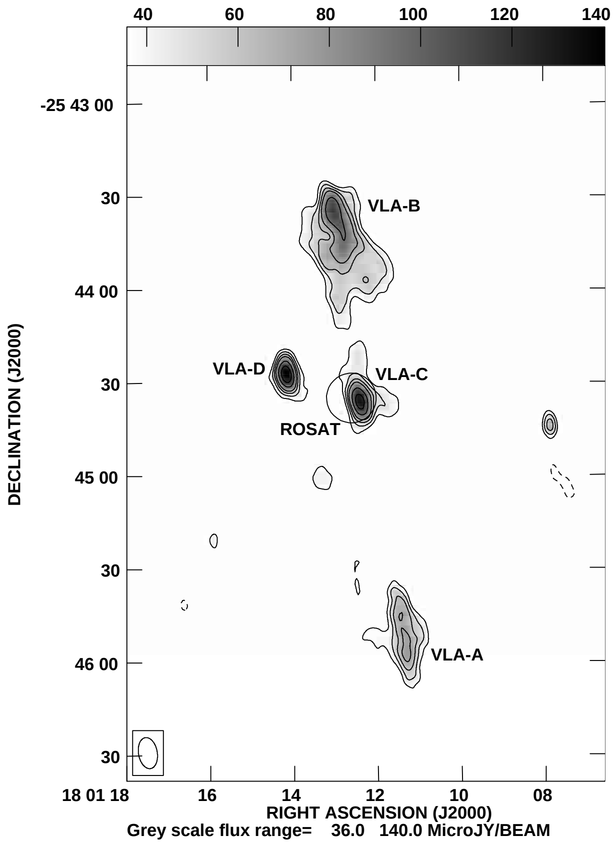

Fig. 3. VLA map of GRS 1758−258 at 6 cm obtained using all the 1992 and 1997 *uv* data. Contours are −3, 3, 4, 5, 6, 8 and 10 times 0.012 mJy beam^{-1}, the rms noise. The synthesized beam is the ellipse shown at the bottom left corner and corresponds to 10.″1 × 6.″0, with a position angle of 9.°7. The X-ray position of GRS 1758−258 from the ROSAT All Sky Survey is also plotted on this map.

central source, as supported by conical jet models (e.g. Hjellming & Johnston 1998; Martí et al. 1992).

The unrelated source VLA-D is clearly non-thermal. The presence of source D is not surprising in a map of this high sensitivity since the a priori probability of finding a 0.14 mJy source in a 1 square arcminute region is ∼10% (Fomalont et al. 1991).

We also remark that an intriguing feature of the 6 cm map in Fig. 1 is that the southern lobe (VLA-A) displays a wavy structure; if this is real, this could reflect precessional changes in the direction of the jet ejection.

4. A deep radio map of GRS 1758−258 at 6 cm

Our 6 cm map in Fig. 1 is separated by 5 yr from the Rodríguez et al. (1992) maps at 6 cm. We cannot make a detailed statement about the lobe variability on time scales of years because this a difficult issue that requires two epochs of matching beam observations with similar *uv* coverage. Unfortunately, these are not available yet. However, we can say that no significant changes in the lobe position were detected in the 5 yr interval. A conservative upper limit for any shift is estimated to be ∼10″, i.e.,

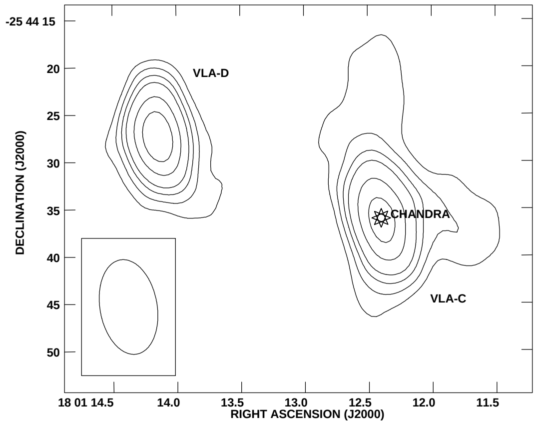

Fig. 4. Expanded view of the central region of GRS 1758−258 at 6 cm showing the radio sources VLA-C and VLA-D in more detail. The star symbol corresponds to the *Chandra* X-ray position of the microquasar, whose uncertainty is smaller than the symbol size. The contours and the synthesized beam are the same as in Fig. 3.

comparable to the major axis of the synthesized beam in the NS direction. At the Galactic Center distance, this is consistent with a projected velocity $\leq 0.3c$ for the lobes.

The absence of detectable motion allows us to concatenate the *uv* data of 1992 and 1997 in order to obtain a very deep radio image of the source at 6 cm. The final result is presented in Fig. 3 both as a grey scale and contour plot. A preliminary version of this map already appeared in Martí et al. (1998) where it was overlayed on an optical NTT image. Figure 3 also includes the 1997 VLA data taken at 6 cm in the B configuration, which contributes to slightly enhance the angular resolution. Figure 3 shows that both lobes are clearly elongated towards the central source VLA-C. By analogy with extragalactic sources, this fact is a strong argument to support a physical connection between them. The additional complexity of the lobe structure is also evident in this image. Using the concatenated *uv* data, we also searched for faint lobe structures beyond VLA-A and VLA-B and aligned with them. None were found within the field covered by the primary beam of the antennae (∼10′).

In Fig. 4, we show a zoomed view of the central core VLA-C as well as the unrelated source VLA-D. The star symbol plotted over the contours of VLA-C is the accurate *Chandra* X-ray position reported by Heindl & Smith (2001), whose 90% confidence radius is 0.″6. The peak of VLA-C is well consistent with the *Chandra* position, thus clearly pointing to both objects being the same.

There is some extended radio emission around the compact source VLA-C and part of it probably comes from the jets. Its presence is likely to have some effect on the measured flux density of VLA-C, but none of our main conclusions are affected by this.

We hope that the maps presented in this note will provide high quality templates for comparison with future studies of the radio jet morphology and spectral index.

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