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Deep VLA images of LS I +61°303: a search for associated extended radio emission

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Abstract. Deep VLA observations at 6 cm of the field around the radio emitting X-ray binary LS I +61°303 have been carried out in an attempt to search for associated extended radio emission. The angular scales explored go from the arcsecond to the arcminute range. Only clumps of extended radio emission within a few arcminutes of the source are detected. However, in contrast with other X-ray binaries with associated extended radio emission, all these clumps seem to be unrelated to LS I +61°303 itself. The fact that some of them are positionally coincident with optical nebulosities in the field strongly suggests an interpretation based on free-free radio emitting material from the nearby HII region W4. The possibility that an undetected radio jet is present in LS I +61°303 is also discussed.

Key words: stars: individual: LS I +61°303– stars: radio radiation of – X-rays: binaries – HII regions

1. Introduction

This paper is based on further exploitation of observations of the radio emitting X-ray binary (REXRB) LS I +61°303 reported by Peracaula et al. (1997a, hereafter Paper I). LS I +61°303 is a massive Be X-ray binary system well known for its 26.5 d periodic radio outbursts discovered by Taylor & Gregory (1982, 1984). For an account of its other main properties and interest of this target source, we refer the reader to the introduction in Paper I and to the recent papers by Paredes et al. (1997a) and Strickman et al. (1997). In these papers, the first detection of the 26.5 d period in X-rays and an extensive multi-wavelength campaign of the possibly associated γ-ray source 2CG 135+1 are respectively discussed.

In the present work, our main goal is to map and to study the field around the REXRB LS I +61°303 in order to search for associated weak extended radio emission. The motivation for this kind of search comes from previous reports of non-thermal extended radio emission in a handful of well known REXRBs, and in the so called galactic microquasars. Examples known so far include SS 433 (Hjellming & Johnston 1981), Cyg X-3 (Strom et al. 1989), Cir X-1 (Stewart et al. 1993), 1E 1740.7−2942 (Mirabel et al. 1992) and GRS 1758−258 (Rodríguez et al. 1992). The different morphologies detected include jet-like structures, surrounding nebulae, and also extended bow shocks. If these features are powered by the central accretion-driven X-ray source, their presence puts important constraints on the capability of compacts objects to accelerate and collimate beams of relativistic particles, and to the total energy injected into the nearby interstellar medium.

All this evidence has lead to the suggestion that extended radio emission in galactic X-ray sources, and specially radio jets, could be a phenomenon much more common that previously expected (Rodríguez et al. 1992). Up to now, such structures have not been often detected in the $\sim$ 20 REXRBs catalogued (Hjellming & Han 1995). However, it could be possible that this apparent absence were due to most interferometric radio observations being aimed to find sub-arcsecond details. Then, if the jet structures had a typical linear size of a parsec, as in the case of microquasars, they should appear with angular diameters in the arcminute range at distances of few kpc. For instance, at the 2.0 kpc distance of LS I +61°303 (Frail & Hjellming 1991), one parsec corresponds to $\sim 2'$. Consequently, any extended emission of this size would be heavily resolved out and undetected by high resolution interferometers.

The previous deepest search for extended radio emission in LS I +61°303 was that of Frail et al. (1987) at 408 and 1420 MHz. Their resolution was between $1'$-$3'$ and they found that LS I +61°303 is actually surrounded by a $47' \times 27'$ extended emission feature (EEF), with an integrated flux density of $\sim$ 10 Jy at both frequencies. The uncertainty in their spectral index determination did not allow to discriminate between a thermal or non-thermal emission mechanism. They concluded that the most likely interpretations of the EEF are either thermal emission from nearby HII complexes or a non-thermal surrounding nebula similar to that of Cir X-1. However, in contrast with the

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case of Cir X-1, the EEF in the maps of Frail et al. (1987) did not exhibit any clear structure or evidences of collimation.

To help solving some of these issues, we present deep interferometric radio maps of LS I +61°303 with different resolutions of $\sim$0.″5 and $\sim$ 15″. Our results are basically negative and the extended emission detected does not seem to be reliably associated to LS I +61°303. This leads us to discuss, from the theoretical point of view, what chances are still left that the LS I +61°303 radio emission is somehow related to possible radio jets. Preliminary results of this work were first reported in Paredes et al. (1996).

2. VLA observations and results

The 6 cm observations on which this paper is based have been carried out with the Very Large Array (VLA) interferometer of NRAO[1]. The observation dates were 1990 June 6 (array in A configuration) and 1993 September 9 and 13 (array in CnD configuration). We refer the reader to Paper I for further details on the observation log and calibration procedures. The only important point to stress here concerning data reduction is the variability problem that one usually encounters when imaging REXRBs with radio interferometers. This kind of radiostars often exhibit strong variability during the several hours that a typical observing run may last. When this happens, it is not possible to use directly the standard CLEAN algorithm to compute maps, since the assumption of a constant brightness distribution is clearly violated. In order to proceed, the variability has to be removed or the data split into sets of approximately constant brightness.

During the 1990 observation, we were fortunate that LS I +61°303 did not vary by more that $\sim$ 5% during a continuous time span of $\sim$ 7 h (60% of the total run). The high resolution VLA map in Fig. 1 has been computed using only visibilities from this stable time interval.

However, the situation was completely different on 1993 September 9 when, as shown in Fig. 1 of Paper I, the LS I +61°303 flux density at 6 cm varied from 131 mJy to 76 mJy in about 7 h. To remove this variability, we divided the observation into data blocks $\sim$30 minutes long. During these intervals, the emission level of LS I +61°303 could be considered to stay safely constant. For each block, maps were computed and the LS I +61°303 flux density was determined for all of them. The next step was to subtract from each (u, v) data block a point source model with the corresponding flux density of LS I +61°303. During the subtraction process, we also removed the clean components of BG 0237+61. This is a relatively strong source $\sim$ 15′ northeast of the phase center (see Fig. 3), being detected through the first primary beam sidelobe. Afterwards, we run the DBCON task of AIPS for concatenating all blocks together. Although the variability on 1993 September 13 was not so severe, we also applied here the same division and subtraction procedure.

[1] The NRAO is operated by Associated Universities, Inc., under cooperative agreement with the National Science Foundation.

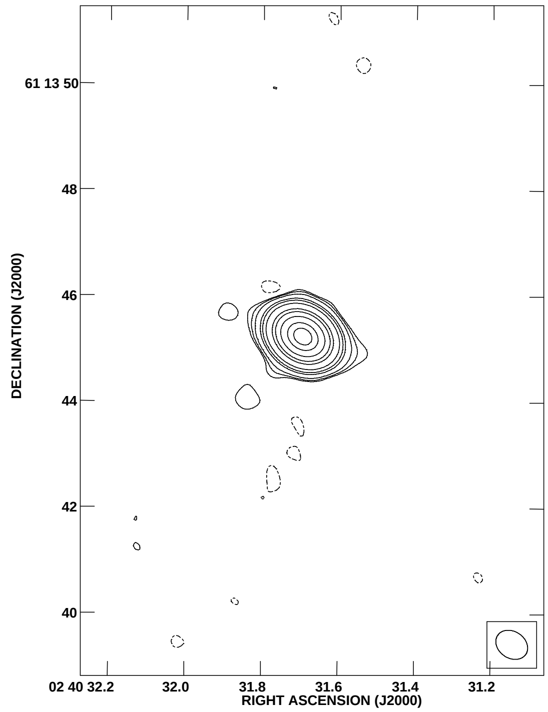

Fig. 1. Natural weight high resolution map of LS I +61°303 from the VLA A configuration data of 1990 June 6. The synthesized beam (shown in the lower right corner) is 0.″64 × 0.″50, with position angle of 56.°1. Contours are −3, 3, 5, 10, 30, 50, 100, 300, 500, 1000, 2000 and 3000 times 0.059 mJy beam^{-1}, the rms noise.

The next step was to concatenate the variability free data sets of both 1993 September 9 and 13 in order to increase sensitivity. Finally, and just for cosmetic reasons, a constant point source at the LS I +61°303 position with an average flux density level was artificially added to the concatenated (u, v) data. In this way, the 6 cm map of Fig. 2a could be finally produced. This map also includes a zero space flux density level parameter of 0.2 Jy, estimated from the single dish maps. Natural weight was used in order to increase sensitivity and to emphasize any extended emission present. Fig. 2b corresponds exactly to the same field as it appears in the visible from the digitized version of the Palomar Observatory Sky Survey[2] (POSS).

3. Upper limits on possible arcsecond extended radio emission

The only VLA map of LS I +61°303 with arcsecond resolution so far published is that by Gregory et al. (1979), where the source

[2] Based on photographic data obtained using Oschin Schmidt Telescope on Palomar Mountain. The Palomar Observatory Sky Survey was funded by the National Geographic Society. The Oschin Shmidt Telescope is operated by the California Institute of Technology and Palomar Observatory. The plates were processed into the present compressed digital format with their permission. The Digitized Sky Survey was produced at the Space Telescope Science Institute (ST ScI) under U.S. Government grant NAG W-2166.

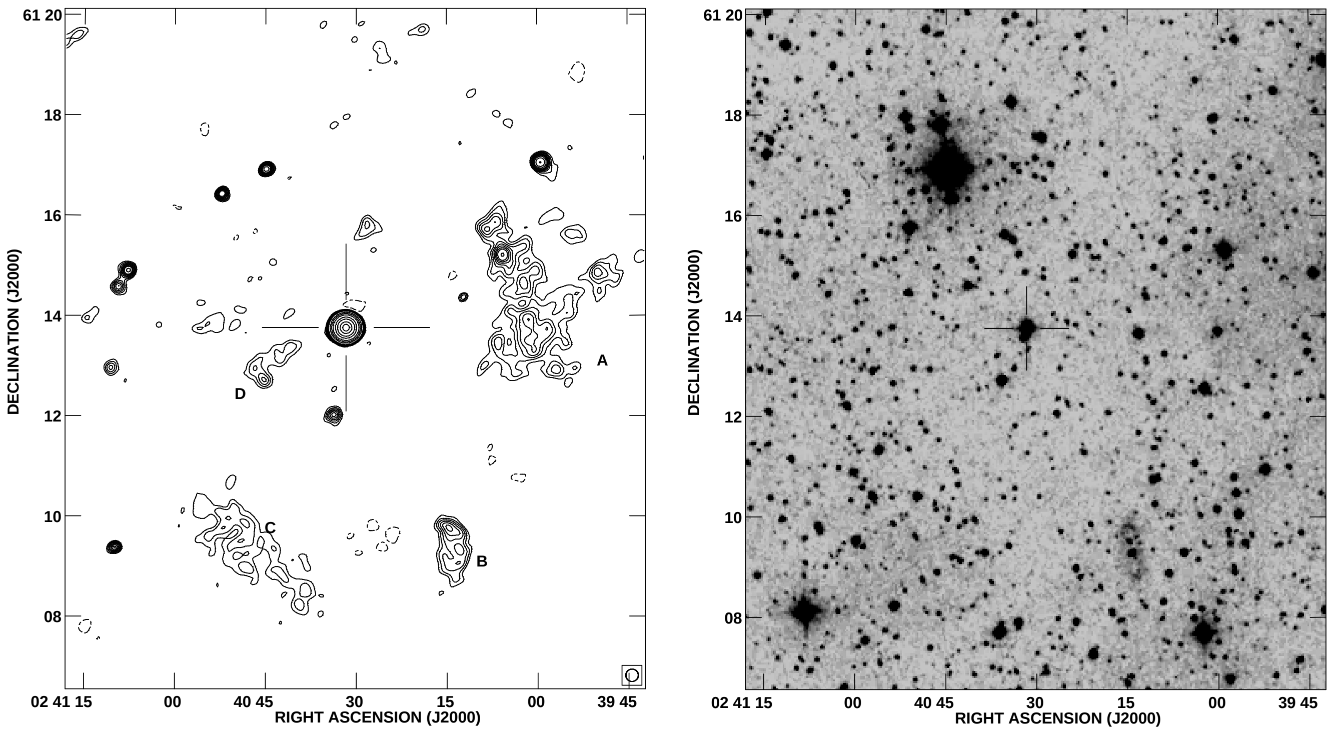

Fig. 2. a Combined map obtained by concatenating the runs of 1993 September 9 and 13 and using the procedure described in Sect. 2. The synthesized beam is $15'' \times 15''$. Contours are −4, 4, 5, 6, 7, 8, 9, 10, 12, 15, 20, 50, 100, 200, 500, 1000, 2000, 4000 and 6000 times 19 μJy beam^{-1}, the rms noise. **b** The same field in the optical from the digitized version of the POSS.

appears to be unresolved ($<0\farcs5$). These authors observed at 6 cm when the VLA was near completition, using only eight antennas with a maximum baseline of 10 km. In Fig. 1, a much better image of LS I +61°303 has been obtained from the flux density stable part of our VLA data of 1990 June 6, when the full array was operative and in its most extended A configuration.

In this map LS I +61°303 also appears unresolved, with a smaller angular size upper limit of $<0\farcs3$. This is consistent of course with the $\sim 1.6 \times 1.0$ mas size reported by Massi et al. (1993) during a simultaneous VLBI experiment. From their VLBI data, these authors concluded that any emission extended at arcsecond scales, if present, contributed only a few mJy to the total flux density. From our VLA map in A configuration, we are able to further constrain this statement to a 4σ upper limit of 0.24 mJy beam^{-1} for possible arcsecond extended features existing at the epoch of observation, corresponding to a limiting surface brightness of 0.9 mJy arcsec^{-2}.

4. Arcminute extended radio sources in the field

The data sets of 1993 September 9 and 13, when the VLA was in a hybrid but relatively compact CnD configuration, are the more suitable to look for extended radio sources in the arcminute range. As can be seen from the corresponding map in Fig. 2a, our main result here is that no significant emission closer than $1'$ to LS I +61°303 is detected. The map 4σ upper limit is 0.076 mJy beam^{-1}, equivalent to 0.43 μJy arcsec^{-2}. Nevertheless, several clumps of extended emission are certainly detected around LS I +61°303, at an angular separation between $2'$-$4'$. We have labeled the most prominent of them as A, B, C and D, in order of right ascension. Their observed parameters are given in Table 1. The flux densities in this table include the correction for primary beam response. The presence of A, B, C and D is also evident in the maps made using each 1993 September observing data set separately. Other compact radio sources, including a new radio star, are also detected in the field. They are briefly discussed in the Appendix to this paper.

Table 1. Observational data for the extended sources in the vicinity of LS I +61°303

Source	α(J2000)[a]	δ(J2000)[a]	Angular Size	S_{6cm} (mJy)
A	$02^h40^m06^s$	+61°15′.2	3′.2×1′.1	15.6 ±0.5
B	$02^h40^m15^s$	+61°09′.7	1′.3×0′.7	4.4 ±0.3
C	$02^h40^m39^s$	+61°08′.2	3′.3×1′.2	13.4 ±0.6
D	$02^h40^m45^s$	+61°12′.7	1′.2×0′.6	0.9 ±0.1

[a] The position given corresponds to the peak of radio emission.

4.1. The nature of the extended radio sources detected

What is the physical nature of these VLA sources? Given their apparent circular clustering around LS I +61°303 one possible interpretation is that they are part of a supernova remnant (SNR). Up to now, there are only two cases known of association between a Be star and a SNR (Hughes & Smith, 1994), both in the

Small Magellanic Cloud. However, several arguments conspire against a SNR origin:
(i) The round shape centered on LS I +61°303 may be an illusion due to the decay of the primary beam response.
(ii) Assuming a typical non-thermal index, a plot of the A, B, C and D surface brightness in the 1 GHz Σ, D diagrams of Green (1991), implies that a SNR two orders of magnitude more subluminous than average would be required.
(iii) None of the extended radio sources in Fig. 2a has any evident counterpart in the ROSAT X-ray image of the same field obtained by Goldoni & Mereghetti (1995), while SNRs are usually X-ray emitters.

The situation is more clear at optical wavelengths from a comparison of the map in Fig. 2a with the original print of the corresponding POSS plate, reproduced in Fig. 2b. The extended radio sources A and C seem to trace the outer limits of some optical nebulosity that is part of the nearby giant HII regions W4 and W5, respectively. Source B is also coincident with an optical nebula surrounding a group containing a few stars. Probably, this is a HII region as well. These coincidences suggest that A, B and C are likely to be thermal free-free radio sources without any physical connection with LS I +61°303 itself.

Source D is also possibly of thermal origin, but we believe deserves some additional comments. It does not have any evident optical counterpart and its elongated appearance, pointing towards the LS I +61°303 position, does resemble a radio jet lobe. The separation between the photocenter of source D and LS I +61°303 is about 2′ (equivalent to 1.2 pc if located at 2.0 kpc). This is in the same range as the radio jets of 1E 1740.7−2942 and GRS 1758−258. However, no opposite D counterpart is detected. Also, we note that the position angle of D is not coincident with that of the double structure seen in the VLBI map by Massi et al. (1993). In any case, D is the only source that could be associated to LS I +61°303. The association is however very doubtful but the data available up to now do not allow us to completely reject such a hypothesis.

4.2. The VLA radio sources and the EEF

Since the largest scale structure visible in our VLA data is $\sim 5'$, these observations alone do not allow us to address the Frail et al. (1987) EEF issue. This feature, however, can be better studied by using the DRAO data from Normandeau et al. (1997) at 6 cm. A sub-image of this modern survey is shown in the map of Fig. 3 centered around LS I +61°303.

Here, the EEF feature appears to consist of a region with steady negative gradient in brightness towards the SE direction. The DRAO image also clearly suggests that the EEF is just part of filaments belonging to the giant HII complex W4 (Wendker & Altenhoff 1977). Furthermore, on arcminute scales, there is no indication in Fig. 3 of special enhancement, clustering or shell-like morphology around LS I +61°303. All these facts together provide further support to our previous preferred suspicion that the extended emission detected with the VLA is likely to be of free-free thermal emission nature.

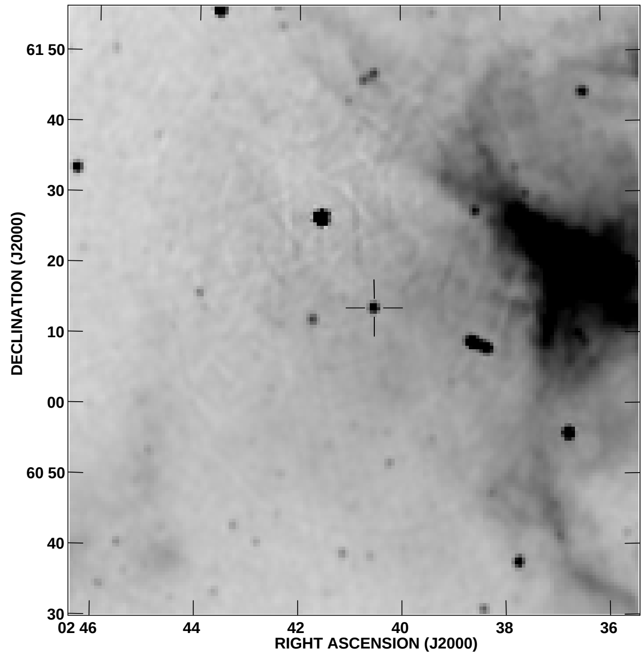

Fig. 3. Radio map of the LS I +61°303 region at 6 cm wavelength from the survey data of Normandeau et al. (1997). The central cross indicates the position of LS I +61°303. The brightest extended emission on the right corresponds to filamentary loop structures of the W4 giant HII region. The strong compact source BG 0237+61 mentioned in the text can also be seen $\sim 15'$ NE from LS I +61°303.

5. Is there a radio jet?

In addition to the observational evidences quoted in the introduction, jets are often invoked as the origin of radio emission in X-ray binaries on the basis of theoretical arguments (e.g., Hjellming & Johnston 1988). The physics involved here is expected to be an scaled down version of the same phenomena giving rise to radio emission and relativistic plasma ejection in extragalactic AGNs. It should be then instructive to compare the LS I +61°303 case with the predictions from such models concerning the expected radio jet properties, and whether or not they fulfill the constrains imposed by observations.

5.1. Theoretical jet models

One of the most recent theoretical models exploring the connection between radio jet X-ray binaries and AGNs is that by Falcke & Biermann (1996). This unifying model assumes that radio emission is due to synchrotron radiation in a bi-conical jet, fed by the accretion disk, and carrying a magnetic field decaying as the inverse of the jet radius. The Falcke & Biermann (1996) model assumes furthermore a steady state jet. Therefore, it should not be directly applicable to flaring REXRBs except for a qualitative discussion as we intend here. Its main predictions can be condensed into two expressions for the expected jet flux density and angular size, namely:

$$S_\nu = 72\ mJy \left(\frac{L_{disk}}{10^{38}\ erg\ s^{-1}}\right)^{1.4} (\gamma_e x_e)^{0.83} \beta_j^{0.42} \gamma_j^{1.8} \qquad (1)$$

and

$$\theta = 1.0\ mas\left(\frac{\nu}{GHz}\right)^{-1}\left(\frac{L_{disk}}{10^{38} ergs^{-1}}\right)^{2/3}\left(\frac{\gamma_e x_e \beta_j}{\gamma_j}\right)^{1/3}, (2)$$

where L_{disk} is the system accretion disk luminosity, $\beta_j c$ the jet bulk velocity, γ_j the corresponding Lorentz factor, γ_e the minimum Lorentz factor of relativistic electrons and x_e the relativistic electron to proton ratio. Both Eqs.1 and 2 are particularized at the 2.0 kpc distance of LS I +61°303 and they do not include Doppler boosting nor inclination effects (edge on jet).

5.2. Model application to LS I +61°303

We do not know for sure if an accretion disk actually exists in LS I +61°303, although some authors have occasionally invoked it in order to interpret details of the optical light curve (Mendelson & Mazeh 1989). On the contrary, recent ASCA observations (Harrison et al. 1997) suggest that X-rays may originate as well in a shock between the Be star wind and a moderately young pulsar companion. In any case, the existence of an accretion disk where high energy emission is released will be assumed throughout this section for the purpose of applying and testing the Falcke & Biermann (1996) model in a jet/disk context.

On average, the 2-10 keV X-ray luminosity of LS I +61°303 has been estimated to vary between $\sim 1 \times 10^{34}$ and $\sim 6 \times 10^{34}$ erg s^{-1} (Paredes et al. 1997a). We can adopt therefore L_{disk} = 10^{35} erg s^{-1} as a reasonable value for the hypothetical disk bolometric luminosity, i.e., the most important model parameter. Plausible values for the other remaining parameters are β_j = 0.3, γ_e = 100 and x_e = 0.5, with our conclusions not being highly dependent on them.

Under such assumptions, the predicted LS I +61°303 radio jet should have $\sim$ 0.1 mJy at 5 GHz with angular scales in the $\sim$ 1 μarcsec range. A theoretical flux density and size so low is basically a consequence of the weak disk luminosity assumed here, as imposed by X-ray observations. Thus, it appears that the model predictions do not agree at first glance with the observational properties of the system. Indeed, we know that the LS I +61°303 radio emission at centimetric wavelengths is usually much higher than 0.1 mJy, even in the quiescent state ($\sim$ 10 mJy). The angular size has also been observed to be comparable, or even larger than, a few milliarcsec according to VLBI experiments (e.g. Massi et al. 1993; Paredes et al. 1997b; Peracaula et al. 1997b).

The values of β_j, γ_e and x_e have been already set at rather powerful numbers for radio jets coming from a neutron star system. The simplest way to try to account for the typical LS I +61°303 flux density levels within the Falcke & Biermann (1996) model is then by using a much higher value of L_{disk}. For instance, a few 10^{36} erg s^{-1} make possible to obtain flux densities of tens of mJy. This is certainly more consistent with the observations but now the problem is how to justify such a large accretion disk luminosity. We note here that LS I +61°303 has been proposed to be associated with the γ-ray source 2CG 135+1 (Strickman et al. 1997 and references therein), with γ-ray luminosities of the order of 10^{36} erg s^{-1}. Nevertheless, the possibility that this high energy luminosity is released in an accretion disk and shifted to γ-ray energies is not easy to understand. Even if this could be solved, the expected jet angular size for $L_{disk} \simeq 10^{36}$ erg s^{-1} is still below the milliarsec scales and, therefore, not consistent with VLBI maps.

We can try finally an AGN-like model with a super-Eddington luminosity ($L_{disk} \simeq 10^{38}$ erg s^{-1}), as assumed in the Taylor et al. (1992) scenario. Reasonably high flux densities are then reproduced, even if x_e is as low as 1%. However, the problem of an expected angular size well below one milliarsec still persists. Significant scattering should be then invoked to account for the observed VLBI angular sizes but this does not seem to be the case, at least at wavelengths shorter than 6 cm (Massi et al. 1993). In addition, one has to bear in mind that the weak X-ray luminosities confirmed by several authors in the recent times currently represent an almost insurmountable challenge for any super-Eddington model to succeed.

5.3. Possible scenarios consistent with the observations

Given this section results, we can state that the apparent lack of extended radio structures that we observe in LS I +61°303 could have two different explanations:

a) Extended radio features do exist in LS I +61°303, but they are below our sensitivity or extending at subarcsec ($\lesssim 0\farcs1$) angular scales not yet sampled. Obtaining very sensitive maps, specially with resolution intermediate between that of VLA and VLBI (e.g. MERLIN), would be necessary to test this subarcsec possibility. Some previous VLBI observations have often suggested that 10-20% of the total flux density is not contained in milliarcsec structures (Massi et al. 1993; Peracaula et al. 1997b). It is therefore conceivable that this missing flux density could be lying at the unexplored $\lesssim 0\farcs1$ scales. In any case, such extended emission is not easy to be produced by an AGN-like radio jet as we have shown above.

b) The outburst mechanism of LS I +61°303 is such that radio emission is restricted close to the binary system, and ejection of radio emitting electrons well outside the orbital volume is not relevant. This second possibility is more in agreement with non-accreting outburst models, where radio outbursts are interpreted as particles accelerated at the shock front between the dense Be star wind and the relativistic wind of the neutron star (Maraschi & Treves 1981; Tavani 1994).

6. Conclusions

1. The analysis of VLA observations has revealed several clumps of extended radio emission within a few arcminutes from the REXRB LS I +61°303. Their most likely interpretation is that all of them correspond to free free radio sources mainly associated to nearby HII regions. This implies that no extended or jet-like radio features, in the arcminute range, are present around LS I +61°303 up to a surface brightness limit of 0.43 μJy arcsec^{-2}.
2. From VLA data in the A configuration, an upper limit of 0.9 mJy arcsec^{-2} has been obtained for extended radio struc-

Table 2. Compact radio sources in the vicinity of LS I +61°303

Source	α(J2000)	δ(J2000)	S_{6cm} (mJy)
1	$02^h39^m59\overset{s}{.}50$	+61°17′03.″1	1.23 ±0.03
2[a]	$02^h40^m12\overset{s}{.}09$	+61°14′22.″7	0.09 ±0.02
3[b]	$02^h40^m31\overset{s}{.}67$	+61°13′45.″6	variable
4	$02^h40^m33\overset{s}{.}69$	+61°12′02.″5	0.23 ±0.03
5[c]	$02^h40^m44\overset{s}{.}95$	+61°16′55.″7	0.33 ±0.03
6	$02^h40^m52\overset{s}{.}23$	+61°16′26.″2	0.30 ±0.03
7	$02^h41^m07\overset{s}{.}76$	+61°14′54.″2	0.51 ±0.04
8	$02^h41^m09\overset{s}{.}38$	+61°14′34.″4	0.35 ±0.04
9	$02^h41^m09\overset{s}{.}89$	+61°09′23.″0	0.68 ±0.04
10	$02^h41^m10\overset{s}{.}71$	+61°12′58.″5	0.32 ±0.04

Optical identifications: [a] POSS object, [b] LS I +61°303, [c] SAO 12383.

tures at arcsecond angular scales. If such structures do exist in LS I +61°303, as detected in other REXRBs, they must be below these respective sensitivity levels or at subarcsec angular scales not explored in this paper.

3. We also show that the LS I +61°303 radio emission is difficult to be accounted for by an AGN-like scaled down model given the observational constraints presently available. This suggests that the non-detection of extended radio features in LS I +61°303 is more consistent with a radio outburst mechanism not involving the ejection of relativistic plasma beyond the orbital volume (e.g. wind shock models).

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Appendix A: other compact radio sources in the field

Several compact radio sources are evident in the map of Fig. 2a. Their positions and 6 cm flux densities are listed in Table 2. In addition to LS I +61°303, source number 5 is the only one having a clear stellar optical counterpart. Its radio position is coincident within 0.″7 with that of SAO 12383. This is a O9.5I star, also catalogued as V482 Cas, which was detected as an X-ray source by Goldoni & Mereghetti (1995). Both the X-ray and radio emission are likely to be originated in its stellar wind. Using the formulation of Felli & Panagia (1981) for free-free emitting envelopes, the observed flux density of SAO 12383 implies a stellar wind mass loss of 5×10^{-6} $M_\odot$ yr^{-1} assuming a wind velocity of 10^3 km s^{-1}.

Source 2 is also coincident within 2″ with an anonymous POSS object. However, its appearance in the POSS plates is not fully star-like, suggesting that it is a background extragalactic object. Possibly, the same statement applies to the rest of sources in Table 2. A search in several star catalogues and the POSS plates yielded negative results for all of them. The extragalactic origin interpretation can be additionally justified from source count analysis (Condon, 1984). Using the formulation of Rodríguez et al. (1989), the number of background extragalactic sources with 0.1 mJy $\leq S_{6cm} \leq$ 100 mJy expected in a 6 cm VLA primary beam is $\sim$8. This is fully consistent with the 8 radio sources in Table 2 without stellar optical counterpart identified.

References

Condon J.J., 1984, ApJ, 287, 461
Falcke H., Biermann P.L., 1996, A&A, 308, 321
Felli M., Panagia N., 1981, A&A, 102, 424
Frail D.A., Seaquist E.R., Taylor, A.R., 1987, AJ, 93, 1506
Frail D.A., Hjellming R.M., 1991, AJ, 101, 2126
Goldoni P., Mereghetti S., 1995, A&A, 299, 751
Green D.A., 1991, PASP, 103, 209
Gregory P.C., Taylor A.R., Crampton D., Hutchings J.B., Hjellming R.M., et al., 1979, AJ, 84, 1030
Harrison F.A., Leahy D., Waltman E., 1997, ApJ (submitted)
Hjellming R.M., Johnston K.J., 1981, ApJ, 246, L141
Hjellming R.M., Johnston K.J., 1988, ApJ, 328, 600
Hjellming R.M., Han X., 1995, in *X-Ray Binaries*, Cambridge Astrophysics Series, 26, 308, W.H.G. Lewin, van Paradijs J. & van den Heuvel E.P.J. Eds.
Hughes J.P., Smith R.C., 1994, AJ, 107, 1363
Maraschi L., Treves A., 1981, MNRAS, 194, 1
Massi M., Paredes J.M., Estalella R., Felli M., 1993, A&A, 269, 249
Mendelson H., Mazeh T., 1989, MNRAS, 239, 733
Mirabel I.F., Rodríguez L.F., Cordier B., Paul J., Lebrun F., 1992, Nat, 358, 215
Normandeau M., Taylor A.R., Dewdney P.E., 1997, ApJSS, 108, 279
Paredes J.M., Martí J., Peracaula M., Massi M., Estalella R., 1996, Proc. *Radio Emission from the Stars and the Sun*, Taylor A.R. & Paredes J.M. (Eds.), ASP Conf. Series, 93, 246
Paredes J.M., Martí J., Peracaula M., Ribó M., 1997a, A&A, 320, L25
Paredes J.M., Peracaula M., Martí J., Estalella R., Massi M., 1997b, *Vistas in Astronomy*, Vol. 41, No. 1, 49
Peracaula M., Martí J.M., Paredes J.M., 1997a, A&A (Paper I, in press)
Peracaula M., Gabuzda D.C., Taylor, A.R., 1997b, A&A (Submitted)
Rodríguez L.F., Myers P.C., Cruz-González, I., Terebey, S., 1989, ApJ 347, 461
Rodríguez L.F., Mirabel I.F., Martí J., 1992, ApJ, 401, L15
Stewart R.T., Caswell J.L., Haynes R.F., Nelson G.J., 1993, MNRAS, 261, 593
Strickman M.S., Tavani M., Steele I.A., Coe M.J., Fabregat J., Martí J., Paredes J.M., Ray P.S., 1997 (in preparation)
Strom R.G., van Paradijs J., van der Klis M., 1989, Nat, 337, 234
Tavani M., 1994, in *The Gamma-Ray Sky with GRO and SIGMA*, Dordrecht: Kluwer, 181
Taylor A.R., Gregory P.C. 1982, ApJ, 255, 210
Taylor A.R., Gregory P.C. 1984, ApJ, 283, 273
Taylor A.R., Kenny H.T., Spencer R.E., Tzioumis A., 1992, ApJ, 395, 268
Wendker H.J., Altenhoff W.J., 1977, A&A, 54, 301

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