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Orbital and superorbital variability of LS I +61 303 at low radio frequencies with GMRT and LOFAR


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ABSTRACT

LS I +61 303 is a gamma-ray binary that exhibits an outburst at GHz frequencies each orbital cycle of ≈26.5 d and a superorbital modulation with a period of ≈4.6 yr. We have performed a detailed study of the low-frequency radio emission of LS I +61 303 by analysing all the archival GMRT data at 150, 235 and 610 MHz, and conducting regular LOFAR observations within the Radio Sky Monitor (RSM) at 150 MHz. We have detected the source for the first time at 150 MHz, which is also the first detection of a gamma-ray binary at such a low frequency. We have obtained the light-curves of the source at 150, 235 and 610 MHz, all of them showing orbital modulation. The light-curves at 235 and 610 MHz also show the existence of superorbital variability. A comparison with contemporaneous 15-GHz data shows remarkable differences with these light-curves. At 15 GHz we see clear outbursts, whereas at low frequencies we see variability with wide maxima. The light-curve at 235 MHz seems to be anticorrelated with the one at 610 MHz, implying a shift of ~0.5 orbital phases in the maxima. We model the shifts between the maxima at different frequencies as due to changes in the physical parameters of the emitting region assuming either free-free absorption or synchrotron self-absorption, obtaining expansion velocities for this region close to the stellar wind velocity with both mechanisms.

Key words: radiation mechanisms: non-thermal – binaries: close – stars: individual: LS I +61 303 – gamma rays: stars – radio continuum: stars

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1 INTRODUCTION

Binary systems comprising a young massive star and a compact object can exhibit non-thermal emission from radio to gamma rays. A fraction of these systems displays a spectral energy distribution dominated by the MeV-GeV photons, thus being classified as gamma-ray binaries (see Dubus 2013 for a review). Only five gamma-ray binary systems are known at present: PSR B1259–63 (Aharonian et al. 2000a, 2003a), LS 5039 (Aharonian et al. 2003a), LS I +61 303 (Albert et al. 2006), HESS J0632+057 (Hinton et al. 2009, Skilton et al. 2009), and 1FGL J1018.6–5856 (Fermi-LAT Collaboration et al. 2012). PSR B1259–63 is the only system which is confirmed to host a pulsar; the natures of the compact objects are currently unknown for the remaining sources.

The multiwavelength emission from these sources can be explained by synchrotron and inverse Compton (IC) emission, within the context of various models. Although the particle acceleration mechanisms remain unclear, two different scenarios have been proposed. On the one hand, the microquasar scenario posits the existence of an accretion disc, corona and relativistic jets in the system, with the particle acceleration driven by accretion/ejection processes (Mirabel 2006). On the other hand, the young non-accreting pulsar scenario establishes the existence of a shock between the relativistic wind of the pulsar and the non-relativistic wind of the companion star (Casares et al. 2005). The system is located at 2°775, the periastron $\phi_0 = 45°72\pm4960\pm49\pm1$ (defined as $\phi_0 \equiv 0$. The gamma-ray binary LS I +61 303 (also known as V615 Cas) is a system composed of a young main sequence B0 Ve star and a compact object orbiting it with a period $P_{\text{orb}} = 26.4960 \pm 0.0028$ d (Gregory 2002) and an eccentricity $e = 0.72 \pm 0.15$ (Casares et al. 2005). The system is located at 2°0.2 kpc according to HI measurements (Frail & Hjellming 1991), with coordinates $\alpha_2000 = 2^h 40^m 31.7^s$ and $\delta_2000 = +61^\circ 13' 45.6''$ (Moldon 2012). Assuming the epoch of the first radio observation as the origin of the orbital phase, $JD_0 = 2443366.775$, the periastron passage takes place in the orbital phase range $0.23\rightarrow0.28$ (Casares et al. 2005, Aragona et al. 2009). LS I +61 303 was initially identified as the counterpart of a gamma-ray source detected by COS B (Hermes et al. 1977), and subsequently an X-ray counterpart was also detected (Bignami et al. 1981). X-ray observations with RXTE/ASM revealed an orbital X-ray modulation (Paredes et al. 1997). The system was also coincident with an EGRET source above 100 MeV (Kniffen et al. 1997) and finally it was detected as a TeV emitter by MAGIC (Albert et al. 2006), which was later confirmed by VERITAS (Acciari et al. 2008). An orbital modulation of the TeV emission was also found by MAGIC (Albert et al. 2009). A correlation between the TeV and X-ray emission was revealed using MAGIC and X-ray observations, which together with the observed X-ray/TeV flux ratio, supports leptonic models with synchrotron X-ray emission and IC TeV emission (Anderhub et al. 2009) but see Acciari et al. 2009). Finally, Fermi/LAT reported GeV emission, orbitally modulated and anti-correlated with respect to the X-ray/TeV emission (Abdo et al. 2009).

The 1–10 GHz radio light-curve of LS I +61 303 is also orbitally modulated, showing a clear outburst each orbital cycle that increases the $\approx 50$–300 mJy steady flux density emission up to $\sim 100$–200 mJy. These outbursts are periodic, although changes in their shape and intensity have been reported from cycle to cycle (Paredes, Estalella & Rius 1990; Ray et al. 1997). Strickman et al. (1998) studied the evolution of a single outburst with multifrequency observations in the range 0.33–23 GHz. The outburst is detected at all frequencies, but the flux density peaks first at the highest frequencies, and later at the lower ones. A low-frequency turnover was also suggested to be present in the range 0.3–1.4 GHz (Strickman et al. 1998).

A long-term modulation is also observed at all wavelengths in LS I +61 303, the so-called superorbital modulation, with a period $P_{\text{orb}} = 1667 \pm 8$ d or $\sim 4.6$ yr (Fomalont 2002). This modulation was firstly found at GHz radio frequencies (Paredes et al. 1979, Gregory et al. 1989; Paredes et al. 1990), affecting the amplitude of the non-thermal outbursts and the orbital phases at which the onset and peak of these outbursts take place, drifting from orbital phases of $\sim 0.45$ to $\sim 0.95$ (Gregory 2002). The source exhibits the minimum activity at GHz frequencies during the superorbital phase range of $\phi_0 \approx 0.2$–0.5, whereas the maximum activity takes place at $\phi_0 \approx 0.78$–0.05, assuming the same JD as for the orbital phase. A similar behaviour is also observed in optical photometric and Hz equivalent width observations that trace the thermal emission of the source (Paredes-Fortuny et al. 2015). The origin of the superorbital modulation could be related to periodic changes in the circumstellar disc and the mass-loss rate of the Be star (Zamanov et al. 2013), although other interpretations within the framework of a precessing jet are still discussed (see Massi & Torricelli-Ciamponi 2014 and references therein).

At milliarcsecond scales LS I +61 303 has been observed and resolved several times (Massi et al. 2001, 2004, Dhawan et al. 2006, Albert et al. 2008, Moldón 2012). Dhawan, Mioduszewski & Rubin (2006) showed a changing morphology as a function of the orbital phase, resembling a cometary tail. Albert et al. (2008) observed similar morphological structures at similar orbital phases to those considered in Dhawan et al. (2006). Later on, Moldón (2012) also reported this behaviour: the morphology of LS I +61 303 changes periodically within the orbital phase. These morphological changes have been interpreted as evidence of the pulsar scenario (Dubus 2006, 2013), although other interpretations have also been suggested (see Massi, Ros & Zimmermann 2012 and references therein). It must be noted that radio pulsation searches have also been conducted with unsuccessful results (McSwain et al. 2011, Catellas et al. 2012).

At the lowest frequencies ($\lesssim 1$ GHz), only a few observations have been published up to now. Pandey et al. (2007) conducted two observations of LS I +61 303 at 235 and 610 MHz simultaneously with the Giant Metrewave Radio Telescope (GMRT: Ananthakrishnan 1995). They observed a positive spectral index of $\alpha = 1.3$ (defined as $S_\nu \propto \nu^\alpha$, where $S_\nu$ is the flux density at a frequency $\nu$) in both epochs and reported variability at both frequencies at a 2.5 and 20-$\sigma$ level, respectively. Although Strickman et al. (1998) also observed the source at 330 MHz three times during one outburst, given the large uncertainties of the measured flux densities they could not infer variability at more than the 1-$\sigma$ level. At these low frequencies we should observe the presence of different absorption mechanisms, such as synchrotron self-absorption (SSA), free-free absorption (FFA) or the Razin effect, as found for other gamma-ray binaries (see e.g. Marcote et al. 2013 for the case of LS 5039). In addition, at these low frequencies we should also expect extended emission at about arcsec scales originating from the synchrotron emission from low-energy particles (Bosch-Krammer et al. 2009, Durant et al. 2011).

In this paper we present the first deep and detailed study of the radio emission from LS I +61 303 at low frequencies through GMRT and LOW Frequency ARray (LOFAR: van Haarlem et al. 2013) data to unveil its behaviour along the orbit. We compare the results with contemporaneous high-frequency observations conducted with the Ryle Telescope (RT) and the Owens Valley Radio
The GMRT monitoring covers the observations performed between 2005 November 24 and 2006 February 7, at 235 and 610 MHz, using the same setup as that described above. The remaining observation was performed at 154 MHz on 2008 February 18, with dual circular polarization (LL and RR) and a bandwidth of 16 MHz divided into 128 channels. 3C 48, 3C 147 and 3C 286 were again used as amplitude calibrators, and 3C 119 was the phase calibrator for the three observations.

The GMRT data were calibrated and analysed using standard procedures within aips, although our data, Parseltongue (Intema et al. 2009) have also been used to develop scripts that call aips tasks to easily reduce the whole data set.

We loaded and flagged the raw visibilities in aips, removing telescope off-source times, instrumental problems or radio-frequency interference (RFI). A first calibration using a unique channel, free of RFI, was performed on the data, and after that we bandpass calibrated them. A more accurate flagging process was performed later on and we finally calibrated the full data set in amplitude and phase, taking into account the previous bandpass calibration. The target source was imaged and self-calibrated several times to correct for phase and amplitude errors that were not properly corrected during the previous calibration, using a Briggs robust weighting of zero in the cleaning process (Briggs 1995). As the GMRT field of view at these low frequencies covers a few degrees (between -5 and 1.5° at 154 and 610 MHz, respectively), we needed to consider the full uv-space during the imaging process (Thompson 1999) and correct the final images for the primary beam attenuation. The GMRT observation performed on 2005 November 28 could not be properly calibrated and hence could not provide results, leading to a total of 24 flux density measurements. In the observations performed on 2005 December 30, 2006 January 19 and 21, the 235 MHz data could not be properly calibrated: the runs were relatively short and a large amount of data had to be flagged, thus providing clean images that were not good enough to self-calibrate the data, preventing the collection of reliable flux densities.

After this data reduction process, we also performed a correction of the system temperature, $T_{sys}$, for each antenna to subtract the contribution of the Galactic diffuse emission, relevant at low frequencies (see a detailed explanation in the appendix of Marcote et al. 2015). The obtained $T_{sys}$ corrections were directly applied to the flux densities of the final target images. We note that these corrections imply an additional source of uncertainty that does not affect the relative flux density variations from one epoch to another at a given frequency. The uncertainties introduced in the flux densities are close to the typical rms values obtained at 235 and 610 MHz, but at 154 MHz the uncertainties increased from ≈5% to ≈20%.

The measurement of the flux densities in each image was done using the twstat and jmfit tasks of aips, both of them providing consistent values in all cases. We determined the root-mean-square uncertainties, $\delta F$, as $\delta F = \delta_{\text{rms}}$ in Table 1. The uncertainties are based on the variation in the measurements from one epoch to another.

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1 The NRAO Astronomical Image Processing System, aips, is maintained by the National Radio Astronomy Observatory (NRAO). http://www.aips.nrao.edu

2 http://www.cv.nrao.edu/~bcotton/Obit.html

3 http://www.jive.nl/jivewiki/doku.php?id=parseltongue

4 http://safe.nrao.edu/wiki/bin/view/Main/HuibIntemaSpam

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square (rms) noise of the images using tvstat in a region around the source without including it nor any background source.

To guarantee the reliability of the measured flux densities we monitored the flux density values of four background sources detected in the field of view of LS I +61 303. The lack of a similar trend in all sources allows us to be confident that the variability described below is intrinsically related to LS I +61 303 and not due to calibration issues.

2.2 LOFAR observations

We have also analysed several LOFAR observations conducted with the High Band Antennas (HBAs). First, we conducted a deep 6-h LOFAR observation at 140 MHz during its commissioning stage on 2011 September 30 to test the system and estimate the expected behaviour of LS I +61 303 at these low frequencies. This observation was performed using 23 core stations plus 9 remote stations, with a total bandwidth of 48 MHz divided in 244 subbands. These data show a large rms noise level, with possible large uncertainties in the absolute flux density scale related to the calibration process. Hence we will not use these in this work (see preliminary results of this observation in Marcote et al. 2012).

In 2013, we conducted five 3-hr LOFAR observations at around 150 MHz within the Radio Sky Monitor (RSM), which observes regularly several variable or transient radio sources (Fender et al. 2007). The target source was always centred on transit, using 23 core stations plus 13 remote stations. In four of these observations we observed the source at 149 MHz with a total bandwidth of ∼0.8 MHz divided into 4 subbands. 3C 48 or 3C 147 were used as amplitude calibrators, observed in runs of 2 min interleaved in 11-min on-source runs. The observation on 2013 January 17 was conducted with a different setup: 20-min on-source runs centred at 142 MHz and divided into 12 subbands, with a total bandwidth of 2.4 MHz.

The LOFAR data were calibrated using standard procedures within the LOFAR Imaging Tools (LOFT, version 2.5.2, see Heal et al. 2010 and van Haarlem et al. 2013 for a detailed explanation). The data were initially flagged using standard settings of the aoflagger (Offringa, van de Gronde & Roerdink 2012), and averaged in time and frequency with the LOFAR New Default Pre-Processing Pipeline (lofpipe) with an integration time of 10 s and 4
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Figure 2. **Left:** field of LS I +61 303 observed with LOFAR at 149 MHz on 2013 July 14 without performing any cut in the $uv$-distance. The synthesized beam, shown in the lower left corner, is $23 \times 15$ arcsec$^2$ with a PA of $64^\circ$, and the rms is $8$ mJy beam$^{-1}$ around the target source position. The positions of the sources present displacements of about half a synthesized beam, on average, with respect to the previously-recorded ones (see text). The location of LS I +61 303 is marked with the white cross. The source is masked by extended emission from the Heart Nebula in this image.

**Right:** zoom around the position of LS I +61 303 in the 154-MHz GMRT observation (top) and in the 2013 March 24 149-MHz LOFAR observation applying the final cut at baselines below $0.2 \, \mathrm{k}\lambda$ (bottom). The source is clearly detected in both images. The synthesized beams, shown on the bottom left corner, are $27 \times 12$ arcsec$^2$ with a PA = $80^\circ$, and $27 \times 15$ arcsec$^2$ with a PA = $49^\circ$, and the rms values are $11$ and $6$ mJy beam$^{-1}$, respectively. Contours start at $5$-$\sigma$ noise level and increase by factors of $2^{1/2}$. In the GMRT image (top), we have applied a shift of 25 arcsec to recover the proper astrometric positions. No shift is required in the LOFAR image (bottom).

channels per subband. In general, very bright sources did not need to be demixed from the target data sets, as they did not contribute significantly to the visibilities.

The calibration was performed on each subband individually with the BlackBoard Selfcal (ms) package using standard settings, and the solutions were transferred to the target field. We used an initial sky model for the field of LS I +61 303 based on the VLA Low-Frequency Sky Survey (VLSS, [Cohen et al. 2007]). A manual flagging was performed using the casaviewer and casaplotms tasks from [casa](http://casa.nrao.edu) and the imaging process was conducted with a development version of awimager ([Tasse et al. 2013]). The resulting model was used in a later phase self-calibration, and we imaged the data again. The last two tasks were performed recursively between 2 and 5 times until the solutions converged. Due to the bright extended emission that is detected in the field of LS I +61 303 (located in the region of the Heart Nebula, see Fig. 2), we only kept baselines larger than $0.2 \, \mathrm{k}\lambda$ (or 400 m) in subsequent analyses. Although the maximum baseline in the recorded data was $\sim 85 \, \mathrm{k}\lambda$ (or 170 km), the baselines $\gtrsim 8 \, \mathrm{k}\lambda$ (17 km) were removed during the data reduction (either during the manual flagging or during the self-calibration process). We used a Briggs robust weighting of zero again, because it produced the lowest noise level in the final images, and a pixel size of 10 arcsec.

We used the imstat and imfit tasks from [casa](http://casa.nrao.edu) (both equivalent to the tvstat and jmfit tasks from [aips](http://www.aips.nrao.edu)) to measure the LS I +61 303 flux densities and the rms of the images. To guarantee the reliability of the measured flux densities in the LOFAR images, we monitored the same four background sources chosen in the GMRT images. The lack of a similar trend in all sources, exhibiting consistent values with the ones inferred from the GMRT images, allows us again to be confident about the absence of flux calibration issues above the noise level in the LOFAR data.

We note that given the large field of view of these low-frequency images (either from the GMRT data or from the LOFAR ones), we detect differences in the ionospheric refractive effects for different regions across the field of view. These effects, in combination with the self-calibration cycles performed during the reduction process, produce slight displacements of the sources from their original positions. In general, it is common to end up with differ-
2.3 Complementary 15-GHz observations

Two complementary observing campaigns that were conducted at the same epochs as the GMRT monitoring and the LOFAR observations have also been included in this work.

The Ryle Telescope (Pooley & Fender 1997) has observed LS I +61 303 at 15 GHz over many years, with contemporaneous observations during the epoch at which the 2005–2006 GMRT monitoring was performed. The observations are centred at 15.2 GHz, recording Stokes I + Q and a bandwidth of 350 MHz. The four mobile and one fixed antennas were arranged in a compact configuration, with a maximum baseline of 100 m.

The observing technique is similar to that described in Pooley & Fender (1997). Given that we used baselines up to 100 m, we obtained a resolution in mapping mode of about 30 arcsec. The observations included regular visits to a phase calibrator (we used J0228+6721) to allow corrections for slow drifts of instrumental phase; the flux-density scale was established by nearby observations of 3C 48, 3C 147 or 3C 286.

Observations of LS I +61 303 were also conducted with the OVRO 40-m dish covering the epoch of the 2013 LOFAR observations. These data are part of a long-term monitoring that has been presented in Massi, Jaron & Hovatta (2015). The data were reduced by these authors following the procedures described in Richards et al. (2011).

3 RESULTS

LS I +61 303 appears as a point-like source in all the images. The resulting synthesized beams for the GMRT data range from 30 × 14 arcsec$^2$ to 15 × 5.4 arcsec$^2$, from 154 to 610 MHz, respectively. The synthesized beam for the LOFAR data is about 20 × 15 arcsec$^2$. The left panel of Fig. 2 shows the field of LS I +61 303 obtained from the LOFAR observation conducted on 2013 July 14 without applying any uv-cut during the imaging process. The zoomed images (Fig. 2 right) show the source as seen from the 154-MHz GMRT observation and from one of the LOFAR runs that we have analyzed in this work. The flux density values of all the GMRT and LOFAR observations are shown in Table 1. In this section we discuss the light-curves obtained from the 235/610-MHz GMRT monitoring and from the 150-MHz LOFAR observations, including the 154-MHz GMRT data.

3.1 Light-curves at 235 and 610 MHz

The dual 235/610-MHz mode in the GMRT observations allows us to observe the state of LS I+61 303 and its evolution simultaneously at these two frequencies. Fig. 3 shows the flux densities of all the analysed GMRT observations (the GMRT monitoring at 235 and 610 MHz and the three isolated GMRT observations) as a function of the Modified Julian Date (MJD, bottom axis) and the superorbital phase ($\phi_{so}$, top axis). We observe that the flux densities obtained in the GMRT monitoring at 610 MHz (conducted at $\phi_{so} \approx 0.2$, around the minimum activity of LS I +61 303 at GHz frequencies) are significantly lower than the ones obtained in the other two observations (conducted at $\phi_{so} \approx 0.8$–0.0, during the maximum activity). We also observe this effect at 235 MHz with respect to the observation at $\phi_{so} \approx 0.8$ (but not at $\phi_{so} \approx 0.0$). This indicates the existence of the superorbital variability at frequencies below 1 GHz.

Fig. 4 focuses on the GMRT monitoring, showing the 610 and 235-MHz light-curve of LS I +61 303 along three consecutive orbital cycles. The 610-MHz data exhibit variability with maxima roughly coincident with the outbursts observed in the 15-GHz RT data (e.g. see MJD \~{} 53720). However, at 610 MHz we observe that the decay of the emission is slower (e.g. compare the decays in MJD 53695–53705, 53720–53725). The average flux density during the whole monitoring is 70 mJy, with a standard deviation of 20 mJy and a significant variability. For these variability analyses...
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3.2 Light-curve at \( \approx 150 \text{ MHz} \)

Several data sets at a frequency around 150 MHz have been analyzed: one GMRT observation at 154-MHz, one LOFAR observation at 142 MHz and four LOFAR observations at 149 MHz. In the following, we will refer to all these observations generically as 150-MHz observations. We note that the differences between these frequencies would not imply any significant change in the flux density values of LS I +61 303 for reasonable spectral indices.

The 150-MHz GMRT data (obtained at a superorbital phase of \( \phi_{\text{orb}} \approx 0.69 \)) reveal for the first time a detection of LS I +61 303 at this frequency\(^7\) being a point-like source with a flux density of 52 \( \pm 11 \) mJy.

The 150-MHz LOFAR observations taken within the RSM in 2013 \( (\phi_{\text{orb}} \approx 0.76–0.87) \) allow us to obtain a light-curve of the source on week timescales (spread along 7 orbital cycles). These results are shown in Fig. 5. With these data we clearly detect variability and a strong increase in the flux density of at least a factor 3 in only 14 d between MJD 56361 and 56375 (approximately half of the orbital period). Folding these data with the orbital period, and adding the GMRT data at approximately the same frequency, we obtain the light-curve shown in Fig. 6. We note that all these observations were conducted at similar superorbital phases. We observe a kind of baseline state with flux densities around 30 mJy on top of which there is a stronger emission between \( \phi_{\text{orb}} \approx 0.7–1.0 \)

\( \phi_{\text{orb}} \approx \frac{150 \text{ MHz}}{142 \text{ MHz}} \), being a point-like source with a flux density of 52 \( \pm 11 \) mJy.

\(^7\) We note that LS I +61 303 was inadvertently detected at \( \approx 150 \text{ MHz} \) in a study of the Galactic emission made by Bernardi et al. (2009) with the Westerbork Synthesis Radio Telescope. The source is marginally detected in the Figs. 2 and 3 of Bernardi et al. (2009), close to the edge of the primary beam. At these positions the flux density measurements are much less reliable, and thus we will not discuss these data here. We also note that the positions of the sources in the mentioned figures present a general displacement of about 5 arcmin to the East direction with respect to the real positions.
Figure 7. Folded light-curve with the orbital period from the data shown in Fig. 5 plus the 150-MHz GMRT observation (orange diamonds). The flux density is orbitally modulated, exhibiting an enhanced emission at φ_{orb} ≈ 0.7–1.0. Despite the poor sampling, this maximum emission appears to be delayed ~0.3 orbital phases with respect to the one detected in the contemporaneous OVRO data.

4 DISCUSSION

We have presented here data of the gamma-ray binary LS I +61 303 at low radio frequencies, from 150 to 610 MHz. This is the first time that a gamma-ray binary is detected at 150 MHz, although previous searches have been performed in other sources (see Marcote et al. [2015] for the case of LS 5039). A multifrequency monitoring conducted with the GMRT in 2005–2006 (at a superorbital phase of φ_{orb} ≈ 0.2) shows significant variability at 610 MHz with the maximum emission at orbital phases of φ_{orb} ≈ 0.8–1.1. This variability is roughly coincident with the outbursts observed at 15 GHz, but with a significantly wider shape, a delay of about 0.2 orbital phases, and a slower decay. However, at 235 MHz we show that the maximum emission of the source occurs in the range between φ_{orb} ≈ 0.3 and ≈ 0.7. The light-curve is thus almost anti-correlated with respect to the 610-MHz one. The LOFAR observations were conducted, in contrast, at a superorbital phase of φ_{orb} ≈ 0.8. In this case we observe a behaviour similar to the one observed at 610 MHz: a large variability with the maximum emission taking place at orbital phases between 0.7 and 1.0.

In this section we discuss the observed behaviour at 150, 235, and 610 MHz and its relationship with the superorbital modulation. It must be noted that the compact VLBI radio emission detected at GHz frequencies represents ≥90% of the total flux density of LS I +61 303, leaving small room for extended radio emission (Paredes et al. 1998). For that reason, and also because of the limited number of frequencies with available light-curves (and the use of data from different orbital cycles), we assume a one-zone model with an homogeneous emitting region. We consider here the two most probable absorption mechanisms: free-free and synchrotron self-absorption (there are not enough data to consider the Razin effect such as in Marcote et al. [2015]). We infer the physical changes required in the system to explain the observed delay between the orbital phases at which the maximum emission takes place at different frequencies.

From Fig. 3 we observe that the superorbital phase still has an important role at these low frequencies, as we detect a much larger flux density at high φ_{orb} than at low ones. Given that we have two isolated observations at high superorbital phases, we cannot determine what was the state of the source during these observations (maximum of the orbital variability, minimum or in between). Therefore, we can not accurately estimate the increase of the emission as a function of the superorbital phase.

A correlation between changes in the thermal emission of the circumstellar disc, observed from optical photometry and Hz observations, and the superorbital modulation of the non-thermal emission has been reported (Paredes-Fortuny et al. 2013 and references therein). A larger amount of material in the disc (higher values of Hz equivalent width) is observed at superorbital phases coincident with the maximum emission at GHz frequencies (φ_{orb} ~ 0.8–0.0). This larger amount of material in the disc might imply more target material for a shock with the putative pulsar wind. This could potentially lead to a more efficient particle acceleration and stronger emission, but also to a larger absorption at low radio frequencies. The presence of stronger radio emission and a clear variability at 150 MHz at these superorbital phases indicates that the emission increase, probably produced as a result of the more efficient particle acceleration, seems to dominate over the decrease due to enhanced absorption at these low radio frequencies.

The positive spectral indices obtained from the GMRT monitoring (Fig. 5 bottom) confirm the suggestion of a turnover between 0.3 and 1.4 GHz made by Strickman et al. (1998), and we constrain it to be in the 0.6–1.4 GHz range. Assuming that the spectrum at low frequencies is dominated by FFA we can estimate the radius of the emitting region with the condition that the free-free opacity is

\[ \tau_{ff} \approx 30 M_{\odot}^{-2} \gamma_{\nu_{\text{max}}}^{-2} r_{Au}^{-3} W_{W,4}^{-2} r_{W,4}^{-3/2} = 1, \]

where \( M_{\gamma} \) is the mass-loss rate of the companion star in units of \( 10^{-7} M_{\odot} \text{yr}^{-1} \), \( \gamma_{\nu_{\text{max}}} \) is the frequency at which the maximum emission takes place (or turnover frequency), in GHz units, \( r_{Au} \) is the radius in the spherically symmetric case, measured in AU, \( W_{W,4} \) is the velocity of the stellar wind, in units of \( 2 \times 10^6 \text{ cm s}^{-1} \), and \( T_{W,4} \) is the wind temperature, in units of 10^4 K (Kubiak & Lightman 1979). Assuming a luminosity of \( L \approx 4.65 \times 10^6 L_{\odot} \) typical from B0 V stars, we derive a mass-loss rate of \( M_{\gamma} \approx 0.5 \) (Howarth & Prinja 1989), for which we will assume reasonable values in the range of \( M_{\gamma} \approx 0.2–1 \). Considering the effective temperature of \( T_{eff} \approx 28 \text{,}000 \text{ K} \), also expected for this type of star (Costamante 2000), we deduce a wind velocity of \( 1 \,500 \pm 500 \text{ km} \text{ s}^{-1} \) (or \( W_{W,4} \approx 0.75 \) (Kudritzki & Puls 2000). We also expect a wind temperature of \( \approx 10 \text{,}000 \text{ K} \) at a distance of the order of the apastron (Krticka & Kubala 2001), and a turnover frequency \( \nu_{\text{max}} \approx 1 \) (as mentioned before). With these values we estimate a radius for the spherically emitting region of 2.4–1.1 AU.

We can compare this result with the displacements of the peak positions obtained with VLBA observations along one orbital cycle by Dhawan et al. (2006). From their Fig. 4 we observe displace-
ments as large as ~2.5 and ~2 mas (~5 and ~4 AU) at 2.2 and 8.4 GHz, respectively, which in our spherically symmetric model imply radii of ~2.5 and ~2 AU. Although we are using a spherical model, we note that the radius that we have derived is clearly compatible with these values, as expected considering that the emission has to be produced far away enough from the massive star to avoid being in the optically thick part of the spectrum due to free-free absorption.

On the other hand, we can consider that the emitting region is expanding, and thus the turnover frequency evolves along the time. In this case we consider that the transition from an optically-thick to an optically-thin region would produce the delay between the different maxima observed at 235 and 610 MHz, as previously reported for other binary systems (Ishwara-Chandra et al. 2002).

From equation (1) we can determine the radius of the emitting region when the turnover is located at a frequency $v$:

$$\ell_c = 30^{1/3} M_T^{2/3} v_{W,8.3}^{-2/3} T_{W,4}^{-1/2} \nu^{-2/3}. \quad (2)$$

With this relation we can infer the velocity of the expanding emitting region, or expansion velocity, assuming it to be constant for simplicity:

$$v = \frac{\Delta \ell}{\Delta t} = \frac{\ell_2 - \ell_1}{\Delta \phi P_{orb}}, \quad (3)$$

where $\Delta \phi$ is the shift in orbital phase for the maximum at a frequency $\nu_2$ and $\nu_1$, and $P_{orb}$ is the orbital period. We can consider for simplicity the case that $M_T$, $v_{W,8.3}$, and $T_{W,4}$ remain constant during this expansion. Figs. 2 and 3 show that the peak of the emission at 610 MHz is located somewhere between $\phi_{orb}$ ~ 0.8 and 1.1. In parallel, we observe that the flux density at 235 MHz remains increasing at $\phi_{orb}$ ~ 0.4, and in the range of 0.6–0.7 the flux density is already decreasing. Therefore, the maximum emission probably takes place in the range of 0.3–0.7. These values imply that the maximum emission exhibits a shift of ~0.2–0.9 in orbital phase between the two frequencies. Although the uncertainty in this shift is large, we can assume a shift of ~0.5 to provide a rough estimation of the expansion velocity for the radio emitting region. Assuming this value and with all the previously mentioned data, we infer that the emitting region should expand by a factor of 2.0 ± 0.5 during this delay of ~0.5 in orbital phase (~13 d) from 610 to 235 MHz, implying a constant expansion velocity of $v_{\text{FFA}} = 400 \pm 300$ km s$^{-1}$. If we also consider the shifts in orbital phase with respect to the maximum at 15 GHz, we can deduce, from equations (2) and (3), the expected delay in orbital phase as a function of the velocity, $v_{\text{FFA}}$, and the frequency, $\nu$:

$$\Delta \phi_{\text{FFA}} = \frac{30^{1/3} M_T^{2/3} v_{W,8.3}^{-2/3} T_{W,4}^{-1/2} \nu^{-2/3}}{v_{\text{FFA}} P_{orb}} (\nu)^{-2/3} - 15^{-2/3}. \quad (4)$$

Fig. 5 shows the velocity curves derived from this equation, where a fit to the considered shifts at 235 and 610 MHz with respect to 15 GHz produces a constant velocity of $v_{\text{FFA}} = 600 \pm 200$ km s$^{-1}$. This velocity is a factor of 2–3 smaller than the one of the stellar wind. However, the derived velocity depends strongly on the assumed mass-loss rate, which is unconstrained from the observational point of view. Fig. 9 shows the derived expansion velocity of the emitting region for different values of the mass-loss rate (in Fig. 8 we assumed $M_T = 0.5$). We note that for mass-loss rates of $M_T \approx 1$ (which is still possible) the derived velocities overlap with the range of possible stellar wind velocities. In any case, these velocities are much lower than the relativistic velocity of the putative pulsar wind (see discussion in Bogovalov et al. 2012).

Dhawan et al. (2006) estimated the outflow velocity along the orbit at 2.2 and 8.4 GHz, obtaining maximum values of ~7500 km s$^{-1}$ near periastron and ~1000 km s$^{-1}$ near apastron. Therefore, the expansion velocities derived here are also close to the one derived by these authors near apastron.

If instead of FFA we consider SSA as the dominant absorption process at low frequencies, we can estimate the properties of the emitting region in the optically thick to optically thin transition. In this case, the SSA opacity is

$$t_{\text{SSA}} = 3.354 \times 10^{-11} (3.54 \times 10^{19}p K B_{p+2/3}^2 b(p) \nu_{\text{GHz}}^{p+4/3}/c) \phi_{\text{AU}} = 1, \quad (5)$$

where $K$ is the normalization of the accelerated particles, $B$ is the magnetic field, and $b(p)$ is a function that only depends on $p$
1 − 2α [Longair 2011]. Assuming \( p = 2 \) (i.e. \( α \sim −0.5 \)) in the optically thin region, similar to the average spectral index observed in LS I +61 303 above \( 2 \) GHz we would expect that the quantity \( K B^2 \ell \) decreases a factor of \( ~18 \) during the delay of \( 0.5 \) in orbital phase between the maximum emission at 235 and 610 MHz. These three quantities \((K, B, \ell)\) are coupled in the equation above and thus we can not estimate them separately. All of them would a-priori change along the orbit, but since we assume an expanding region from the same population of accelerated particles, \( K \) should remain constant (provided that losses are not significant). Additionally, one can consider different dependences of \( B \) as a function of \( ℓ \): \( B \sim ℓ^{-2} \) (as in a spherical expansion) or \( B \sim ℓ^{-1} \) (as in a conical or toroidal expansion, as it happens either in a relativistic jet from the microquasar scenario or in a cometary tail from the young non-accreting pulsar scenario). With these considerations we expect an expansion factor of \( ~2.6 \) (if \( B \sim ℓ^{-2} \)) or \( ~18 \) (if \( B \sim ℓ^{-1} \)). To derive the expansion velocity of the emitting region, we can assume the radius of \( ℓ = 2.4^{+1.7}_{−1.1} \) AU that we have obtained at 1 GHz in the FFA case, which is also compatible with the results from [Dhawan et al. 2006]. With these assumptions, and the equations (5) and (6), we obtain the shifts in orbital phase between the maximum at a frequency \( ν \) and at 15 GHz:

\[
\Delta φ_{\text{SSA}} = \frac{ν_{\text{GHz}}^2}{v_{\text{SSA}}P_{\text{orb}}3.354 \times 10^{-11}(3.54 \times 10^{15})^2 KB^2ℓ(2)}
\]

Fig. 10 shows the derived velocity curves as a function of the frequency and the orbital phase shift for the SSA case. In the case of \( B \sim ℓ^{-2} \) we can fit the data with a constant velocity of \( v_{\text{SSA}} = 1~000^{+400}_{−200} \) km s\(^{-1} \), where the uncertainties result from the propagation of the uncertainties in \( ℓ \) at 1 GHz. The fitted velocity is also compatible with the one of the stellar wind. In the case of \( B \sim ℓ^{-1} \) we obtain velocity curves that can not reproduce the considered phase delay between frequencies. A constant velocity of \( 17~000^{+12000}_{−3000} \) km s\(^{-1} \) produces the best fit to the data, although with a reduced \( χ^2 \) of 2.6. In any case, these velocities are significantly faster than the stellar wind velocity, but clearly slower than the relativistic velocity of the putative pulsar wind. In conclusion, a dependence of \( B \sim ℓ^{-2} \) is more plausible in the considered model where SSA dominates. This would suggest a different geometry than the one expected in the considered scenarios, but compatible with our initial assumption of a simple spherically symmetric emitting region. We note that if energy losses were considered, the derived expansion velocities would be even lower than the ones discussed.

Extrapolating these results to 150 MHz, we infer an orbital phase delay of about 0.9 (assuming FFA) or \( ~1.0 \) (assuming SSA). However, these results cannot be directly compared with the obtained light-curves at 150 MHz. These data were taken at different superorbital phases (\( φ_0 \sim 0.9 \) instead of \( ~0.2 \)), and we observe a larger flux density emission and a larger variability at these 150 MHz data than the ones expected from an extrapolation of the 235 and 610-MHz light-curves. This implies, as mentioned before, that the superorbital phase still plays a significant role at low frequencies. In any case, the shift at 150 MHz with respect to the 15-GHz data is not well constrained and it could be between \( ~0.0 \) and \( ~0.5 \) orbital phases, with the possibility of observing a full cycle shift (and thus between 1.0 and 1.5). We note that these values are roughly compatible with the ones derived from the 235 and 610-MHz data assuming a one-cycle delay. However, we cannot discard the possibility of being observing a delay of only \( ~0.0−0.5 \) orbital phases, as we would expect less absorption at these high superorbital phases, which would also explain why we see a large orbital variability.

5 CONCLUSIONS

We have detected for first time a gamma-ray binary, LS I +61 303, at a frequency as low as 150 MHz. This detection establishes the starting point to explore the behaviour of gamma-ray binaries in the low frequency radio band, which will allow us to unveil the absorption processes that can occur in their radio spectra or light-curves. Additionally, we have obtained light-curves of LS I +61 303 at 150, 235 and 610 MHz, observing orbital and superorbital variability in all cases. In the folded light-curve with the orbital period we observe quasi-sinusoidal modulations with the maxima at different orbital phases as a function of the frequency. The observed delays between frequencies seem to be also modulated by the superorbital phase. The flux density values are also modulated by the superorbital phase, with the source displaying a stronger emission at \( φ_0 \sim 1 \).

Assuming a simple spherically symmetric model we have obtained a coherent explanation for the delays considered between the maxima as a function of the frequency. Within this model, we observe that either FFA or SSA can explain the delays of the low-frequency emission of LS I +61 303. We have also estimated an expansion velocity for the radio emitting region of \( ~1000 \) km s\(^{-1} \) for both absorption mechanisms, which is close to the stellar wind velocity. The obtained velocity could hardly be obtained if there was a relativistic jet, expected in the microquasar scenario, giving further support to the scenario involving a shock between the relativistic
Radio variability of LS I +61 303

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