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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 analyzing all the archival GMRT data at 150, 235 and 610 MHz and conducting regular LOFAR observations within the Radio Sky Monitor 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 low frequency. We have obtained the light-curves of the source at 150, 235 and 610 MHz, showing orbital and superorbital modulation. A comparison with contemporaneous RT and OVRO 15-GHz observations shows remarkable differences. At 15 GHz we see clear outbursts, whereas at low frequencies we observe variability with wider maxima. The light-curve at 235 MHz seems to be uncorrelated with the one at 610 MHz. 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 subrelativistic expansion velocities which are close to the stellar wind velocity for some of the cases.

1. Introduction

LS I +61 303 is composed of a compact object orbiting a young main sequence B0 Ve star every ≈26.5 d (Gregory 2002). The radio emission of the source above 1 GHz is clearly orbitally modulated, exhibiting an outburst per orbital cycle, although these outbursts exhibit changes from cycle to cycle (Ray et al. 1997). The shape of a single outburst is similar in the range of 1.4–23 GHz (Strickman et al. 1998), but the flux density peaks first at the highest frequencies. A long-term modulation of $1\,667 \pm 8$ d, the so-called superorbital modulation, is also observed in the light-curve of LS I +61 303, affecting not only the amplitude of the emission but also the orbital phases at which the outbursts take place (Gregory 2002).

2. Observations and results

We have performed the first detailed study on the low-frequency ($\lesssim$1 GHz) radio emission of LS I +61 303. We have analyzed the whole archival data from the Giant Metrewave Radio Telescope (GMRT), which include a monitoring at 235 and 610 MHz performed in 2005–2006 and three isolated observations at 235/610 MHz and 150 MHz. We have also conducted observations with the Low Frequency Array (LOFAR) at 150 MHz within the Radio Sky Monitor (RSM). Contemporaneous observations with the Ryle Telescope (RT) and the Owens Valley Radio Observatory (OVRO) at 15 GHz are used as a reference of the behavior of the source.

The data from all the analyzed observations show that the superorbital modulation known at GHz frequencies is still present at the low frequencies (see Marcote et al. 2016, for a detailed review). The left panel in Figure 1 shows the GMRT monitoring and RT data folded with the orbital phase. At 610 MHz we observe a light-curve that is orbitally modulated, with a quasi-sinusoidal shape. The increase of the emission takes place at the same orbital phases than at 15 GHz, but exhibiting a significantly slower decay. Given the differences observed at different orbital cycles, we can only constrain the position of the peak emission to take place between orbital phases $\phi_{\rm orb} \sim 0.8$–1.1, whereas the peak at 15 GHz is clearly located at $\phi_{\rm orb} \approx 0.8$. We observe that the 235 MHz light-curve is not correlated with the 610-MHz or 15-GHz ones. The maximum emission at 235 MHz takes place in the range of $\phi_{\rm orb} \sim 0.3$–0.7.

The source is also detected at 150 MHz with GMRT and LOFAR. Figure 1, right, shows the obtained light-curve at this frequency together with the 15-GHz OVRO data. Despite the poor sampling the light-curve suggests it could be orbitally modulated. Although we cannot clearly constrain the location of the peak emission, there seems to be a delay with respect to the 15-GHz light-curve.

3. Discussion and modeling

We have presented the first detection of a gamma-ray binary at a frequency as low as 150 MHz (searches in other sources have been performed with null results, Marcote et al. 2015), and we have revealed the low-frequency

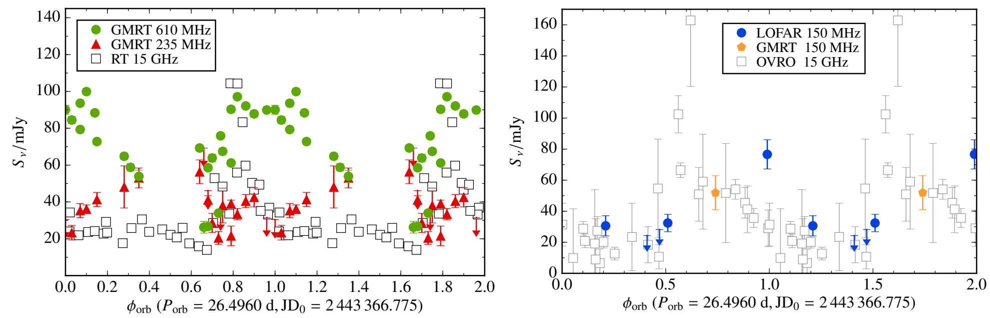

Figure 1. Folded light-curve of LS I +61 303 with the orbital period obtained from the archival GMRT monitoring at 235/610 MHz (*left*) and with GMRT and LOFAR at 150 MHz (*right*). Contemporaneous 15-GHz RT and OVRO data are also shown for comparison. Error bars represent 1-σ uncertainties. Reproduced from Marcote et al. (2016).

variability and provided first evidences of orbital modulation. We report significant differences between the light-curves at 150, 235 and 610 MHz. Whereas the 610-MHz light-curve is roughly coincident with the one observed at 15 GHz and we only observe a slight delay of the peak emission, the 235-MHz light-curve is uncorrelated with respect to that at 610 MHz. More data at low frequencies are essential to determine accurately the variability of the source.

The observed delays between the orbital phases at which the peak emission takes place at different frequencies can be explained by changes in the opacity of the radio emitting region as due to an expansion of this region, producing a shift of the turnover frequency along the orbit. We have considered a one-zone synchrotron emitting region assuming either free-free absorption or synchrotron self-absorption with two different magnetic field dependences. We have obtained in all cases subrelativistic expansion velocities, close to the stellar wind velocity for some of the cases. Although these velocities seem to favor a wind interaction (pulsar) scenario, they could still be explained by the microquasar scenario (see Marcote et al. 2016 for further discussion).

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References

Gregory, P. C., 2002, ApJ, 575, 427

Marcote, B., et al. 2015, MNRAS, 451, 4578

Marcote, B., et al. 2016, MNRAS, 456, 1791

Ray, P. S., et al. 1997, ApJ, 491, 381

Strickman, M. S., et al. 1998, ApJ, 497, 419