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GMRT and LOFAR low frequency observations of the gamma-ray binaries LS 5039 and LS I +61 303

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Abstract. Radio observations of gamma-ray binaries are fundamental to reveal their nature, as well as to understand the physics behind these energetic sources. Only a handful of systems are known and their low frequency emission remains almost unexplored up to now. Here we present the results of GMRT and LOFAR observations of two gamma-ray binaries: LS 5039 and LS I +61 303. For the first one, a turnover in the spectrum is reported for frequencies below 1 GHz. For LS I +61 303 the preliminary data analysis shows that enhanced radio emission around orbital phase $\phi = 0$ is observed at 610 MHz, while emission with only a small variability on secular timescales is detected at 235 MHz.

Keywords : gamma rays: binaries – radio continuum:stars – radiation mechanism: non-thermal

1. Introduction

Gamma-ray binaries are binary star systems which consist of a compact object and a young massive star. The non-thermal spectral energy distribution in these systems is dominated by the

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MeV-GeV photons. All of them display TeV emission (Paredes 2011; Dubus 2013). Only a handful number of gamma-ray binaries have been discovered up to now: PSR B1259–63, LS 5039, LS I +61 303, HESS J0632+057 and 1FGL J1018.6–5856. The first one is the only system which hosts a confirmed pulsar. The nature of the compact object for the rest of the gamma-ray binaries still remains unknown. Further details can be found in the review of Dubus (2013).

The gamma-ray emission of these systems is probably produced by inverse Compton upscattering of stellar UV photons by relativistic electrons. Their synchrotron emission produces the observed radio spectrum. Extended emission at milliarcsecond scales ($\sim$ 1–100 AU) has been reported for nearly all gamma-ray binaries at GHz frequencies (see Moldón 2012 for a complete update). At low radio frequencies (hundreds of MHz) we detect the emission from low-energy electrons, possibly located in a region far away from the binary system (Bosch-Ramon 2009; Durant et al. 2011). Therefore, we expect synchrotron radio emission on scales of 100–1000 AU (arcsec scales) with less variability along the orbit due to the larger dynamical timescales (Dubus 2006). At these low frequencies, absorption mechanisms such as synchrotron self-absorption or free-free absorption are also expected to be present in these systems (Bosch-Ramon 2009).

LS 5039 is a gamma-ray binary with a young O6.5 star and a compact object orbiting it every 3.9 d, with an eccentricity of 0.35 and located at a distance of 2.9 ± 0.8 kpc (Moldón et al. 2012). The radio emission of LS 5039 at GHz frequencies is non-thermal, persistent, and variable (Ribó 2002). No strong outbursts or periodic variability have been detected. Martí et al. (1998) determined that the radio flux of LS 5039 in the range 1–15 GHz is described by $S_\nu[\mathrm{mJy}] = (52 \pm 1)\ \nu[\mathrm{GHz}]^{-0.46\pm0.01}$. The amplitude of the variability is below 25%, calculated with respect to the mean flux value detected. Through VLBI observations, Paredes et al. (2000; 2002) showed an asymmetric bipolar extended emission on both sides of a bright core. Ribó et al. (2008) pointed out that the microquasar scenario could not easily explain the observed changes in the morphology of the source from observations five days part. Finally, Moldón et al. (2012) determined that a binary pulsar scenario, which involves a young non-accreting pulsar with a shock between its wind and the wind of the massive star, is clearly supported by the periodic morphological variability observed at mas scales.

LS I +61 303 is a gamma-ray binary with a B0Ve star and a compact object orbiting it every 26.5 d, with an eccentricity of 0.54 and located at a distance of 1.9 ± 0.1 kpc (Aragona et al. 2009). The radio emission displays periodic radio outbursts on average coincident with its orbital period (Strickman et al. 1998). A binary pulsar scenario has also been proposed to explain the VLBA observations of this system (Dhawan et al. 2006).

2. Observations and results

LS 5039. There were only three published low frequency GMRT observations in Godambe et al. (2008) and Pandey et al. (2007) with contradictory conclusions: the first one reported a cut-off visible below 1 GHz and the second one observed a continuous power-law below this frequency.

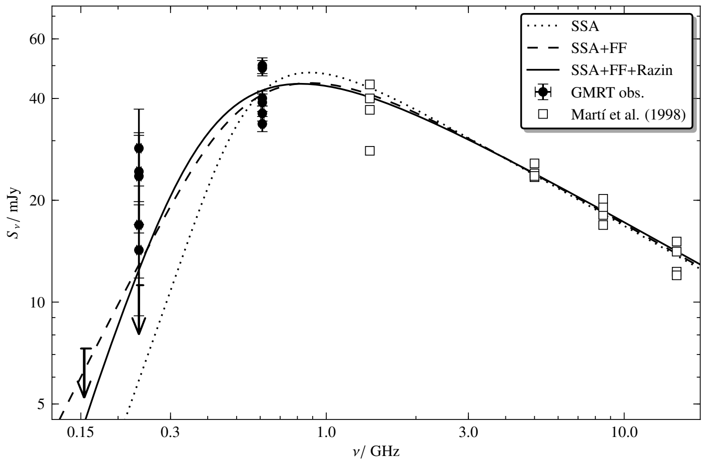

Figure 1. LS 5039 spectrum from 150 MHz to 15 GHz. The white squares are data from VLA observations (Martí et al. 1998). Black circles show the analyzed GMRT data with simultaneous observations at 235 and 610 MHz. The 3-σ upper-limit at 150 MHz comes from a single GMRT observation.

We have reanalyzed them together with the rest of the 7 unpublished GMRT observations. To reduce these data we have taken into account system temperature corrections for the GMRT antennas in order to remove the strong background emission with new data taken with GMRT. In Figure 1 we show these non-simultaneous results together with the VLA observations from Martí et al. (1998). We can clearly see the turnover in the spectrum at frequencies below 1 GHz. The variability along time is clear for the range 235 MHz–15 GHz. We also show for the first time a 3-σ upper-limit for the flux density of LS 5039 at 150 MHz.

In order to get a more reliable spectrum at low and high frequencies, we have conducted quasi-simultaneous observations with GMRT (150, 235 and 610 MHz) and WSRT (1.4, 2.3 and 5 GHz) during July 2013 at two different orbital phases. The preliminary analysis of these data points out the presence of different absorption mechanisms at different orbital phases, which produces different shapes in the spectrum at all the frequencies. A synchrotron self-absorption model reproduces one of the two observations but a component taking into account the Razin effect appears to be required in order to explain the other observation.

LS I +61 303. We have reduced almost all the archival GMRT data at 150, 235 and 610 MHz. The preliminary results from the analysis of the GMRT observations along three consecutive orbital cycles, shown in Figure 2, indicate different behaviours as a function of the frequency. At the higher frequency, 610 MHz, enhanced emission is detected around $\phi = 0$. This quasi-periodic enhanced emission is also reported at GHz frequencies (Strickman et al. 1998), although in this case the peak of the emission lies in the range $\phi = 0.5$–0.8. However, LS I +61 303 displays a different behaviour at 235 MHz: it exhibits a smaller amplitude variability on secular timescales.

The only GMRT observation of LS I +61 303 at 150 MHz shows a detection with a flux density $S_\nu \sim 40$ mJy. This is in agreement with the LOFAR observations conducted during 2013 at 150 MHz. The four preliminary LOFAR results report a variable emission at this frequency, with a 3-σ upper-limit of 30 mJy and three detections with flux densities between 30 and 80 mJy.

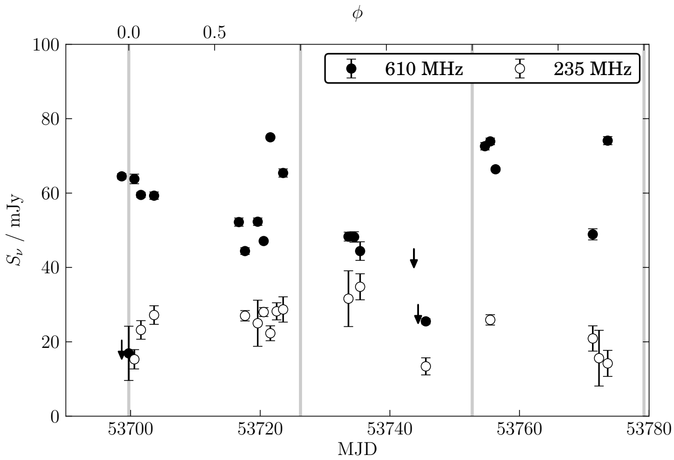

Figure 2. LS I +61 303 emission at 235 and 610 MHz along three consecutive orbital cycles. At 610 MHz enhanced emission is seen around $\phi = 0$, while emission with only a small variability on secular timescales is observed at 235 MHz.

3. Conclusions

The behaviour of LS 5039 and LS I +61 303 changes at very low frequencies, either with absorption mechanisms observed in the spectrum or with a different variability along the orbit.

The exploration of the radio emission of gamma-ray binaries at very low frequencies can therefore provide us additional information about these systems and the nature of this emission. The variability and absorption mechanisms exhibited in these binaries stablish new constraints for the models which explain the origin of this radio emission.

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