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First LOFAR Observations of Gamma-Ray Binaries

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Abstract. A few binary systems display High Energy (100 MeV – 100 GeV) and/or Very High Energy ($\gtrsim$ 100 GeV) gamma-ray emission. These systems also display non-thermal radio emission that can be resolved with long-baseline radio interferometers, revealing the presence of outflows. It is expected that at very low frequencies the synchrotron radio emission covers larger angular scales than has been reported up to now. Here we present preliminary results of the first deep radio observations of the gamma-ray binary LS I +61 303 with LOFAR, which is sensitive to extended structures on arcsecond to arcminute scales.

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

Less than 10 binary systems have been reported as High Energy (HE: 100 MeV – 100 GeV) and/or Very High Energy (VHE: $\gtrsim$ 100 GeV) gamma-ray emitters. All of them consist of a young massive star and a compact object (either neutron star or black hole). Some of these systems are X-ray binaries that accrete matter from their companion stars, and display a non-thermal spectral energy distribution (SED) dominated by the X-ray photons. The two known sources belonging to this class are Cygnus X-3, clearly detected by both *Fermi* [1] and *AGILE* [2], and Cygnus X-1, possibly detected by *AGILE* [3] and MAGIC [4].

There is another family of these systems in which the SED is dominated by the MeV-GeV photons (see [5] and [6]). In analogy with the definition of X-ray binary, we refer to these sources as gamma-ray binaries. Their emission is displayed across all the electromagnetic spectrum, from radio to VHE gamma rays. Up to now, five Galactic gamma-ray binary systems are known: PSR B1259−63, LS 5039, LS I +61 303, HESS J0632+057 and 1FGL J1018.6−5856. Only in the case of PSR B1259−63 the nature of the compact object is known: a young non-accreting pulsar displaying a strong relativistic wind [7]. In the other cases, the nature of the compact object, either black hole or neutron star, is unknown, but up to now there is no evidence of the presence of an accretion disk in these binaries. In this observational context, two competing scenarios have been proposed to explain the broadband emission from gamma-ray binaries: the *microquasar scenario* and the *binary pulsar scenario*. The first one involves an accreting black hole or neutron star with relativistic jets (displayed by many X-ray binaries), and the second one a young non-accreting pulsar with a shock between its wind and the wind (and/or circumstellar envelope) of the massive star.

In both, X-ray and gamma-ray binaries, we detect synchrotron radio emission that has been resolved by interferometers at centimeter wavelengths. For example, Cygnus X-3 has been resolved with the VLA [8] and the VLBA [9], while PSR B1259−63 has been resolved with LBA [10]. In the gamma-ray binaries LS 5039 and LS I +61 303 extended radio emission at mas scales showing periodic morphological variability has been observed [11][12][13][14].

At meter wavelengths we should observe the synchrotron radio emission from the low-energy electrons. In the binary pulsar scenario this emission would be located in a region farther away from the binary system than at higher frequencies. These electrons should remain unaffected either by inverse compton or synchrotron cooling [15]. Therefore, we would expect to see synchrotron radio emission on much larger angular scales than it has been reported up to now, without variability along the orbit [16]. This emission has remained unobserved due to the very poor resolution of the previous radio observatories at these very low frequencies.

LS I +61 303

LS I +61 303 is a gamma-ray binary discovered as a gamma-ray emitter 30 years ago, with periodic radio outbursts coincident with its orbital period of $P = 26.5$ days [17]. Although both the microquasar and the binary pulsar scenario have been proposed for this source, the VLBA observations showing periodic morphological changes [12] are typically interpreted as evidence of the second scenario. In this case we could expect to detect extended radio emission at very low frequencies [15]. We note that evidence of an extended X-ray structure has been reported in this source [18].

From radio observations, LS I +61 303 displays periodic orbital variability in the range of 1 to 10 GHz [17][19]. At lower frequencies, from 260 to ~ 700 MHz, variability on $\sim$ 1-year scales has been reported [20]. If this variability at the lower frequencies follows the orbital period or has larger timescales is unknown.

LOFAR

The Low Frequency Array (LOFAR) is a digital radio interferometer with stations in The Netherlands, France, Germany, Sweden and the United Kingdom which will regularly monitor a large fraction of the northern sky (see [21] for a recent update). LOFAR detects photons in the frequency range 30–240 MHz, which has never been explored by any large-scale interferometer before. Operating in this new frequency window LOFAR promises to revolutionize wide ranging areas of astrophysics. LOFAR has some Key Science Projects (KSPs) defined to drive the design of its operational performance. These KSPs are: Epoch of Reionisation, Deep Extragalactic Surveys, Transient Sources and Pulsars, Ultra High Energy Cosmic Rays, Solar Science and Space Weather, and Cosmic Magnetism. The LOFAR radio telescope consists of many low-cost antennas,

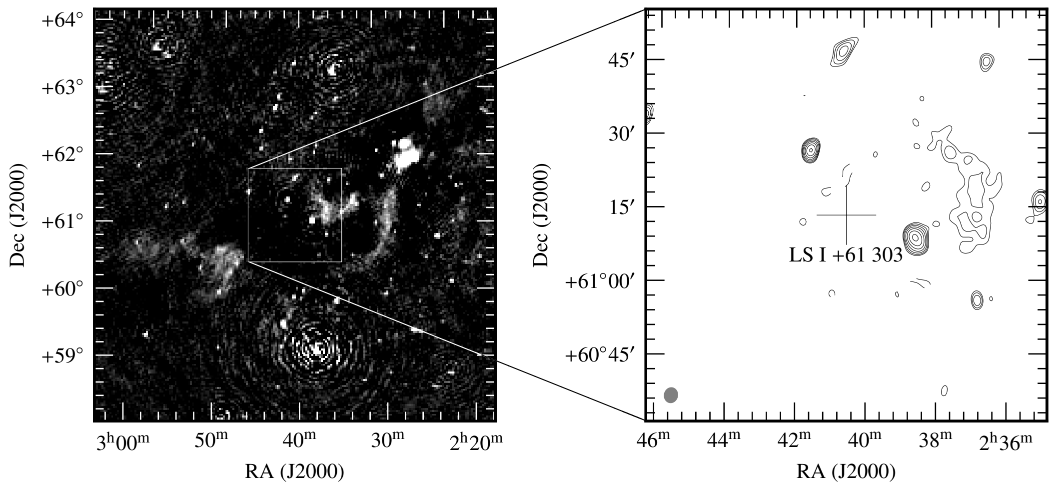

FIGURE 1. Preliminary image of LS I +61 303 from a 6-hour observation with LOFAR at 120–130 MHz. On the **left** we can see a large fraction of the primary beam (6 degrees) and on the **right** we show a 1.4×1.4 degrees zoom around LS I +61 303. The synthesized beam has a size of ~ 2.5 arcmin and is shown in the bottom-left corner of the right image. The *rms* of the image is ≈ 40 mJy beam^{-1} around the LS I +61 303 position and the contours start at 3σ *rms* level.

distributed in 24 core, 18 remote and 8 international stations, with baselines from 100 m to 1 500 km. There are two types of antennas: Low Band Antennas (LBA) observing at 30–80 MHz and the High Band Antennas (HBA), in the range 120–240 MHz. LOFAR started preliminary observations in 2008, and detailed commissioning observations in 2011. In the final configuration, the resolution and sensitivity of LOFAR will reach 0.7 arcsec and 10 mJy beam^{-1} at 60 MHz or 0.2 arcsec and 0.3 mJy beam^{-1} at 240 MHz in one hour of observation.

OBSERVATIONS AND RESULTS

We present the first LOFAR observation of LS I +61 303, made on September 30, 2011 for a 6-hour run with the HBA at 120–180 MHz. For this observation 23 core stations + 9 remote stations were used. The orbital phase of LS I +61 303 during the observation was 0.55 (the periastron takes place at 0.23 [22]). The data were analyzed with the LOFAR Standard Imaging Pipeline and CASA software (NRAO). We have used standard procedures developed by the LOFAR team during the commissioning stage for the calibration, and the CASA routines for the imaging.

Figure 1 shows the resulting image for the integration of the frequency range 120–130 MHz, with *uv*-distances shorter than 100λ removed to avoid the introduction of extended emission from the Galactic plane. The primary beam is ~ 6 degrees. There is no significant excess at the position of LS I +61 303, with a *rms* ≈ 40 mJy beam^{-1} and a resolution of ≈ 2.5 arcmin. Extrapolating the results of [19], we expect a flux density of ≈ 44 mJy at 125 MHz. This is close to the *rms* of our preliminary image. However, in the final image including all subbands we expect to have a *rms* of ~ 10 mJy beam^{-1}, and therefore LS I +61 303 should be detectable above a 3-σ confidence level.

Any extended structure in arcsecond to arcminute scales is not detected in deep VLA observations at 5 GHz with a *rms* $\gtrsim 0.1$ mJy beam^{-1} [23]. However, according to the theoretical models discussed above [15, 16], we could expect emission at scales from arcsec up to arcmin at very low frequencies.

Although a better performance is required to detect LS I +61 303, LOFAR will experience significant improvements during the following years, with the addition of international stations and future software developments. At the end of the commisioning stage, LOFAR will have a much better sensitivity and angular resolution for low-frequency observations. This will allow us to determine if the variability along the orbit seen at higher frequencies in LS I +61 303 is still present or not at low frequencies and if extended emission from gamma-ray binaries is plausible.

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