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The radio morphological variability of LS 5039 and its birth place

Javier Moldón[1], Marc Ribó[1], and Josep M. Paredes[1]

[1] Departament d'Astronomia i Meteorologia, Institut de Ciències del Cosmos (ICC), Universitat de Barcelona (IEEC-UB)

Abstract

LS 5039 is one of the few X-ray binaries detected at VHE, and potentially contains a young non-accreting pulsar. We present VLBA observations of LS 5039 covering an orbital cycle, which show periodic morphological changes, and astrometric variability of the peak of the emission at mas scales. On the other hand, both LS 5039 and the ms pulsar PSR J1826-1446 are close to the supernova remnant SNR G0 16.8-01.1. We present an astrometric project to measure the proper motion of PSR J1826-1446 and LS 5039, and we discuss the possible association of each of these sources with the SNR. The birth place of the compact object in LS 5039 has direct implications on the age of this gamma-ray binary, on the nature of the compact object, and hence on the mechanism that produces the VHE emission.

1 Introduction

LS 5039 is a high mass X-ray binary containing a compact object of unknown mass (1.5–10 $M_\odot$) that orbits an O6.5 V((f)) star every 3.9 days. The system has an eccentric orbit ($e =$ 0.35), and it is located at 2.5 kpc [7, 5]. LS 5039 is one of the few known binaries that displays high-energy (HE) and very high energy (VHE) gamma-ray emission ($E >$ 100 GeV) with a clear orbital modulation [3, 2]. Several theoretical models have been developed to explain the multiwavelength orbital behavior of LS 5039. The HE/VHE emission is basically interpreted as the result of inverse Compton upscattering of stellar UV photons by relativistic electrons. The acceleration of electrons seems to be produced by shocks between the relativistic wind of a young non-accreting pulsar and the wind of the stellar companion [8, 14]. No radio pulses have been detected at 1.4 GHz, although the strong free-free absorption with the stellar wind may prevent any detection of pulsed radio emission. Therefore, the nature of the compact object (black hole or pulsar) is unknown.

The high-mass binaries PSR B1259−63 and LS I+61 303 have also been detected at VHE, and show a broadband spectral energy distribution (SED) similar to the one of

PSR B1259−63/LS 2883, see [8]. Contrary to X-ray binaries, all three sources have the peak of the SED at MeV–GeV energies. For these reasons, they can be considered gamma-ray binaries. However, the nature of the compact objects in LS 5039 and LS I+61 303 is unknown because their masses are not well constrained by the system mass functions [6, 7, 5], and no pulsations have been found. These systems have been extensively observed at VHE during several orbital cycles, while the observations of PSR B1259−63, the only system with a confirmed pulsar, are scarce due to the long orbital period. Any observational link between the three gamma-ray binaries would shed light in the understanding of this kind of systems.

On the other hand, Cygnus X-3 was detected above 100 MeV by the *AGILE* and *Fermi* satellites [15, 1]. The MAGIC collaboration reported evidence of a short flare of 80 minutes from Cygnus X-1 at TeV energies [4], and [13] reported a flare with *AGILE*. However, the nature of these detections, flares not correlated with the orbital phase but probably with the spectral accretion state, seems different from the observed behavior in the gamma-ray binaries.

In all the proposed models the multiwavelength emission depends on the geometry of the region where particles are accelerated, and its location with respect to the observer. In this context, VLBI radio observations can provide a direct view of the small scale morphology of these binaries. At scales of a few AU the radio structure produced by the binaries outflow becomes relevant. LS 5039 is located at 2.5 kpc, and hence the morphology can be studied at scales of 1–10 mas (2.5–25 AU).

2 Radio observations and proper motion

LS 5039 was observed with the VLBA at 5 GHz in 1999. The data showed bipolar extended emission of a few mJy extending over 6 mas on the plane of the sky [10]. In [12] the authors conducted similar observations at two different orbital phases that showed a changing morphology at mas scales: the Position Angle (P.A.) of the direction of the elongated emission changed by $12 \pm 3^\circ$ between both runs, with a remarkable symmetry change. Therefore, morphological changes at 5 GHz occur on timescales of the order of the orbital period.

To further study the morphological variability, we observed the source in 2007 during five consecutive days. The observations were centered at the orbital phases 0.98, 0.23, 0.49, 0.75, and 0.00, each one spanning 6 hours (0.07 in phase), computed using the ephemerides of [5]. The observations were phase-referenced to the phase calibrator J1825−1718, and an astrometric check source was observed regularly during the runs. The self-calibrated images show a main core and extended emission up to ~ 6 mas, as in previous observations. The P.A. of the extended emission from the main core changes significantly every day, covering angles between -50 and -85° for phases in the range 0.5–0.0, and P.A. 120° at phase 0.23. Therefore, a subtle change in morphology happens in less than 20 hours after periastron.

The resolution of the phase-referenced images is limited by the scatter broadening of the calibrator. The astrometric accuracy, extrapolated from the mean dispersion of the astrometric check source, is 0.23 and 0.27 mas in right ascension and declination, respectively [9]. The positions of the peak of the emission for phases 0.5–0.0 are compatible within errors. The

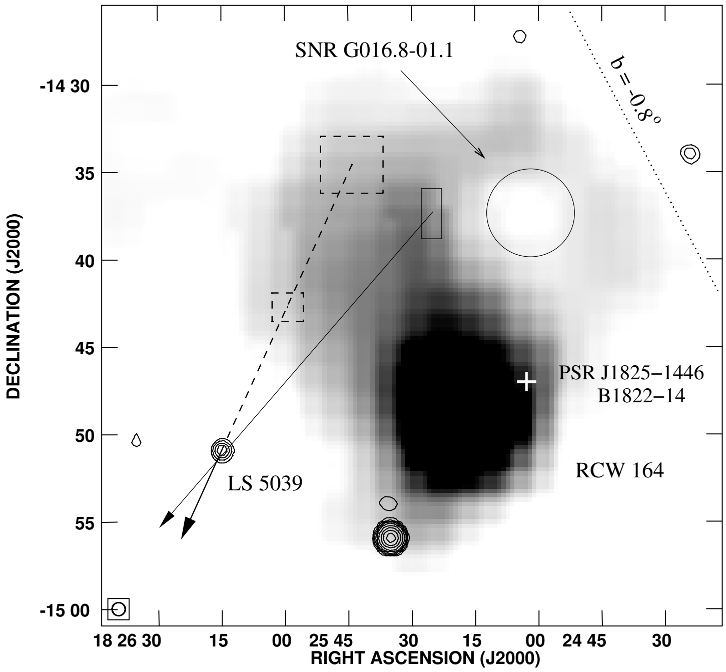

Figure 1: Wide field radio map of LS 5039, showing the position of the nearby SNR G016.8−01.1. The grey scale emission is at the 6 cm wavelength. The overlaid contours correspond to the NVSS map at the 20 cm. The arrows mark the proper motion senses. The dashed line is the computed trajectory reported in [11], whereas the solid line is the computed trajectory from our fit (see text). The error boxes are calculated for 10^5 yr ago.

peak of the emission at phase 0.23 shows a displacement of 2.3 ± 0.3 mas in P.A. 26°, nearly opposite to the extended emission sense. This indicates that the variations of the extended emission with respect to the core are a combination of intrinsic variability of this extended emission and an absolute displacement of the core component.

As a by-product, these phase-referenced observations provide one average precise position of the source in the sky. In [11] the authors computed the trajectory of LS 5039 for the last 10^5 yr using optical/radio astrometry from 1905 to 2002. Their result marginally suggests an association with SNR G016.8−01.1. This new VLBA position, combined with previous radio interferometric measurements spanning 9 years, allow us to calculate a more precise proper motion and past trajectory of the source (see solid line in Fig. 1). The new past trajectory of LS 5039 is compatible with the center of the SNR. With a firm association, a kinematical age of the compact object would be obtained, which would have direct implications on its properties. In case the system contains a pulsar, it would probably be a young pulsar in the non-accreting phase, and therefore, compatible with the shocked winds scenario.

3 Discussion

The emission at 5 GHz traces the short-lived electrons of the outflow up to 15 AU. The morphological changes along the orbit allow us to model the velocity, the energy, and the cooling time-scale of the flow of particles that originates the extended emission. The morphological and astrometric information constrains the inclination of the orbit (i), a key parameter of the system. The mass function of the system and i yield the mass of the compact object. On the other hand, it should be possible to clearly trace the peak position along the orbit with observations at higher frequencies (where the phase calibrator is much more compact), yielding direct information on the absorption around the system.

The VLBA images from 2007 at 5 GHz contain relevant information to test the models [9], but the lack of continous astrometric information following the peak of the emission at all orbital phases is a key point to better constrain the physical properties of the system. If the peak position is expected to be shifted between 1–2 mas, it is not possible to unambiguously distinguish the displacement of the peak from intrinsic variations of the extended emission. The flow velocity and cooling times strongly depend on this ambiguity, which can be disentangled with accurate astrometry, to be obtained in the future.

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