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Hints for a fast precessing relativistic radio jet in LS I +61°303

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Abstract. Here we discuss two consecutive MERLIN observations of the X-ray binary LS I +61°303. The first observation shows a double-sided jet extending up to about 200 AU on both sides of a central source. The jet shows a bent S-shaped structure similar to the one displayed by the well-known precessing jet of SS 433. The precession suggested in the first MERLIN image becomes evident in the second one, showing a one-sided bent jet significantly rotated with respect to the jet of the day before. We conclude that the derived precession of the relativistic ($\beta = 0.6$) jet explains puzzling previous VLBI results. Moreover, the fact that the precession is fast could be the explanation of the never understood short term (days) variability of the associated gamma-ray source 2CG 135+01/3EG J0241+6103.

Key words. stars: individual: LS I +61°303, 2CG 135+01, 3EG J0241+6103 – X-rays: binaries – radio continuum: stars – gamma-rays: observations – gamma-rays: theory

1. Introduction

In 1978 Gregory and Taylor reported the discovery of a highly variable radio source within the 1σ error circle of the γ-ray source 2CG 135+01 (Gregory & Taylor 1978). The radio source turned out to be periodic, with a periodicity of about 26 days and coincident with the stellar binary system LS I +61°303 (Taylor et al. 1980; Hjellming et al. 1978; Gregory 2002).

In 1993 Massi and collaborators showed by a Very Long Baseline Interferometry (VLBI) observation that the radio emission had a structure of milliarcsecond (mas) size corresponding to a few AU at the distance of 2.0 kpc (Massi et al. 1993; Frail & Hjellming 1991). Whereas the evidence of such a structure included LS I +61°303 in the small subclass of X-ray binaries having associated relativistic radio-jets (Fender et al. 1997), systems now generally called microquasars (Mirabel & Rodríguez 1999; Fender 2003), the complex morphology in this and successive VLBI observations made an interpretation in terms of a collimated ejection with a constant position angle difficult (Peracaula et al. 1998; Paredes et al. 1998; Taylor et al. 2000). The turning point came from an image at a larger scale (up to tens of AU) performed with part of the European VLBI Network (EVN). This showed an elongation in a clear direction, interpreted as a one-sided Doppler-boosted jet (Massi et al. 2001). Thus the very confusing structure close to the binary system seemed to be better distinguished at a larger distance from the core. Consequently, we decided to explore LS I +61°303 at even larger scales (up to hundreds of AU) using the Multi-Element Radio-Linked Interferometer Network (MERLIN).

2. Observations and results

We performed the observations of LS I +61°303 with MERLIN at 5 GHz on 2001 April 22 and April 23. The log of the observation is given in Table 1. The total bandwidth was 32 MHz, the sampling was 2-bit and the correlator integration time 8 s. The data were calibrated using the pipeline available at Jodrell

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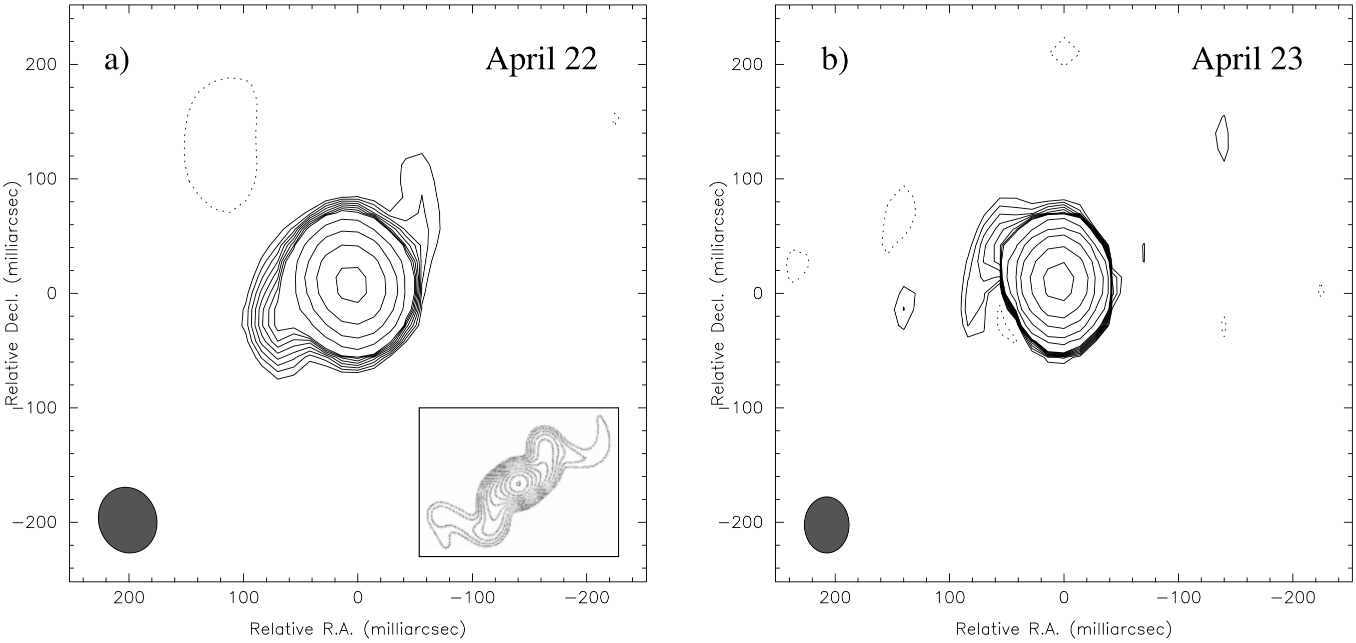

Fig. 1. a) MERLIN self-calibrated image of LS I +61°303 at 5 GHz and using natural weights, obtained on 2001 April 22. North is up and East is to the left. The synthesized beam has a size of 51 × 58 mas, with a PA of 17°. The contour levels are at −3, 3, 4, 5, 6, 7, 8, 9, 10, 20, 40, 80, and 160σ, being $\sigma = 0.14$ mJy beam^{-1}. The S-shaped morphology strongly recalls the precessing jet of SS 433, whose simulated radio emission (Fig. 6b in Hjellming & Johnston 1988, rotated here for comparison purposes) is given in the small box. **b)** Same as before but for the April 23 run and using uniform weights (see text). The synthesized beam has a size of 39 × 49 mas, with a PA of −10°. The contour levels are the same as those used in the April 22 image but up to 320σ, with $\sigma = 0.12$ mJy beam^{-1}.

Table 1. Log of the MERLIN observations. Start and Stop are given in Modified Julian Date (MJD = JD−2 400 000.5). The corresponding orbital phases have been computed using the new ephemerides, t_0 = JD 2 443 366.775 and P = 26.4960 d, from Gregory (2002).

Date	Start MJD	Stop MJD	$\phi_{\rm start}$	$\phi_{\rm stop}$
April 22	52 021.73	52 022.10	0.670	0.684
April 23	52 022.68	52 023.17	0.706	0.724

Table 2. Parameters of the jet components. The distance and PA are relative to the Core, which is not at the phase center in Fig. 1.

Date	Component	Flux (mJy)	Distance (mas)	PA (°)
April 22	Core	28.0	–	–
	South-East	1.8	73	116
	North-West	1.0	75	−48
April 23	Core	51.4	–	–
	North-East	1.1	61	67

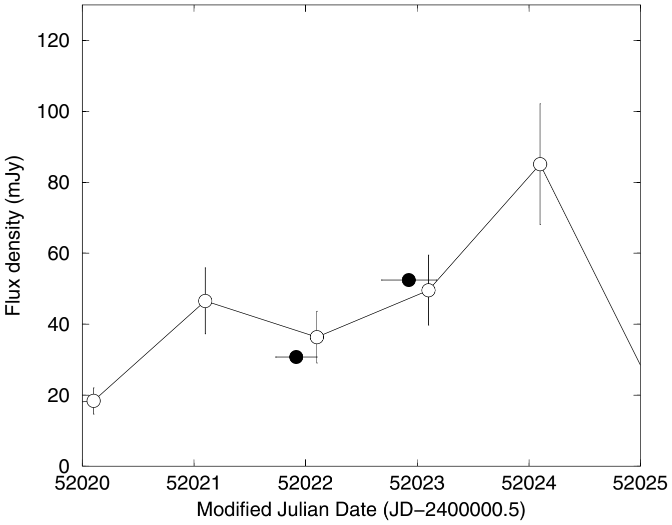

Fig. 2. Lightcurve of LS I +61°303 at 3.9 GHz obtained with RATAN-600 (open circles). Indicative error bars of 20% of the flux density have been plotted. The filled circles represent the MERLIN flux densities of the structures quoted in Table 2, while the horizontal bars extend from the start to the stop of each observing run.

Bank Observatory within the AIPS software package. The image processing was performed with DIFMAP.

The image for April 22, shown in Fig. 1a, has been made with natural weights in order to enhance faint and extended structures. The morphology of the radio emission is a two-sided jet emanating from a central core. The fluxes of the components are given in Table 2. The jet has a total length of ~200 mas (~400 AU at a distance of 2.0 kpc) and the line joining the two lobes has a position angle (PA) of 124 ± 16°. The morphology of the MERLIN image has a bent, S-like structure. We show in the small box in Fig. 1a the simulated radio emission by the Hjellming & Johnston (1988) model of the precessing jet of SS 433 (rotated here for comparison purposes). The similarity between the MERLIN image of LS I +61°303 and the precessing model for SS 433 suggests a precession of the jet.

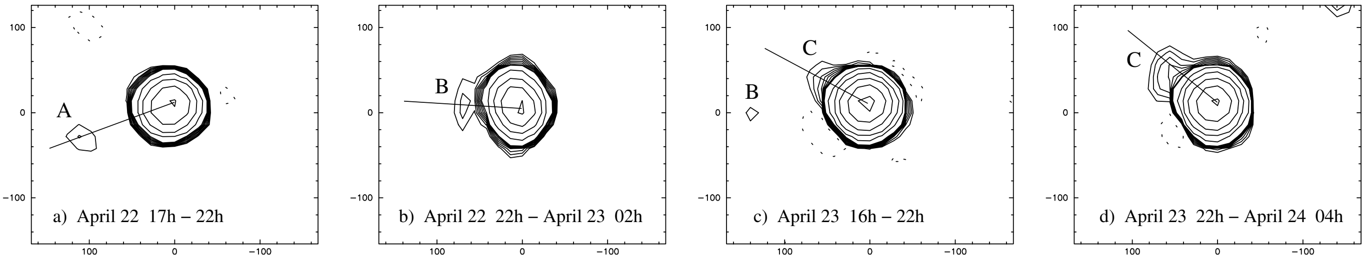

Fig. 3. MERLIN self-calibrated images of LS I +61°303 at 5 GHz using uniform weights, obtained on 2001 April 22 and April 23. The data set of each epoch has been split into two blocks. A convolving beam of 40 mas has been used in all images for better display. The first contour represents the 3σ level in all images except for c), where we start from the 2σ level to display the faint B component. The rms noises are $\sigma = 0.13$ mJy beam^{-1}, $\sigma = 0.20$ mJy beam^{-1}, $\sigma = 0.13$ mJy beam^{-1}, and $\sigma = 0.15$ mJy beam^{-1}, respectively. The PA of the ejections is indicated by a bar (see text).

The precession suggested in the first MERLIN image becomes evident in the second one, shown in Fig. 1b, where a new feature is present oriented to North-East at a position angle (PA) of 67°. The Northwest-Southeast jet of Fig. 1a has a PA = 124°. Therefore a quite large rotation has occurred in only 24 hours. This fast precession causes a deformation of the morphology during the second observation, and the one-sided jet appears bent in Fig. 1b. Only 3σ features can be associated with the double jet of the day before, the feature at 3σ to the East is well compatible with a displacement of $0.6c \times 24$ hours (see discussion on the jet velocity in Sect. 3).

The MERLIN images could be affected to some degree by the variations in the source structure and brightness during the 9 and 12 hour time span of each observation, respectively. We show in Fig. 2 the RATAN-600 data at 3.9 GHz (monitoring program of microquasars by Trushkin et al. 2001), together with our MERLIN flux density measurement at 5 GHz. As can be seen, the April 22 observation was performed during the decaying phase of a small outburst, whereas the second run was performed during the rising phase of a new ejection. While these variations would affect high resolution VLBI observations, at the low MERLIN resolutions (as pointed out by Fender et al. 1999) flux and structural variations would only increase uncertainties in the position of the components (at the level of a few mas) and in their flux density (of a few percent of their peak).

We have split the data of each epoch into two blocks and imaged them separately (Fig. 3). We see that the Eastern bent structure present in Fig. 1a is the result of a combination of an old ejection A (Fig. 3a), already displaced 120 mas from the core, and a new ejection B (Fig. 3b). After 19 hours (Fig. 3c) the feature B is reduced at 2σ and the new ejection C, at a clearly different PA with respect to B, is present. In Fig. 3d, 6 hours later, little rotation of the PA is compatible with $\Delta\ \mathrm{PA}_{(\mathrm{B-C})}/3$ of the previous image.

3. Variable Doppler boosting

Position angle PA and θ, the angle between the jet and the line of sight, may both change as a function of time due to precession. It is θ the angle of physical relevance, because it influences the observed flux density of the approaching (S_{a}) and the receding (S_{r}) jet through the Doppler factor: $\delta_{\mathrm{a,r}} = [\Gamma(1 \mp \beta\cos\theta)]^{-1}$, where $\Gamma = (1-\beta^2)^{-1/2}$ is the Lorentz factor and $\beta\, c$ the jet velocity. The observed flux density of the approaching and receding jets will be boosted and de-boosted respectively as $S_{\mathrm{a,r}} = S\,\delta_{\mathrm{a,r}}^{k-\alpha}$, where α is the spectral index of the emission ($S_\nu \propto \nu^{+\alpha}$) and k is 2 for a continuous jet and 3 for discrete condensations. The resulting ratio, given by $\frac{S_{\mathrm{a}}}{S_{\mathrm{r}}} = \left(\frac{1+\beta\cos\theta}{1-\beta\cos\theta}\right)^{k-\alpha}$, implies that for relativistic jets only for large θ values will the two fluxes be comparable (as seems to be the case in Fig. 1a).

As proved for a case of multiple ejections in GRS 1915+105 (Fender et al. 1999) the value of k for each single ejection should be close to 2. This implies that the discrete components might be just the bright parts of a continuous jet (Fender et al. 1999). Regarding α, LS I +61°303 is always optically thin at frequencies (5–9) GHz, even during the onset of radio outbursts (Strickman et al. 1998), and remains quite constant at a value of −0.5.

In Massi et al. (2001) we used the values $\alpha = -0.5$ and $k = 3$ resulting in $\beta > 0.4$ and $\theta \sim 0°$ for the EVN data. By adopting the more convincing value of $k = 2$ the value of β derived from the EVN image becomes 0.6, while θ remains approximately zero. In the case of the MERLIN image of April 22 we derive $\beta\cos\theta = 0.12$, which for $\beta = 0.6$ leads to an ejection angle of $\theta = 78°$. This is an average of the ejection angles θ_{A} and θ_{B} of features A and B in Figs. 3a and 3b. A direct estimate of these angles is prevented by the lack of the receding jets. By using the rms noise we derive $\theta_{\mathrm{A}} < 90°$, $\theta_{\mathrm{B}} < 80°$ and for the C ejection in Fig. 3c, $\theta_{\mathrm{C}} < 68°$.

4. Conclusions and discussion

We have shown, for the first time, the presence of a double-sided jet in LS I +61°303.

The comparison of the MERLIN 2001 April 22 observation with our previous EVN results allows us to establish a variation of the angle (θ) between the jet and the line of sight up to 78° between the two epochs. The variation is attributable to a precession of the jet. Because of such a precession the position angle (PA) of the projection of the jet onto the sky changes as well. This explains the different alignments of PA $\simeq$ 30° or PA $\simeq$ 120–160° measured in different epochs (see Table 2 in Massi et al. 2001).

The MERLIN 2001 April 23 image confirms a precession of the jet by the large variation of both the values of PA and of θ. In addition it reveals quite short time-scales for the precession, since the time interval between the two observations is of only 24 hours.

LS I +61°303 coincides with the high-energy gamma-ray source 2CG 135+01 (3EG J0241+6103) (Hartman et al. 1999). The emission could consist of inverse Compton upscattered UV photons from the stellar companion by the relativistic electrons of the jet as discussed by Taylor et al. (1996). In this case the fast precession, pointing the jet intermittently closer and farther from the line of sight with an excursion of several degrees in one day, should produce noticeable variable γ-ray emission on the same (short) time-scales. The amplification due to the Doppler factor for Compton scattering of stellar photons is $\delta^{3-2\alpha}$, and therefore even higher than that for synchrotron emission, i.e. $\delta^{2-\alpha}$ (Georganopoulos et al. 2001; Kaufman Bernadó et al. 2002). Indeed, such daily variations have been well established in EGRET observations (Tavani et al. 1998; Wallace et al. 2000) and never understood, because the other class of galactic gamma-ray sources, namely the pulsars, have steady properties. These variations can now be well understood: LS I +61°303 hosts a microquasar with a very fast precessing jet. At some epoch the jet points directly toward the Earth and is therefore a micro-blazar (Kaufman Bernadó et al. 2002; Romero et al. 2002).

Our discovery, explaining the nature of the enigmatic source 2CG 135+01, has two important consequences. On the one hand LS I +61°303 becomes the ideal laboratory to test the recently proposed model for microblazars with INTEGRAL and MERLIN observations, and by AGILE and GLAST in the future. On the other hand this discovery implies that other variable galactic-gamma ray sources could also be precessing microquasars. Therefore, identification of their radio counterparts and subsequent high resolution interferometric observations could increase the still small (<20) number of these fascinating miniatures of the AGNs, called microquasars.

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