The milliarcsecond radio structure of LS 5039

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The bright (V = 11.2) star LS 5039 has been recently identified as a nearby high mass X-ray binary with spectral type O7V((f)) and persistent radio emission. Here we report high resolution radio observations with the Very Large Baseline Array (VLBA) and the Very Large Array (VLA). Our results reveal that LS 5039 is resolved into bipolar radio jets emanating from a central core. In addition, this object appears to be associated with one of the enigmatic γ-ray sources detected by the Energetic Gamma Ray Experiment Telescope (EGRET) on board the COMPTON-GRO satellite. All this evidence, together with an improved analysis that gives a distance of about 3 kpc, points to LS 5039 as being one of the closest microquasars with non-flaring, but persistent activity. This is also the first time that a microquasar is discovered after cross-correlating astrophysical survey data without a previous outburst alert. The success of this alternative approach for systematic identifications opens the possibility of new findings which may confirm that the microquasar phenomenon is not as rare as it seemed before, when only a few 'exotic' cases were known.

1. Introduction

Attention to the peculiar nature of the early type star LS 5039 was recently called by the report of a bright non-thermal radio counterpart (Martí et al. 1998). This finding was possible as a result of extended cross-correlation between public databases and catalogs in the X-ray, radio and optical domains. The object had been previously identified as a high mass X-ray binary candidate by Motch et al. (1997) using ROSAT. The system has a O7V((f)) companion, with visual magnitude $V = 11.2$, at an estimated distance of about 3 kpc according to the reddening free parameter formulation. Therefore, LS 5039 appears as a new member in the selected class of radio emitting X-ray binaries, that includes about 20% of the total population.

A follow up monitoring with the Green Bank Interferometer (GBI) started at our request revealed a persistent level of non-thermal radio emission for at least 11 months (Ribó et al. 1999). The flux density levels observed, at centimetric wavelengths, were usually in the $\sim$ 20-30 mJy range. A pre-discovery radio detection, going back to 1989, was also found in an old radio survey by Helfand et al. (1992) at a similar flux density. The best radio spectra available for LS 5039 are shown in Figure 1 for illustrative purposes (Martí et al. 1998), where $S_\nu \propto \nu^{-0.5}$ on average. Further observations conducted at the VLA indicated a compact radio source at 0.1 arcsecond scales.

In view of this situation, and given the non-transient but persistent nature of LS 5039, the source appeared as an ideal target for further studies with the VLBA. Our interest on LS 5039 increased even more when we noticed that its position was consistent with that of a high-energy (> 100 MeV) unidentified γ-ray source, i.e., 3EG J1824$-$1514 in the third EGRET catalog (Hartman et al. 1999).

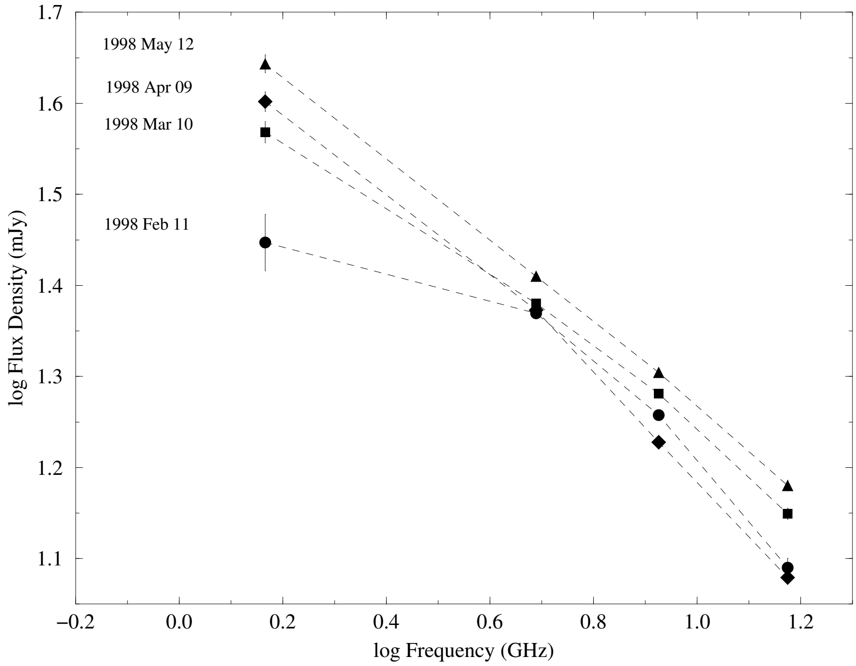

FIGURE 1. Radio spectrum of LS 5039 observed at different epochs with the VLA. The negative spectral index is consistent with non-thermal synchrotron radiation.

2. Observations and results

LS 5039 was observed with the VLBA plus the VLA, in phased array mode, on 1999 May 8th at the 6 cm wavelength. The calibration was performed using the AIPS package of NRAO. The strong radio source 3C345 was used as fringe-finder, whereas J1733−1304 was the phasing source for the VLA.

The final map, presented in Figure 2, reveals the existence of extended radio emission at angular scales of a few milliarcsecond. The source appears also with an elongated morphology of approximately 6×2 milliarcsecond^2 along position angle 125°. The total flux density is 16 mJy, implying an overall brightness temperature of $\sim 9.4 \times 10^7$ K consistent with non-thermal synchrotron radiation. From equipartition arguments between the radio emitting relativistic electrons and the magnetic field, we derive an energy content of $\sim 4.8 \times 10^{39}$ erg with an equipartition magnetic field of ~ 0.2 G. These numbers must be considered as very rough estimates since we still do not have enough information for appropriate calculations in the rest frame of the ejecta.

3. Discussion

The most likely interpretation of Figure 2 is that we are seeing radio jets emanating from a bright central core in LS 5039. This is in fact the main justification for our claim that we have found a new microquasar system. The brightness assimetry between the jet components, with an estimated flux density ratio of 2.1 ± 0.4, is likely to arise due to Doppler boosting effects, as in other microquasar systems (see e.g. Mirabel & Rodríguez 1999 for a review). Assuming a continuous jet flow, the projected velocity required is then $v \cos\theta = (0.15 \pm 0.04)c$, where c is the speed of light and θ the ejection angle with the line of sight. We expect to confirm this interpretation by future observations.

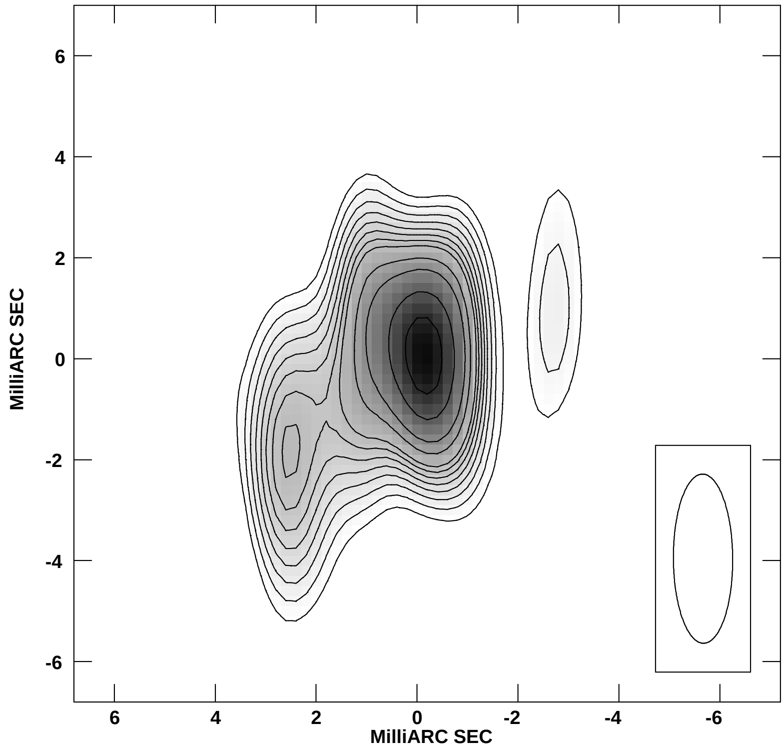

FIGURE 2. The milliarcsec radio structure of LS 5039 observed at 6 cm with the VLBA+VLA. The contour levels correspond to 6, 8, 10, 12, 14, 16, 18, 20, 25, 30, 40 and 50 times 0.085 mJy beam^{-1}, the map rms noise. The synthesized beam at the bottom right corner is 3.3×1.2 milliarcsecond^2.

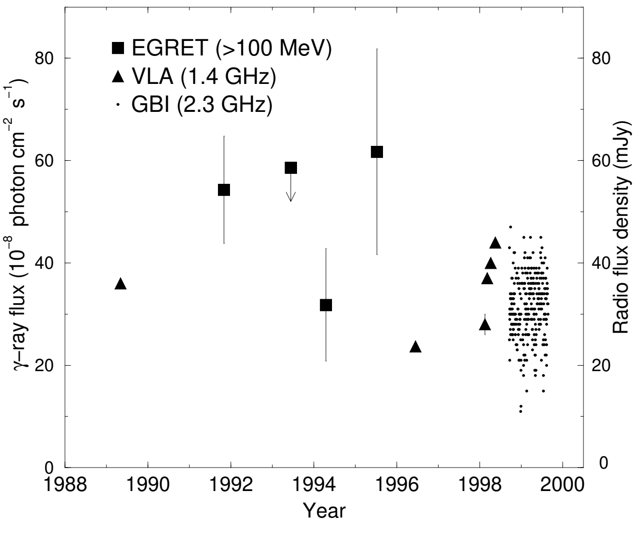

FIGURE 3. The persistent light curves of 3EG J1824−1514 and LS 5039 at γ and radio wavelengths. Both sources are proposed to be the same object.

At the time of our observation, nor in the weeks before, LS 5039 did not undergo any significant flaring event. Therefore, the presence of radio jets in a state of normal persistent radio emission strongly suggests that they are a permanent feature of the system. Not all microquasar systems display this kind of behaviour and sometimes the presence of radio jets is detected only after a transient flaring event. Somehow, LS 5039 is reminiscent of the persistent radio emission of Cygnus X-1, and probably it contains a black hole companion as well. The lack of X-ray pulsations and the hardness of the X-ray spectrum (Ribó et al. 1999) support this idea, although a neutron star cannot be ruled out yet.

The presence of radio jets can be reconciled with the proposed association with the EGRET source 3EG J1824−1514 through Inverse Compton effect. The idea is that high energy γ-rays are likely to result from Inverse Compton scattering of UV photons, emitted by the hot O-type companion, by the same radio emitting electrons. The details of the calculation are worked out in Paredes et al. (2000). They find that this scenario is conceivable provided that the jet flow is higher that $v > 0.05c$, so that the relativistic electrons are able to avoid strong Inverse Compton losses and still be able to power the radio jets. In this scenario, both the radio and γ-ray emission are expected to be persistent in time, as long as the microquasar is able to accelerate relativistic electrons with Lorentz factors of $\gamma \sim 10^3$. The long term flux history of LS 5039 at radio and γ-ray wavelengths (see Figure 3) gives support to this persistent activity.

To conclude, it is interesting to point out that LS 5039 was considered to be a luminous but otherwise ordinary star prior to the discovery of its radio and X-ray counterpart. We believe that this fact opens the possibility that several other microquasar systems may be discovered in the Galaxy in a similar way as in the LS 5039 case.

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