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LETTER

*Letter to the Editor*

# The system LS 5039: a new massive radio emitting X-ray binary

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**Abstract.** We report the discovery of a bright and unresolved radio counterpart to the massive X-ray binary LS 5039. The optical position of this early type star is in excellent agreement with that measured in the radio. The observed spectrum is clearly of non-thermal synchrotron nature and some evidences of variability, although with moderate amplitude, have been detected at both radio and optical wavelengths. All the available data strongly support that LS 5039 is a new member in the reduced family of radio loud massive X-ray binaries.

**Key words:** stars: individual: LS 5039 – stars: variables: other – radio continuum: stars – X-rays: stars

## 1. Introduction

Radio emitting X-ray binaries (REXRBs) are among the most efficient radio sources in the Galaxy. Their radio emission is usually of non-thermal synchrotron origin and it is sometimes dramatically related to violent and exotic phenomena, such as the relativistic ejection of plasma clouds in a scaled down microquasar scenario (see e.g. Mirabel & Rodríguez 1998 for a recent review). There are today not more than $\sim 30$ REXRBs identified, and this is a relatively small amount compared to $\sim 200$ systems catalogued (van Paradijs 1995). The precise mechanisms why some systems are radio loud and others are not are still not completely understood. Additional progress in this field may be significantly assisted by increasing the current population of known REXRBs, so that meaningful statistical comparisons could be made.

The NRAO VLA Sky Survey (NVSS) (Condon et al. 1998) provides a valuable tool to search for new REXRBs, and we are currently involved in a project of this kind. In a first step, the most obvious objects to inspect in the NVSS are those new X-ray binary candidates already proposed from previous researches. In particular, a systematic cross-correlation of the ROSAT All Sky Survey (RASS) (Voges et al. 1996) with OB star catalogues in the SIMBAD database has been recently carried out by Motch et al. (1997), hereafter M97. Nearly two tens of OB/X-ray accreting binary candidates have resulted from this work with different degrees of reliability. For all of them, we have examined the corresponding NVSS maps at the 20 cm wavelength in a search for possible radio counterparts. We find at least one interesting object in the M97 list that deserves special attention, namely LS 5039 ($l^{II} = 16\overset{\circ}{.}88$; $b^{II} = -1\overset{\circ}{.}29$).

LS 5039 has been proposed by M97 to be an X-ray binary system of the massive type with a high degree of confidence. The hardness of its X-ray spectrum is well consistent with a neutron star, or a black hole, accreting directly from the companion's wind. The unabsorbed X-ray luminosity in the 0.1–2.4 keV band, at an estimated distance of 3.1 kpc, amounts to $L_X \sim 8.1 \times 10^{33}$ erg s$^{-1}$. The optical counterpart of the system appears as a very luminous ($V \simeq 12$) star of the main sequence, with an early O7V spectral type.

The existence of a radio counterpart to LS 5039 was first suspected after inspection of the corresponding field in the NVSS. The 24 mJy source NVSS J182614$-$145054 lies outside, but very close to, the 90% confidence error circle of RX J1826.2$-$1450 with $22''$ radius. This is the RASS source identified with LS 5039 in the M97 paper. These authors also quote another pointed ROSAT observation that yields a 90% confidence radius of $35''$, again consistent with NVSS J182614$-$145054. In addition, the NVSS coordinates were found to agree within $2''$ with the optical position of LS 5039, as derived from the USNO-A1.0 catalogue (Monet 1996).

All these coincidences together stimulated our interest about this source and lead us to carry out higher resolution radio observations. This was considered to be the next logical step in order to better measure both its position and spectral properties. This paper summarizes a multi-epoch and multi-frequency radio study of LS 5039 that clearly points towards its REXRB nature. A short account of optical photometric observations is also presented.

## 2. Radio observations and results

We observed LS 5039 on several epochs at the wavelengths of 20, 6, 3.5 and 2.0 cm with the Very Large Array (VLA) interferometer of the NRAO[1]. The VLA data were processed following

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**Table 1.** Radio observations of LS 5039

| Date | Julian Day (JD−2400000) | VLA Configuration | $S_{20\mathrm{cm}}$ (mJy) | $S_{6\mathrm{cm}}$ (mJy) | $S_{3.5\mathrm{cm}}$ (mJy) | $S_{2.0\mathrm{cm}}$ (mJy) |
|---|---|---|---|---|---|---|
| 02 May 1989[a] | 47649 | B | 36 | – | – | – |
| 19 Jun 1996[b] | 50254 | D | $23.7 \pm 0.9$ | – | – | – |
| 11 Feb 1998 | 50856.2 | D | $28 \pm 2$ | $23.4 \pm 0.1$ | $18.1 \pm 0.1$ | $12.3 \pm 0.3$ |
| 10 Mar 1998 | 50883.1 | A | $37 \pm 1$ | $24.0 \pm 0.1$ | $19.1 \pm 0.1$ | $14.1 \pm 0.2$ |
| 09 Apr 1998 | 50913.0 | A | $40 \pm 1$ | $23.6 \pm 0.1$ | $16.9 \pm 0.1$ | $12.0 \pm 0.2$ |
| 12 May 1998 | 50946.0 | A | $44 \pm 1$ | $25.7 \pm 0.1$ | $20.2 \pm 0.1$ | $15.1 \pm 0.2$ |

[a] Helfand et al. (1992)
[b] NVSS maps; Condon et al. (1998)

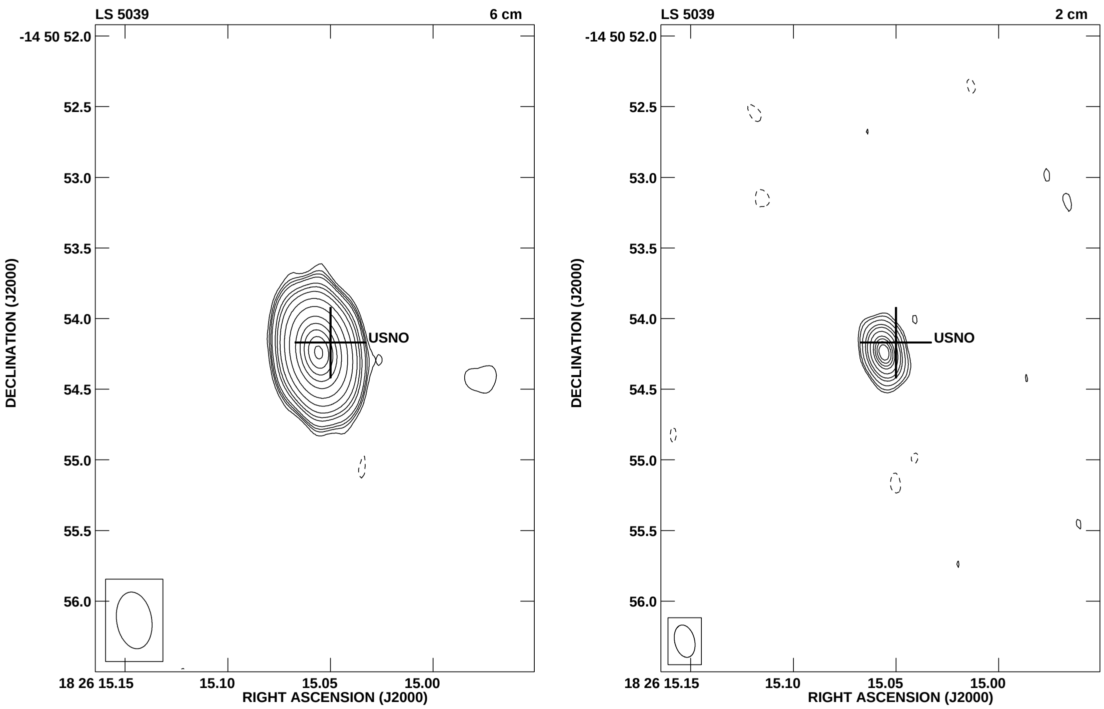


**Fig. 1. Left.** Self-calibrated map of LS 5039 at the 3.5 cm wavelength obtained from the concatenation of all our VLA data in the A configuration. Natural weight of the visibilities was used. The thick cross indicates the optical position of LS 5039 as listed in the USNO-A1.0 catalogue. Contours are −3, 3, 5, 7, 10, 20, 30, 50, 100, 200, 400, 600, 800, 1000 and 1200 times 0.015 mJy beam$^{-1}$, the rms noise. The synthesized beam is shown at the bottom left corner and corresponds to $0\farcs40 \times 0\farcs25$, with position angle of $9\fdg1$. **Right.** The same at the 2.0 cm wavelength. Contours are −3, 3, 5, 10, 20, 30, 50, 80, 100, 120 and 140 times 0.082 mJy beam $^{-1}$, the rms noise. The 2.0 cm synthesized beam is $0\farcs23 \times 0\farcs14$, with position angle of $13\fdg4$.

standard procedures within the AIPS package of NRAO. 3C 286 was used as the amplitude calibrator, while the phase calibrators observed were $1834-126$ at 20 cm, $1820-254$ at 6 and 3.5 cm, and $1911-201$ at 2 cm, respectively.

The results of the interferometric runs on LS 5039 are summarized in Table 1, where the flux density at several wavelengths is listed for the different dates observed. Some 20 cm values collected from the literature have been also included. The VLA data obtained in A configuration were further concatenated at 3.5 and 2.0 cm in order to obtain very sensitive sub-arcsec resolution maps. These are displayed in Fig. 1, where LS 5039 appears always as an unresolved point source ($\leq 0\farcs1$). For the epochs when nearly simultaneous multi-frequency observations are available, we have plotted in Fig. 2 the observed radio spectrum of LS 5039.

## 3. Optical observations and results

Optical CCD observations were carried out at Calar Alto observatory (Spain) soon after the VLA runs. Our main goal here was to search for photometric variability that could evidence the active nature of LS 5039 as an X-ray binary. We used the 1.52 m telescope of the Spanish Observatorio Astronómico Nacional (OAN) from June 1st to 8th 1998. The Richtey-Chrétien focus was available together with a Tektronics TK1024AB chip. This provides a scale factor of $0\farcs4$ per pixel and a $6\farcm9 \times 6\farcm9$ field of view. Images were acquired through the $VRI$ Johnson filters

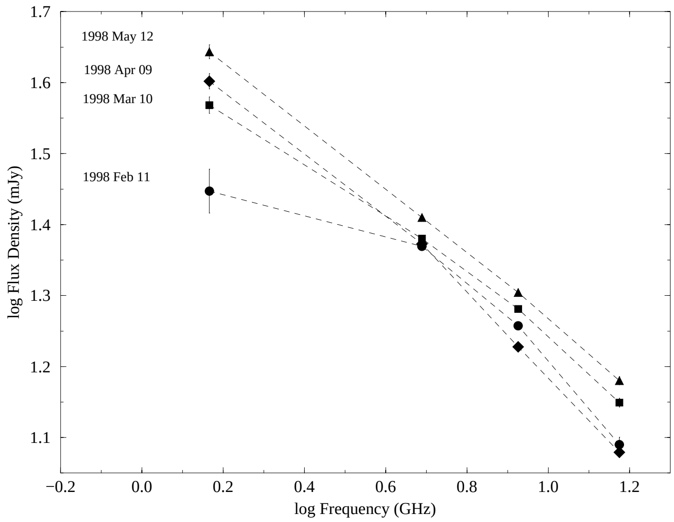


**Fig. 2.** The radio spectrum of LS 5039 on different epochs during the 1998 observations with the VLA. Error bars not shown are smaller than the symbol size.

**Table 2.** Optical photometry of LS 5039.

| Date | Julian Day (JD−2400000) | $V$ | $R$ | $I$ |
|---|---|---|---|---|
| 1998 Jun 2 | 50966.5 | 11.35 | – | – |
| 1998 Jun 3 | 50967.6 | 11.33 | – | – |
| 1998 Jun 7 | 50971.6 | 11.35 | 10.64 | 9.90 |
| 1998 Jun 8 | 50972.5 | 11.39 | 10.69 | 9.95 |

and they were reduced using standard procedures based on the IRAF image processing system. In Fig. 3 we show a 30 s exposure of the LS 5039 field in the $V$-band. Differential photometry was performed against two nearby comparison stars (C1 and C2 in Fig. 3).

Based on several observations of Landolt et al. (1992) standards, the adopted magnitudes of the comparison stars are $V = 12.53$, $R = 12.01$, $I = 11.55$ and $V = 10.10$, $R = 9.36$, $I = 8.68$ for C1 and C2, respectively. This absolute photometry is accurate to $\pm 0.03$ mag. Relative variations in the final photometric results of Table 2 can be nevertheless traced at the $\pm 0.01$ mag level.

## 4. Discussion

### *4.1. Astrometric identification*

The radio position derived from the VLA-A configuration maps in Fig. 1 is found to be: $\alpha_{J2000} = 18^h 26^m 15\overset{s}{.}056 \pm 0\overset{s}{.}001$ and $\delta_{J2000} = -14^\circ 50' 54\overset{''}{.}24 \pm 0\overset{''}{.}01$. These coordinates agree within $0\overset{''}{.}1$ with those of LS 5039 in the optical USNO-A1.0 catalogue, whose typical astrometric error is about $0\overset{''}{.}25$. Therefore, we conclude that the identification of the LS 5039 radio counterpart on the basis of astrometrical coincidence at the sub-arcsec level is virtually certain. From source count analysis (e.g. Ledden et al. 1980), the a priori probability of having a background extragalactic source with $S_{20\mathrm{cm}} \simeq 30$ mJy, or brighter, within $0\overset{''}{.}2$ of the LS 5039 optical position is as low as $\lesssim 10^{-7}$. To our knowledge, this discovery increases to four the number of confirmed massive X-ray binaries with associated radio emission, the other three being SS 433, Cygnus X-1 and LSI+61°303.

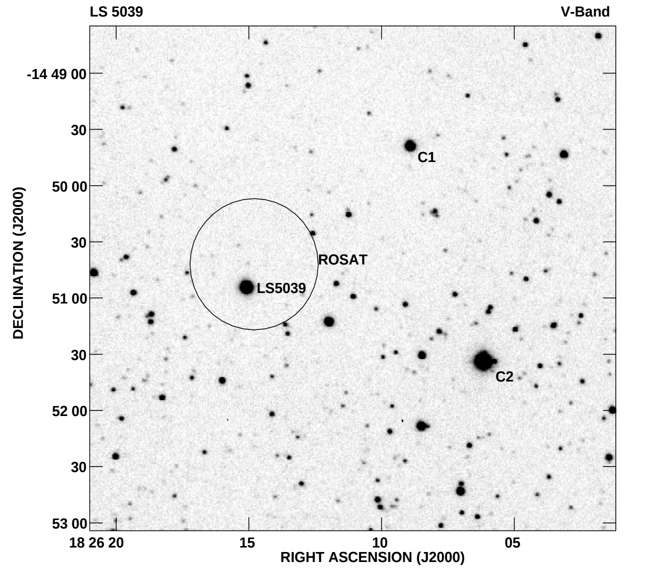


**Fig. 3.** CCD image of LS 5039 obtained on 1998 June 7 with the 1.52 m OAN telescope in the $V$-band. The circle with $35''$ radius represents the 90% confidence position from the ROSAT PSPC pointed observations quoted in M97. The two comparison stars used for differential photometry are labeled as C1 and C2.

### *4.2. Radio behavior*

The radio spectra of LS 5039 in Fig. 2 are very suggestive of non-thermal radio emission. A typical one can be well represented by $S_\nu = (52 \pm 1)$ mJy $(\nu/1\ \mathrm{GHz})^{-0.46\pm0.01}$. Given the unresolved angular size ($\theta \leq 0\overset{''}{.}1$), the brightness temperature

$$T_b = 1.76 \times 10^3 \mathrm{K} \left[\frac{\nu}{\mathrm{GHz}}\right]^{-2} \left[\frac{\theta}{\mathrm{arcsec}}\right]^{-2} \left[\frac{S_\nu}{\mathrm{mJy}}\right] \quad (1)$$

can be estimated, for example at the 20 cm wavelength, as $T_b \geq 4 \times 10^6$ K. Such a high value, together with the significantly negative spectral index, safely rules out a thermal emission mechanism. Non-thermal synchrotron radiation remains therefore as the most plausible interpretation for the LS 5039 radio emission. We can also obtain a lower limit to the source angular size by preventing catastrophic inverse Compton losses to occur ($T_b \leq 10^{12}$ K). This condition yields $\theta \geq 0.2$ mas, implying that further progress in studying the LS 5039 structure may be feasible by the use of VLBI techniques. We ignore at present if the radio emission is originated in collimated milliarcsec radio jets or, alternatively, some other mechanism is at work.

Assuming equipartition arguments for synchrotron radio sources (Pacholczyk 1970), the total energy content and magnetic field in LS 5039 can be expressed as:

$$E_{\mathrm{total}} = c_{13}(1+k)^{4/7} \phi^{3/7} R^{9/7} L_{\mathrm{rad}}^{4/7} \quad (2)$$

and

$$H = 4.5^{2/7}(1+k)^{2/7}c_{12}^{2/7}\phi^{-2/7}R^{-6/7}L_{\rm rad}^{2/7}, \qquad (3)$$

where $L_{\rm rad}$ is the integrated radio luminosity, $R$ the linear size of the emitting region, $\phi$ the fraction of its volume covered by the magnetic field, $k$ the electron to proton energy ratio, and $c_{12}$ and $c_{13}$ some special functions of the synchrotron theory tabulated in Pacholczyk (1970).

For a distance of 3.1 kpc, and assuming that the spectrum extends from 0.1 to 100 GHz, the total radio luminosity of the system can be evaluated as $L_{\rm rad} \sim 1.3\times10^{31}$ erg s$^{-1}$. The radio to X-ray luminosity ratio is thus $L_{\rm radio}/L_X \sim 10^{-3}$. Adopting $\phi = 1$ and $k = 1$, the range of angular sizes found above ($0.2$ mas $\leq \theta \leq 0\farcs1$) translates into the following allowed source parameters: $1.6\times10^{38}$ erg $\leq E_{\rm total} \leq 5.0\times10^{41}$ erg and 0.01 G $\leq B \leq$ 2.2 G.

The radio emission level seems also to be persistent on time scales of, at least, few years. This is deduced from the historical detections listed in Table 1. On shorter time scales, the 20 cm flux density was observed to vary between 27 and 44 mJy between our first and last observing epochs, that are separated by four months. We also find some indications of radio variability for the remaining shorter wavelengths. The amplitudes of variations at 6, 3.5 and 2.0 cm are however not larger than $\sim 10\%$. The overall spectral evolution in Fig. 2 can be conceivably understood in terms of a progressive decrease in the synchrotron self-absorption opacity. Unfortunately, the time sampling was not frequent enough to determine what sort of radio events could configure the LS 5039 light curve during our VLA monitoring. In any case, both the non-thermal spectral indices and the radio variability observed from month to month are not unusual features in REXRBs (see e.g. Hjellming & Han 1995).

From the radio point of view, the LS 5039 behavior appears so far consistent with the general properties of REXRBs, thus supporting the M97 identification. In particular, the radio emission of LS 5039 is somehow reminiscent of LSI+61°303. This is another massive REXRB whose individual $L_{\rm radio}/L_X$ ratio is remarkably similar to that of LS 5039 (Taylor et al. 1996; Paredes et al. 1997). The energy and magnetic field estimates for LSI+61°303 (Massi et al. 1993) would also fit comfortably well within the limits found above for LS 5039. The analogy between both sources is however not complete, i.e., there is no evidence yet for LS 5039 radio outbursts in time scales of days or weeks. Observations in this sense will need to be carried out.

### 4.3. Optical behavior

Optical photometry of LS 5039 has been published in the past by Drilling (1975) and Lahulla & Hilton (1992) while carrying out different studies of its field. Their respective measurements, as well as those reported in Table 2, are consistent within $\sim 0.1$ mag. This suggests that no strong optical variations appear to be present on time scales of years. Nevertheless, from our OAN observations we propose that there may be day-to-day variations with amplitudes of a few hundreths of magnitude. This appears specially evident in the latest two days of Table 2. Here, the LS 5039 brightness decreased by about 0.04 mag in $V$ and 0.05 mag in $R$ and $I$ from one day to the next. In doing so, all the differences between the two comparison stars remained constant within less than 0.01 mag, thus supporting the reality of this variation. Comparable day-to-day, and intra-day, photometric variations at the $\sim 0.1$ mag level increasing towards longer wavelengths have been observed for instance in LSI+61°303 (Paredes et al. 1986, 1994). For this source, they are known to be correlated with the radio light curve. Further photometry is therefore required to confirm our variability detection and to find out if this is also the case in LS 5039.

## 5. Conclusions

We have reported the discovery that the star LS 5039 appears to be a new REXRB of high mass. The proposed radio counterpart is consistent, within astrometric errors, with both the optical and X-ray position of the system. Its appearance at radio wavelengths is that of a compact source, even at the highest VLA resolution.

The observed radio spectrum is characterized by a negative spectral index, i.e, suggestive of non-thermal synchrotron emission. LS 5039 also exhibited some evidences of radio variability during our VLA runs carried out on a monthly basis. The variations were specially important at the 20 cm wavelength, where the source flux density increased by almost a factor of two. This kind of behavior, although moderate, strongly supports the identification of the radio counterpart. Optical indications of day-to-day variability have been also gathered. Future multi-wavelength observations are currently planned.

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