Low-frequency radio spectrum and spectral turnover of LS 5039

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ABSTRACT

LS 5039, a possible black hole X-ray binary, was recently observed with Giant Metrewave Radio Telescope. The observed spectrum presented here shows that the spectrum is inverted at low frequency. When combined with the archival data with orbital phase similar to the present observations, it shows a clear indication of a spectral turnover. The combined data are fitted with a broken power-law and the break frequency signifies a possible spectral turnover of the spectrum around 964 MHz. Truly simultaneous observations in radio wavelength covering a wide range of frequencies are required to fix the spectrum and the spectral turnover which will play a crucial role in developing a deeper understanding of the radio-emitting jet in LS 5039.

Key words: radiation mechanisms: non-thermal – methods: observational – galaxies: jets – radio continuum: general – X-rays: binaries – X-rays: individual: LS 5039.

1 INTRODUCTION

LS039 is an X-ray binary system consisting of a compact object and a companion star of ON6.5V(f) type with mass 22.9 M⊙. The mass of the compact object is not accurately known, but a recent study shows that the mass of the compact object is 3.7 M⊙ (Casares et al. 2005). Although there is much discussion regarding the true nature of LS 5039 (Mirabel 2006), the dynamical mass estimate indicates that it is a possible black hole X-ray binary candidate. The orbital period of the binary system is 3.9 d (Casares et al. 2005). The binary orbit is highly eccentric, with an eccentricity of 0.35, and has an inclination angle 24.9 ± 2.8 (Casares et al. 2005).

LS039 was proposed to be a very high energy γ-ray emitter by Paredes et al. (2000) and was recently seen at TeV γ-ray energies by the γ-ray telescope High-Energy Stereoscopic System (Aharonian et al. 2006). The γ-ray light curve shows an orbital modulation of ~3.9 d. The γ-ray flux, as well as the spectral hardness, varies with the orbital phase. The variation in flux with orbital phase can be accounted for by considering the absorption of γ-rays due to γγ pair production. This also implies that γ-photons are emitted from a region within 1 au of the compact object (Aharonian et al. 2006). The observed spectrum is very steep at the superior conjunction and becomes harder as the compact object moves away from it, and the spectral index goes below 2.0 as the compact object reaches the inferior conjunction. However, this variation of spectral hardness cannot be adequately explained by the γ-ray absorption via pair production alone.

This source was observed in X-ray by the ROSAT (Motch et al. 1997), RXTE (Ribó et al. 1999), ASCA (Martocchia, Motch & Negueruela 2005), BeppoSAX (Reig et al. 2003), Chandra (Bosch-Ramon et al. 2005) and XMM–Newton (Martocchia et al. 2005) missions between 1996 and 2003. These observations were effectively carried out during different orbital phases of the binary system. All these observations revealed different flux levels and different spectral indices in the X-ray energy band, but no X-ray spectral state transition was reported in these observations. More recently, Bosch-Ramon et al. (2005) reported results of RXTE observations when the source was observed consecutively for four days in 2003 July. The X-ray flux is found to vary with the orbital phases and it maximizes near periastron passage. This phase dependence of the X-ray flux is due to the motion of the compact object accreting matter from the wind of the massive companion while moving in a highly eccentric orbit (Bosch-Ramon et al. 2005). However, the observed anticorrelation between the photon index and the X-ray flux does not fit the scenario where X-rays are considered to be produced in and around an accretion disc. Bosch-Ramon et al. (2005) argued that the X-ray emission might, due to inverse-Compton/synchrotron process, be in a relativistic jet which might possibly explain the observed anti-correlation between the photon index and the observed flux. However, the photon indices reported in these observations are very similar to those generally observed in the case of the hard-state spectrum of black hole X-ray binaries.

LS039 was first observed by Martí, Paredes & Ribó (1998) in radio with the Very Large Array (VLA), and the observation resulted in a power-law spectrum with a negative power-law index. This indicates an optically thin synchrotron emission by non-thermal electrons. This observation also revealed a moderate variability in the radio flux. Later, Ribó et al. (1999) carried out an observation campaign in radio with the VLA at 2.0-, 3.6-, 6.0- and 20.0-cm wavelengths and with the Green Bank Interferometer (GBI) at 3.6- and 13.3-cm wavelengths. The observed spectrum was a power law with a power-law index of −0.46 ± 0.01, supporting the
previous observation of Martí et al. (1998), Paredes et al. (2002) first resolved the source by observing with the European VLBI Network (EVN) and the Multi-Element Radio-Linked Interferometer Network (MERLIN) and it was found that LS 5039 consists of an asymmetric two-sided jet with a maximum extension of one side ~1000 au. Recently, Ribó et al. (2008) studied the radio morphology of LS5039 using the Very Long Baseline Array (VLBA) and it was found that the radio morphology changed to asymmetric from a very symmetric configuration within five days, but the radio emission from the core did not vary appreciably. However, the most interesting find in these radio observations is the optically thin non-thermal radio spectrum of the source, which is in direct contradiction to the generally observed trend of flat or inverted radio spectrum for persistent black hole X-ray binaries in the hard state (Fender 2001; Gallo, Fender & Pooley 2003). Therefore, it is important to study LS5039 in the low-frequency radio band.

We observed LS5039 at wavelengths 21, 50 and 128 cm (1280, 614 and 234 MHz, respectively) using the Giant Meterwave Radio Telescope (GMRT). In this Letter, we discuss the results of the observation. In Section 2, we discuss the observation and data reduction, results are discussed in Section 3 and we conclude the Letter in Section 4.

2 OBSERVATIONS AND DATA REDUCTION

The GMRT consists of 30 steerable antennas of 45-m diameter in an approximate ‘Y’ shape similar to the VLA but with each antenna in a fixed position. 14 antennas are randomly placed within a central 1 × 1 km² (the ‘Central Square’) and the remaining antennas form the irregular Y shape (six on each arm) over a total extent of about 25 km. We refer the reader for details about the GMRT array to http://gmrt.ncra.tifr.res.in and Swarup et al. (1991). We observed LS 5039 at 1280 MHz on 2006 February 23 and simultaneously observed at 234 and 614 MHz on 2006 March 13.

The observations were made in standard fashion, with each source observation (30 min) interspersed with observations of the phase calibrator (4 min). The primary flux density calibrator was either 3C 48 or 3C 286, with flux densities being on the scale of Baars calibrator (4 min). The primary flux density calibrator was either observation (30 min) interspersed with observations of the phase calibrator (4 min). The primary flux density calibrator was either 3C 48 or 3C 286, with flux densities being on the scale of Baars calibrator (4 min). The primary flux density calibrator was either 3C 48 or 3C 286, with flux densities being on the scale of Baars calibrator (4 min). The primary flux density calibrator was either 3C 48 or 3C 286, with flux densities being on the scale of Baars calibrator (4 min). The primary flux density calibrator was either 3C 48 or 3C 286, with flux densities being on the scale of Baars calibrator (4 min). The primary flux density calibrator was either 3C 48 or 3C 286, with flux densities being on the scale of Baars calibrator (4 min). The primary flux density calibrator was either 3C 48 or 3C 286, with flux densities being on the scale of Baars calibrator (4 min).

After editing, the data were calibrated and collapsed into fewer channels. A self-calibration was performed on the data to correct for the phase-related errors and to improve the image quality.

3 RESULTS AND DISCUSSION

LS5039 was observed simultaneously at 234 and 614 MHz during the orbital phase 0.61–0.67 whereas the observation at 1280 MHz was carried out during the orbital phase 0.02–0.06. The details of the observation are tabulated in Table 1. As previously reported observations (Martí et al. 1998; Ribó et al. 1999; Paredes et al. 2002) show, the radio emission is core-dominated and therefore the major contribution to the radio flux detected in present observations where the source could not be resolved is mainly due to the emission from the core. Given that the source did not undergo any X-ray state transition over the period of observation concerned, it can be safely assumed that the variability of the source spanning this frequency range is not significant. The plot of the spectrum is shown in Fig. 1. It is evident that the spectrum is inverted and it shows the trend of a possible turnover around 1000 MHz. To have a much clearer picture of the spectrum, we plot the present data with the archival data. We have chosen the data reported by Martí et al. (1998) which were obtained during the orbital phase 0.63 similar to that of our second spell of observation. The combined spectrum is shown in Fig. 2. The combined spectrum is fitted with a broken power-law given by

\[ F(v) = \begin{cases} 
F_0 v^{-\alpha_1} & \text{for } v < v_b \\
F_0 v_b^{-\alpha_1+\alpha_2} v^{-\alpha_2} & \text{for } v > v_b,
\end{cases} \]

where \( v_b \) is the break frequency, \( \alpha_1 \) and \( \alpha_2 \) are the power-law indices and \( F_0 \) is the normalization. We have used Levenberg–Marquardt

![Figure 1. Radio spectrum of LS 5039 as observed with GMRT.](image1)

![Figure 2. Broken power-law fitting of the combined data set (filled circle: present data; filled triangle: archival data from Martí et al. 1998).](image2)
algorithm (Press et al. 1992) to fit the spectrum. The fitted parameters are $F_0 = 0.282 \pm 0.183, \alpha_1 = -0.749 \pm 0.111, \alpha_2 = 0.429 \pm 0.008$ and $\nu_b = 964 \pm 104$ MHz. This shows that the source has an inverted spectrum with a positive spectral index of 0.749; inverted spectrum extends up to the break frequency at 964 MHz and then the spectrum becomes a power law with a spectral index $-0.429$. The power-law spectrum for frequencies greater than 964 MHz indicates optically thin synchrotron spectrum by non-thermal electrons with spectral index 1.86. The break frequency at 964 MHz gives an indication that the spectrum has a possible turnover around that frequency. This needs to be confirmed by further truly simultaneous observations covering the complete frequency range. The inverted spectrum indicates an optically thick self-absorbed synchrotron spectrum. In ideal conditions, the self-absorbed, optically thick synchrotron spectrum produced by relativistic electrons in a magnetized plasma is given by a power law with index 5/2. However, in case of a magnetized plasma in a relativistic jet, the physical condition of the plasma varies from point to point and it is very much dependent on the flow pattern and on the shape of the jet. Therefore, the resultant synchrotron spectrum from an unresolved jet differs substantially from the ideal situation and the power-law index of the self-absorbed, optically thick synchrotron spectrum differs from 5/2. While the model by Blandford & Konigl (1979) or disc-jet symbiosis model by Falcke & Biermann (1995) explains the flat spectrum radio sources, Falcke (1996) discussed an extended disc-jet symbiosis model to explain the inverted spectra from Sgr A* and M81*. They extended the disc-jet symbiosis model by including a longitudinal pressure gradient which induces a moderate acceleration to a free conical jet along its flow direction. This longitudinal expansion leads to energy losses due to adiabatic expansion and makes the proper velocity of the jet dependent on its distance from the central engine. This model explains the inverted spectra of Sgr A* (Falcke 1996) and M81* (Falcke & Markoff 2000) and may also be applicable to radio cores in general (Falcke 1996). Moreover, it predicts, for a maximal jet (where the internal power of the jet equals the kinetic power), the slope of the inverted spectra for different inclination angles of the source. As the microquasars are scaled down versions of the radio galaxies, the generic model by Falcke (1996) can be used to model the inverted spectrum of LS5039 presented here. However, a detailed theoretical modelling, which is required to constrain the jet parameters and the radiative processes active in the source, is beyond the scope of this Letter.

4 CONCLUSION

Here we have reported the low-frequency radio spectrum of an X-ray binary LS5039 as observed with the GMRT. The spectrum is inverted and shows an indication of spectral turnover. With the assumption that the variability of radio emission from the source is not appreciable, present data are plotted with the archival data. The fitting of the data with a broken power-law reveals a possible indication of a spectral turnover at 964 MHz and an inverted spectrum with spectral index 0.749. This estimation of turnover frequency is indeed obtained using the archival VLA data (Martí et al. 1998) with the assumption that the source is not variable. However, this estimation may depend on the variability of the source. To have an idea about the sensitivity of the spectral break frequency on flux variability, we introduced a moderate ($\sim$10 per cent) flux variation to VLA data and fitted the spectrum. The spectral fitting shows that the break frequency $\nu_b$ does not change appreciably and it is well within the uncertainties of the statistical fit.

As LS 5039 is a possible black hole X-ray binary persistently in low/hard X-ray spectral state, the results of the present observation are consistent with the trend of inverted radio spectrum observed for persistent black hole X-ray binary and this is the first source of this kind for which the indication of a spectral turnover is obtained. The spectral turnover can be used to determine the magnetic field in the jet provided the size of the source is known at that frequency. However, it is to be noted that the magnetic field depends on the fourth power of the angular size. Therefore, a reliable measurement of magnetic field is possible if and only if the angular size of the source at the turnover frequency is determined with sufficient accuracy. This result will further help to constrain the theoretical models to explain the broad-band spectrum from the source.

To have a deeper understanding of the radio spectrum and its dependence on the orbital phases, it is important to have simultaneous observations over the entire radio band. Nevertheless, we are conducting a long-term campaign to study the spectral behaviour at frequencies 234, 614 and 1280 MHz over different orbital phases of LS5039. This will allow us to constrain the low-frequency end of the spectrum of LS5039.

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