Low frequency radio spectrum of LS 5039 during periastron and apastron passages

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ABSTRACT

We have recently studied LS 5039, a gamma-ray binary, with Giant Meterwave Radio Telescope (GMRT) during its periastron and apastron passage. The results presented here show that the spectra are inverted at the low frequency and the flux densities do not differ significantly for two different orbital phases. Assuming that the free-free absorption of radio in stellar wind environment is responsible for the optically thick radio emission we calculated the free-free absorption optical depth and constrained the height of the radio emitting region from the orbital plane. The height is found to be around 1.6 AU for a spherical stellar wind geometry. This estimate may change if the stellar wind is focussed or the radio absorption is due to synchrotron self-absorption.

Key words: Microquasar – LS 5039 – radio – X-rays – $\gamma$-rays.

1 INTRODUCTION

The major unresolved issues regarding the gamma-ray binary LS 5039 are (i) the nature of the compact object is not known, (ii) till date there is no convincing evidence in favour of the existence of any accretion disc in the source, and (iii) the nature of the stellar wind is not clearly understood.

Liu et al. (2006) showed LS 5039 to be a high mass X-ray binary with a ON6.5V(f) type primary star of mass 22.9 $M_\odot$. McSwain et al. (2004) and Casares et al. (2005) studied the source in UV and optical. Through UV and optical spectroscopy McSwain et al. (2004) found P Cygni line profiles in the UV Nv $\lambda 1204$ and CIV $\lambda 1550$ lines indicating the presence of strong wind. Casares et al. (2005) studied the optical H $\beta$ and HeI and HeII lines and determined the orbital parameters.

In a recent study carried out by Sarty et al. (2011) using simultaneous observations with the space based Canadian Microvariability and Oscillation of Stars (MOST) and ground based 2.3 m optical telescope Australian National University (ANU), the stellar wind properties and the orbital parameters were studied extensively. Orbital parameters were better constrained as compared to Casares et al. (2005). The eccentricity of the orbit is found to be 0.24 as compared to 0.35 by Casares et al. (2005) and 0.48 by McSwain et al. (2004).

Since the compact object mass was found to be $> 1.8 M_\odot$, we find it is difficult to conclude about the nature of the compact object because with favourable equation of states the masses of neutron stars can easily approach such a value.

From their observations of H$\beta$ and HeI spectral lines Sarty et al. (2011) revealed that equivalent width (EW) varies with the orbital phase and, particularly, EW is lower at inferior conjunction. This observation suggests that the stellar wind is possibly focussed towards the compact object instead of being spherically symmetric. A focussed wind is also observed in case of Cyg X-1 (Gies & Bolton (1986); Miller et al. (2005)), a high mass X-ray binary and it was modelled by Gies & Bolton (1986). Even though the presence of focussed stellar wind in LS 5039 needs further study and is to be modelled properly, but it possibly has direct implications on the results we present in this paper.

In our previous work (Godambe et al. (2008), Paper I), it was shown that the spectrum in the low frequency range is optically thick and there is a possible spectral turn over at around 1 GHz. The spectral index was found to be $-0.749 \pm 0.111$. The slope of the optically thick spectrum differs from the ideal condition of synchrotron self-absorbed spectrum which shows a spectral slope of $-\frac{2}{3}$. The optically thick spectrum in radio can also be generated by free-free absorption of radiation in presence of the stellar wind from the hot and massive companion star. Considering the above two possible scenarios of absorption of radio spectrum Bosch-Ramon (2009) constrained the physical conditions of the radio emitting region in LS 5039 jet. In case of free-free absorption of radio wave in the stellar wind the companion the magnetic field in the emission region was estimated.

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We observed LS 5039 at 1280 MHz on February 23, 2006 and simultaneously observed at 234 and 614 MHz on March 13, 2006.

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 and 3C 286, with all flux densities being on the scale of [Baars et al. (1977)]. Either of these flux calibrator was observed for 20 min at the beginning and end of each observing session.

The data recorded with the GMRT was converted to FITS format and analyzed with the Astronomical Image Processing System (AIPS) using standard procedures. During the data reduction, we had to discard a fraction of the data affected by radio frequency interference and system malfunctions. After editing the data were calibrated and collapsed into a fewer channels. A self-calibration on the data was used to correct for the phase related errors and improve the image quality. The observation dates, the observed frequencies and the corresponding spectral phases are given in Table 1.

Table 1. Log of GMRT observations

| MJD  | Frequency (MHz) | Phase range |
|------|-----------------|-------------|
| 54573 | 234            | 0.63 – 0.70 |
|      | 605.2          | 0.63 – 0.70 |
| 54670 | 1280          | 0.65 – 0.72 |
| 54684 | 1280          | 0.98 – 0.05 |
| 54688 | 605.2         | 0.99 – 0.06 |

3 RESULTS AND DISCUSSION

The spectra obtained for the two orbital phase ranges corresponding to the periastron and apastron passage are shown in Fig. 1 along with the data points from our previous observations (Paper I, Godambe et al. (2008)) and archival data points from Martí et al. (1998) and Ribó et al. (1999). The flux points obtained from Ribó et al. (1999) do not match with the points obtained by Martí et al. (1998). This is because the observation by Ribó et al. (1999) with VLBI resolved the source and we have used the flux values reported for the core. The overall flux from the core and the wings is of the same order as reported by Martí et al. (1998). It is evident that the spectra remain optically thick and the flux values at frequencies 605 and 1280 MHz are almost equal during the periastron (phase range : 0.65 – 0.72) and apastron (phase range : 0.99 – 0.06) passages. Because of poor quality of data at 234 MHz, we could not produce source image for both the observing spells. Compared to the flux values of our previous observations, the present flux values fall within the error bars of the previous observations. It is to be noted that the exposure time for our previous observations was less compared to that of the present observations.

The optically thick spectrum in radio frequencies can be produced due to the absorption of radiation either by free-free absorption or by synchrotron-self absorption in the emitting region of the source. The free-free absorption of radio waves may occur in LS 5039 due to the presence of stellar wind from the primary star. The relativistic jet where the radio emission takes place by synchrotron process, moves through an environment of such a stellar wind. For the time being, let us assume that the wind from the companion star is spherically symmetric. If so, the free-free absorption opacity is given by [Rybicki & Lightman (1986)]

\[ \alpha_{\nu}^{ff} = 0.018 T^{-\frac{5}{2}} Z^2 n^2 \nu^{-2} \bar{g}_{ff} \]

(1)

where T is the temperature of the stellar wind, n is the number density of the stellar wind and \( \nu \) is the frequency of radiation.
For a binary orbit inclined at an angle \( i \) with respect to the sky plane, the jet will make an angle \( i \) with the detection of observation. It is assumed that the jet is perpendicular to the orbital plane. If the semi-major axis of the orbit is \( a \) and the eccentricity is \( e \) then the equation of the orbit is given by

\[
\rho^2 = \frac{a^2(1 - e^2)}{(1 - e^2 \cos^2 \theta)}
\]

where \( \theta \) is the phase angle and \( \theta = 2\pi \phi, \ 0 \leq \phi \leq 1 \) is orbital phase. From Figure 2 using simple geometry, one can write

\[
O'C^2 = \rho^2 + a^2 e^2 - 2\rho a e \cos \theta + z^2 \tag{3}
\]

If the radio emitting region is located at a height \( z \) from the base of the jet then

\[
s^2 = O'C^2 + z^2 = \rho^2 + a^2 e^2 - 2\rho a e \cos \theta + z^2 \tag{4}
\]

In Figure 2 \( \angle O'FC = (\frac{\pi}{2} - \chi) \), so

\[
r^2 = s^2 + x^2 - 2sx \cos \left( \frac{\pi}{2} + (\chi - i) \right) \tag{5}
\]

Using equations (2) and (4) equation (5) can be written as

\[
r^2 = \frac{a^2(1 - e^2)}{1 - e^2 \cos^2 \theta} + a^2 e^2 - 2\sqrt{\frac{a^2(1 - e^2)}{1 - e^2 \cos^2 \theta} \cos \theta + z^2 + x^2} + 2sx \sin(\chi - i) \tag{6}
\]

Expressing all distances in the units of \( a \), equation (6) can be rewritten as

\[
\tilde{r}^2 = \tilde{K}^2(\theta) + \tilde{z}^2 + \tilde{x}^2 + 2\tilde{x} \tilde{z} \sin(\chi - i) \tag{7}
\]

where \( \tilde{r} = \frac{r}{a}, \tilde{z} = \frac{z}{a}, \tilde{x} = \frac{x}{a} \) and

\[
\tilde{K}^2(\theta) = \frac{1 - e^2}{1 - e^2 \cos^2 \theta} + e^2 - 2e \sqrt{\frac{1 - e^2}{1 - e^2 \cos^2 \theta} \cos \theta + x^2 + z^2} \sin(\chi - i) \tag{8}
\]

Using the geometry of Figure 2 one can finally write

\[
r^2 = (\tilde{x} + \tilde{z})^2 + \tilde{z}^2 \tag{9}
\]

where \( \tilde{z} = \tilde{z} \cos i - \tilde{K}(\theta) \sin i \) and \( \tilde{z} = \tilde{z} \sin i + \tilde{K}(\theta) \cos i \).

For an aligned jet, where \( i = 0 \), \( \tilde{z} = \tilde{z} \) and \( \tilde{z} = \tilde{K}(\theta) \).

For a spherical wind the wind density at a distance \( r \) from star is given by \((\text{Puls et al. (1990)})\),

\[
n = \frac{M}{4\pi\rho^2 v_\infty^2 (1 - \frac{R_\star}{r})} = \frac{M}{4\pi\rho^2 R_\star^2 v_\infty^2 (1 - \frac{R_\star}{r})} \tag{10}
\]

Here \( M \) is the mass loss rate of the wind, \( R_\star \) is the radius of the star, \( v_\infty \) is the terminal velocity of the wind at far away distance. The free-free absorption optical depth is given by

\[
\tau_{ff}(\tilde{z}) = \frac{0.018 T^{-3/2} \nu^{-2} M^2}{16\pi^2 a^3 v_\infty^2 m_e^2} \int_0^\infty \tilde{r}^{-4} \left( 1 - \frac{R_\star}{\tilde{r}} \right)^{-2} d\tilde{r}. \tag{11}
\]

As \( r > R_\star \), so with the approximation that \((1 - \frac{\tilde{r}}{R_\star})^{-2} \approx (1 + \frac{\tilde{r}}{R_\star})\), the optical depth is given by

\[
\tau_{ff}(\tilde{z}) = \frac{0.018 T^{-3/2} \nu^{-2} M^2}{16\pi^2 a^3 v_\infty^2 m_e^2} \left\{ \frac{1}{2} \frac{\pi}{\tilde{z}^2} - \tan^{-1}\left( \frac{\tilde{z}}{\tilde{r}} \right) \right\} - \frac{1}{2} \sin \left( 2 \tan^{-1}\left( \frac{\tilde{z}}{\tilde{r}} \right) \right) + \frac{2}{\tilde{r}^4} \left[ \frac{1}{2} - \sin \left( 2 \tan^{-1}\left( \frac{\tilde{z}}{\tilde{r}} \right) \right) \right] + \frac{1}{3} \sin^3 \left( 2 \tan^{-1}\left( \frac{\tilde{z}}{\tilde{r}} \right) \right) \right\}. \tag{12}
\]

For LS 5039, the parameter values are \( T = 37500\mathrm{K}, M = 10^{-7} M_\odot \mathrm{yr}^{-1}, a = 20 R_\odot, e = 0.24, R_\star = 9.5 R_\odot, \ i = 24^\circ \) and \( v_\infty = 2440 \mathrm{km} \mathrm{s}^{-1} \) (McSwain et al. 2004; Casares et al. 2005; McSwain et al. 2011). The variation of optical depth with orbital phase for three different locations of the radio emitting regions are shown in Figure 3 for frequencies 1280 and 605 MHz. For the inner jet it is evident that the optical depth varies periodically. It is maximum during the periastron passage (\( \phi = 0 \)) and is minimum during apastron passage (\( \phi = 0.5 \)). This is true for both 0° and 24° inclination angle of the jet vis-a-vis the inclination of orbital plane with respect to the sky plane. As the height of the radio emission zone increases the periodic variation of the optical depth diminishes and essentially the optical depth becomes almost independent of the orbital phase for \( \tilde{z} \approx 17 \) (\( z = 17a = 1.6 \mathrm{AU} \)). For \( z \approx 1.6 \mathrm{AU} \), the optical depth for 1280 MHz, \( \tau_{ff}(\nu = 1280\mathrm{MHz}) \approx 1 \) for the inclination angle 24°. As the spectral turnover is found to be around 1000 MHz, so \( \tau_{ff} \approx 1 \) is the necessary condition to constrain the emission height for the given physical condition. Since the optical depth at this height becomes independent of the orbital phase so the emitted radio flux densities will also be phase-independent. The approximately constant observed flux during periastron and apastron passages reported here does not contradict the present absorption model. For an aligned jet (\( i = 0 \)), the estimated height of the radio emission zone will be little less than 1.6 AU. These estimates indeed assume that the basic emission process remains unchanged for all orbital phases. It is only the wind density changes for different orbital phases offering different optical depth to the emitted radiation.

However these estimations may change if (i) the stellar wind is focussed or (ii) the absorption is due to synchrotron self-absorption in the jet. In fact recent observation of He I and Hβ lines from LS5039 by Sarty et al. 2011) indicates the presence of focussed wind in the binary system. Sarty et al. 2011) observed significant changes in the Hβ and He I spectral lines with the orbital phase. They attributed the low equivalent width of the spectral line to the focussing of the stellar wind towards the compact object due to its strong gravity. Bosch-Ramon et al. 2007) anal-

1 Similar estimation of free-free optical depth is also done by Zdziarski (2011).
spectrum. But observation shows that the spectral slope of the radio emitting region in the jet.

Figure 3. Variation of free-free absorption optical depth with orbital phase for 605 MHz and 1280 MHz for three different heights of the radio emitting region in the jet. Red curve: $i = 24^\circ$ and Green curve: $i = 0^\circ$. Here the semi-major axis $a$ is taken as $20R_\odot$.

ysed the XMM-Newton data of LS 5039 during the periastron and apastron passage to study the effect of stellar wind on the X-ray absorption properties in this source. The spectral fitting of the data gave a value of equivalent hydrogen column density ($N_H$) which is consistent with the interstellar value, for all observation spells. [Bosch-Ramon et al. (2007)] used the photoelectric absorption model $phabs$. We reanalyzed the same XMM-Newton data and fitted the spectrum with $powerlaw$ and the improved X-ray absorption model $tbabs$ using the spectral analysis tool, XSPEC. The X-ray absorption cross-section used in the model $tbabs$ includes the cross-section for X-ray absorption by gas-phase ISM, by grain-phase ISM and by the molecules in the ISM. The fitted parameters for different observations are tabulated in Table 2. The value of $N_H$ obtained in our fitting is compatible to the ISM value. This again indicates that the stellar wind does not contribute to the photoelectric absorption of the X-rays. This could be possible if the wind geometry is not spherical. Thus if the wind is focussed then the radio emission may take place at a lower height compared to the spherical wind scenario. So it is important to confirm the nature of stellar wind geometry for the companion star in LS 5039. In this context it is important to mention that Cyg X-1, a high mass X-ray binary, also exhibits focussed stellar wind from massive companion ([Gies & Bolton (1986); Miller et al. (2003)].

Another possibility of absorption of the radiation is due to synchrotron self-absorption of radio emission in jet. This scenario was discussed by [Bosch-Ramon (2003)] also. The absence of any orbital modulation of low frequency radio spectrum rule out this picture for the inverted radio spectrum of LS 5039. The estimation by [Bosch-Ramon (2004)] assumed an ideal $1/2$ slope in the self-absorbed region of the spectrum. But observation shows that the spectral slope of optically thick portion of the spectrum deviates substantially from $1/2$ (Paper I). It requires the modeling of the spectrum possibly generated in an inhomogeneous jet which is beyond the scope of this paper. To estimate the physical parameters of the jet it is important to model the multiwavelength data from the source. Such a model, incorporating the data from the low-frequency radio to gamma-rays, will be used to self-consistently produce the inverted radio spectrum, to reproduce the spectral turn over at around 1 GHz and to fit the broadband spectra, will be discussed in our next work.

4 CONCLUSION

We observed the gamma-ray binary LS 5039 in the low frequency radio by using Giant Meterwave Radio Telescope (GMRT) during the periastron and apastron passage of the source. Observations were carried out at frequencies 234, 605 and 1280 MHz. The data at 234 MHz were discarded due to its poor quality. The analysed results show that the flux values at 605 and 1280 MHz are consistent with our previous observations and they do not vary with the orbital phase. The spectrum is found to be inverted at low frequencies indicating an optically thick radio spectrum. Present data, when combined with the archival data, indicate a spectral turn over around 1GHz (Figure 1). To understand the constancy of flux during apastron and periastron passages and to constrain the location of radio emitting region we estimated the free-free absorption optical depth at radio frequencies due to the spherical stellar wind from the companion star in the binary system. From the free-free absorption optical depth estimates it is argued that the height of the radio emitting region along the jet is around 1.6 AU.

It is to noted that the observed results presented here do not rule out the other possibility of radio absorption by synchrotron self-absorption (SSA) process. If SSA is the responsible process then the above estimates may change. Also the estimation of the height of the radio emitting region as described above assumes a spherical geometry of the stellar wind. Recent observations indicate the presence of focussed wind in LS 5039 ([Sarty et al. (2011)]. If a model for focussed wind in this source is evolved and used to estimate the free-free absorption optical depth then also the above estimates may change. Therefore to develop better understanding of radio emission and absorption processes in LS 5039 it is important to have more simultaneous multiwavelength observations of the source.

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Table 2. Spectral parameters for XMM-Newton observations for two different absorption models

| MJD      | ObsID | Phase | $tb_{abs}$*powerlaw | $w_{abs}$*powerlaw |
|----------|-------|-------|---------------------|--------------------|
|          |       |       | photon index | $N_H \times 10^{22}$ cm$^{-2}$ | photon index | $N_H \times 10^{22}$ cm$^{-2}$ |
| 54573    | 0151160201 | 0.53  | 1.50 ± 0.03 | 0.62 ± 0.02 | 1.49 ± 0.03 | 0.63 ± 0.03 |
| 54670    | 0151160301 | 0.54  | 1.48 ± 0.04 | 0.66 ± 0.03 | 1.47 ± 0.04 | 0.67 ± 0.03 |
| 54684    | 0202950201 | 0.51  | 1.53 ± 0.03 | 0.69 ± 0.02 | 1.52 ± 0.03 | 0.71 ± 0.02 |
| 54688    | 0202950301 | 0.03  | 1.63 ± 0.04 | 0.69 ± 0.03 | 1.62 ± 0.04 | 0.71 ± 0.03 |

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