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# Radio and high energy characteristics of the gamma-ray binary LS I +61°303

**Lisa Zimmermann***
*Max Planck Institute for Radio Astronomy, Bonn*
*E-mail:* lzimmerm@mpifr-bonn.mpg.de

**Maria Massi**
*Max Planck Institute for Radio Astronomy, Bonn*
*E-mail:* mmassi@mpifr-bonn.mpg.de

LS I +61°303 is a high mass X-ray binary, where a compact object travels on an eccentric orbit around a Be star with an orbital period of 26.5 d. The most peculiar radio characteristics of LS I +61°303 are two periodicities. A large periodic radio outburst exhibits the same period as the orbit (Φ). A second periodicity of 4.6 yr (Θ) modulates the orbital phase and amplitude of the large outburst. Recent analysis of the radio spectral index and high energy observations can be explained by a two-peak accretion/ejection microquasar model. Nonetheless, the emission processes leading to the high and very high energy emission are still under debate. Summing up the high energy observations done so far on LS I +61°303 and putting them in comparison with the radio spectral index could yield new insights into the emission processes creating the high energy emission.

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PoS(INTEGRAL 2010)157

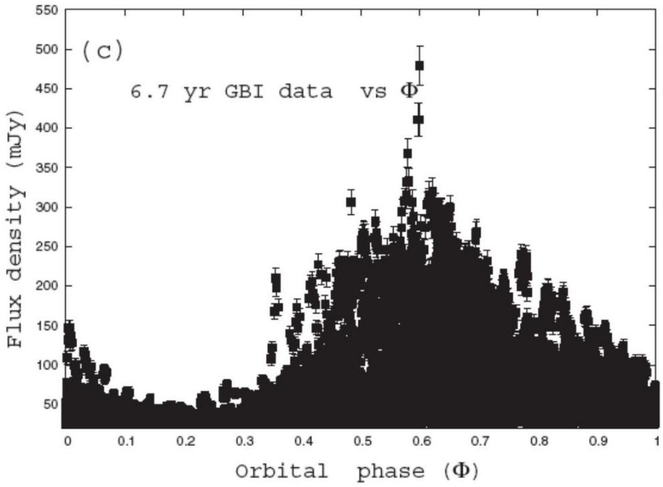


**Figure 1:** Radio light curve of LS I +61°303 from the Green Bank interferometer vs. orbital phase [5]. The large outburst towards apoastron is clearly observable. The broadness of the curve stems from the 4.6 yr period which modulates the orbital occurrence of the peak.

## 1. Introduction

LS I +61°303 is an X-ray binary formed by a compact object and a massive star with an optical spectrum typical for a rapidly rotating B0 V star [1]. The nature of the compact object, if neutron star or black hole, is still unknown due to the large uncertainty in the inclination of the object [2, 3]. It travels around its companion star on an eccentric orbit with a period of 26.5 days [4].

Radio spectral index analysis by [5] have found two peaks along the orbit of LS I +61°303 . Each peak shows the microquasar characteristic of a switch from a steady (optically thick) to a transient (optically thin) jet. Furthermore, the peak in the spectral index around apoastron is accompanied by two distinguishable peaks in the radio flux. This confirms that there are really two different outbursts (an optically thick and an optically thin one). Also high energy observations with EGRET [6] and Fermi-LAT [7] indicate two peaks along the orbit. The high energy peaks are supposed to be due to UV photons from the donor star upscattered by the relativistic electrons of the jet: external Inverse Compton process which in turn strongly attenuates the radio peak around periastron (see discussion in [8] and [9]).

It has been shown from theory that for a microquasar with an eccentric orbit (LS I +61°303 : e=0.54-0.7 [2, 3]), indeed, the different relationship between the accretion rate for density and velocity described by [10], creates two peaks in the accretion rate curve, one at periastron and a second one towards apoastron [11, 12].

The clear periodicity in LS I +61°303 is amongst its most peculiar characteristics. The orbital period (Φ) modulates the flux at radio, H-alpha, X-rays and also in gamma-rays (high and very high energy) [4, 13 – 17, 6, 7, 18, 19]. But LS I +61°303 holds another peculiarity: A second period, which modulates the radio flux over a long period of Θ=4.6 yr [4]. This modulation in radio is shown in Fig. 1 (radio flux density vs. Φ), which shows how the peak flux shifts around apoastron, and in Fig 3, where the radio flux density is given vs. Θ. In addition, this long period has also been shown in H-alpha (see Fig. 2 in [20]). It is suggested that this modulation could be due to periodic

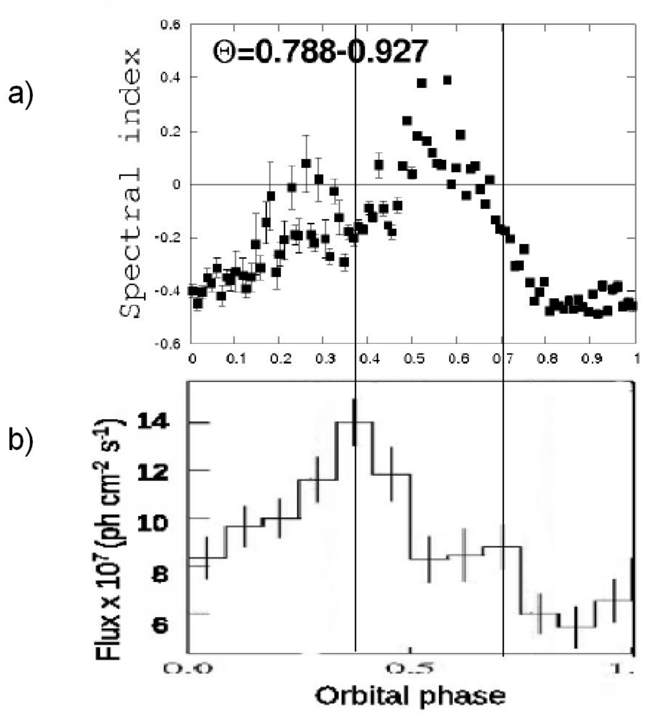


**Figure 2:** Top: Radio spectral index data for Θ=0.788-0.927 from GBI [9]. Bottom: FERMI lightcurve obtained by [7]. The two vertical lines indicate the peaks around periastron and around apoastron. They both correspond to a negative spectral index in the radio data, which corresponds to optically thin emission in both cases.

shell ejections from the circumstellar disk of the Be star [21].

## 2. High energy observations and the radio spectral index

The radio spectral index analysis by [5] have shown the importance of the large phase Θ for the analysis of radio data from LS I +61°303 . It has thereby proven that the radio outbursts really consist of two consecutive outbursts. These outbursts have completely different characteristics. In the microquasar model, an optically thick outburst in radio is associated with a steady jet, centered on the compact object. The optically thin outburst comes from a transient jet, detached from the central engine. In the unified model of X-ray states with radio jets, the radio states in microquasars are clearly associated with two X-ray states. A steady jet corresponds to the low hard state, where the X-ray spectrum is characterized by $\Gamma \approx 1.5$, whereas a transient jet corresponds to the steep power law with $\Gamma > 2.4$ [22–24]. Furthermore, high energy emission is directly connected to the steep power law state, as the power law is without cut-off and extends into the gamma-ray regime.

As a matter of fact, when LS I +61°303 was detected by MAGIC and VERITAS the spectrum was always fitted with a power law with an index $\Gamma \geq 2.4$ [19, 18, 7]. Moreover, as discussed in the next section, INTEGRAL observations seem to indicate a change of the photon index consistent with a change from the low hard to the steep power law state in agreement with the radio spectral index.

If the radio spectral index now tells us about the nature of the outburst, then the high and very high energy observations should corroborate this nature and might give additional information about the emission processes. But in order to get the complete information from the radio spectral index for LS I +61°303 , it was neccessary to take into account the long period $\Theta$. Therefore, to compare high energy data with the radio spectral index, it is neccessary as well to take only data of the same $\Theta$ phase. [9] has done so for the FERMI observations and the results are shown in Fig. 2. The almost nine complete orbital cycles, observed by FERMI, fall into the $\Theta$ interval $\Theta = 0.788 - 0.927$. In [9] the radio spectral index is calculated for the same $\Theta$ interval and the two figures are compared in terms of the orbital phase $\Phi$.

Inspection of Fig. 2 shows that in this comparison the high energy peaks established by FERMI both correspond to the optically thin outbursts of LS I +61°303 . One could draw the conclusion that the population of relativistic particles, producing the optically thin outburst (and therefore the transient jet), are also responsible for the production of the high energy emission.

It is evident that folding data only on the orbital period, without respect to the long period, might result in mixing up different ejection processes, because the orbital phase of the peaks and therefore of the switch from optically thick to thin emission does not stay the same over the 4.6 yr period. This point will be discussed in the next section.

## 3. High energy observations of LS I +61°303 and $\Theta$

In Fig. 3 high energy and very high energy observations of LS I +61°303 with different instruments are shown with respect to the $\Theta$ intervals in which they have been carried out. MAGIC covers different parts of $\Theta$, though all three intervals lie around the minimum of the long period. VERITAS covers two rather large intervals, one during the minimum and one at the onset of the maximum. What can not be seen in this figure is the sampling within these intervals. For MAGIC, VERITAS and EGRET this sampling is rather sparse, although at least EGRET observed one complete orbital cycle at each of the two given intervals [19, 18, 6]. The coverage by FERMI is of almost nine full orbital cycles [7].

For INTEGRAL, the long-term monitoring of LS I +61°303 covers vast parts of the 4.6 yr period. We have denoted the three big INTEGRAL observations with respect to $\Theta$ by I1, I2 and I3, as noted in Fig. 3. When looking at the sampling within those three intervals with respect to observations along the orbital phase $\Phi$, shown in Fig. 4, it is obvious that none of the three intervals cover an orbital cycle completely. Folding the data by orbital phase, of course, increases the sampling. By doing so, it was established that the emission between 10-100 keV is clearly modulated by the orbital phase [16, 25, 17].

Following the radio spectral index though, folding over almost a complete $\Theta$ cycle would imply that the resulting light curves could show something similar in X-rays/high energies as Fig. 1 does for the radio emission. The overall periodicity of the source at these energies can be established, but deeper insight about the ejections can be obscured by again mixing different ejection processes (namely optically thick and thin ejections). More important though, the spectral analyses can get corrupted, because of the same mixing of ejection processes.

I1 and I3 are covering most of the maximum of $\Theta$ and the onset of the decay (see Fig. 3). Together, already a rather good orbital sampling is achieved as seen from Fig. 2 when comparing

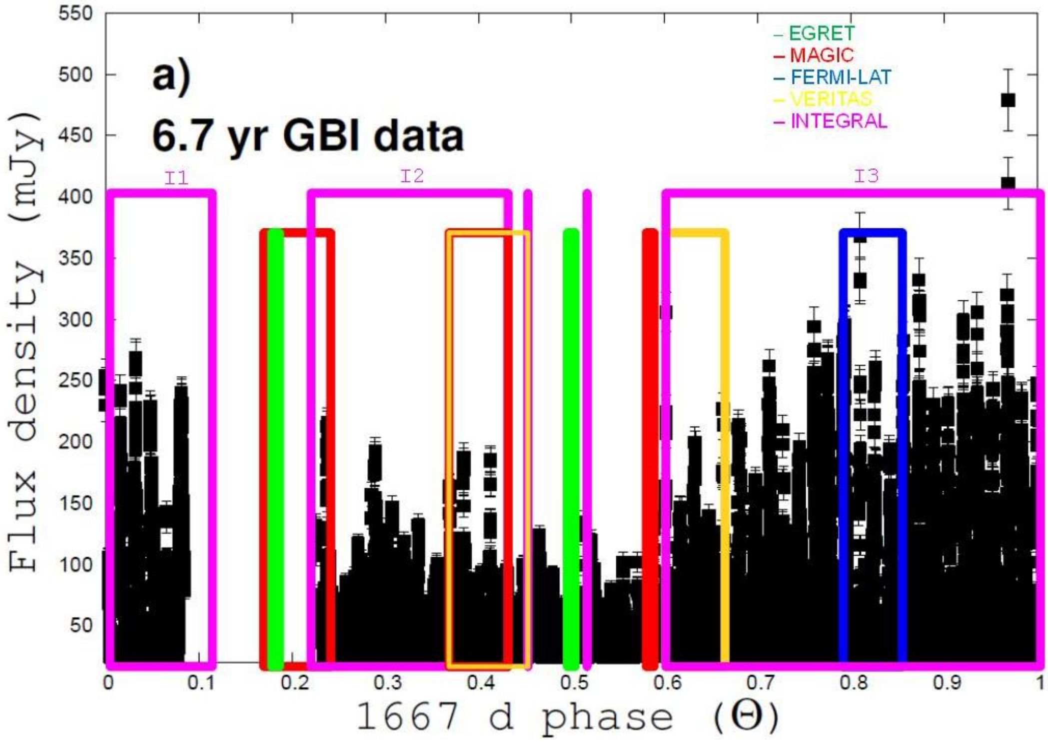


**Figure 3:** High energy observations of LS I +61°303 by EGRET, MAGIC, FERMI-LAT, VERITAS and INTEGRAL shown in the context of the 4.6 yr radio period (Θ). The underlying light curve gives the radio flux at 8.3 GHz against Θ [5]. The minimum lies around Θ ≈0.5 and the maximum around ≈0.97. The three largest Θ intervals where the source was observed with INTEGRAL are named here I1, I2 and I3.

the upper two panels. An interpretation of these data with respect to the flux and the spectrum should be less corrupted than a mix of data from the maximum and the minimum. [16], who used I3 and some data from the beginning of I1 (covering $\Phi = 0.84$ and $\Phi = 0.29$), have found not only the modulation of the lightcurve with the orbital period, but also found that along the orbit the spectral index $\Gamma$ changed from ≈1.5 around periastron to ≈3.2 around apoastron. This result strengthens the two-peak accretion model, as for the Θ-intervals covered by these observations an optically thin ejection (a transient jet) is expected around apoastron (see [5] and discussions therein). As mentioned above, in the unified X-ray states model with radio jets, a transient is associated with the steep power law, characterized by a spectral index $\Gamma > 2.4$ [22–24].

## 4. Conclusions

In the high mass X-ray binary LS I +61°303 , two clear radio periodicities are present, one coincident with its orbital period (see Fig. 1) and the other modulating the strength of the large radio outburst over a period of 4.6 yr [4, 21]. Both periods have also been observed in H-alpha emission. This system is amongst a few to have been detected not only in radio and X-rays, but also at high and very high energies. It is from these observations that, together with radio spectral index analysis, important insights into the nature of the system and its emission processes can be deduced. The radio spectral index tells us about the nature of the observed outburst. There are

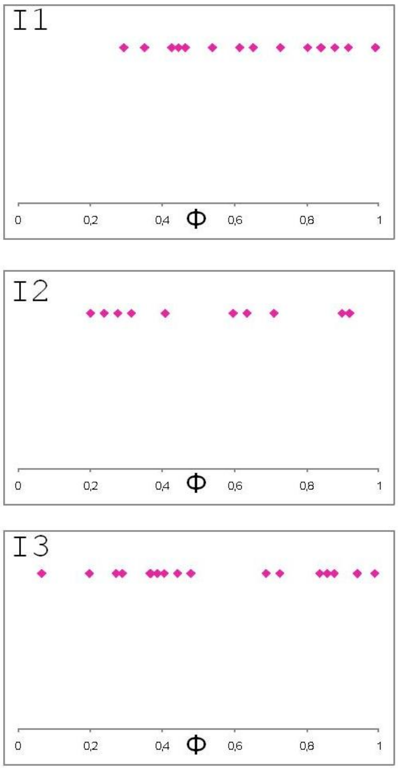


**Figure 4:** The data from I1, I2 and I3 in terms of coverage of the orbital period Φ. For all three intervals, an orbital lightcurve would not be completely sampled. Nevertheless, though folding of all three intervals would increase sampling along the orbital period, it can lead to mixing and blend important information, because outbursts with different characteristics in flux density and radio spectral index [5] get treated as one, as indicated by the modulation of the large radio outburst with Θ.

two different kinds of outburst: optically thick (spectral index $\alpha$>0) and optically thin ($\alpha$<0). The first is attributed in the microquasar model to a slow outflow, while the latter is associated with an ultrarelativistic transient jet.

Recent spectral index analysis of LS I +61°303 show that a subsequent realization of these two types of outburst takes places not only once, but twice along the orbit (see Fig. 2 top). This can be explained by the two peak accretion/ejection microquasar model for systems with an eccentric orbit like LS I +61°303 (e=0.54-0.7) ([5] and references within). In this model an expected radio peak around periastron is attenuated by inverse Compton losses due to the dense stellar UV field. Accordingly a related peak at high energies is observed (see Fig. 2 at Φ=0.3-0.4). A second (but smaller) high energy peak is observed coincident with the large radio outburst around apoastron (Φ=0.65-0.75). It becomes evident that the high energy peaks are both associated with a negative spectral index, which indicates therefore that they are created by the population of particles that stem from the fast transient jet [9]. Comparison of the high energy data from FERMI-LAT and the radio spectral index data shows the importance to compare data on the same Θ interval. Similar treatment of existing or forthcoming INTEGRAL and other high energy data for LS I +61°303 (see Fig. 3) could yield new insights into the physical processes underlying the hard X-ray and high energy emission in this exciting source.

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## References

[1] Hutchings, J. B., Crampton, D. 1981, *Spectroscopy of the unique degenerate binary star LS I +61°303* , PASP, 93, 486

[2] Aragona, C., McSwain, M. V., Grundstrom, E. D., Marsh, A. N., Roettenbacher, R. M., Hessler, K. M., Boyajian, T. S., & Ray, P. S. 2009, *The Orbits of the $\gamma$-Ray Binaries LS I +61°303 and LS 5039*, ApJ, 698, 514 [arXiv/0902.4015]

[3] Casares, J., Ribas, I., Paredes, J. M., Martí, J., & Allende Prieto, C. 2005, *Orbital parameters of the microquasar LS I +61°303* , MNRAS, 360, 1105 [arXiv/0504332]

[4] Gregory, P. C. 2002, *Bayesian Analysis of Radio Observations of the Be X-Ray Binary LS I +61°303* , ApJ, 575, 427

[5] Massi, M., & Kaufman Bernadó, M. 2009, *Radio Spectral Index Analysis and Classes of Ejection in LS I +61°303* , ApJ, 702, 1179 [arXiv/0908.2600]

[6] Massi, M., Ribó, M., Paredes, J. M., Garrington, S. T., Peracaula, M., & Martí, J. 2005, *The gamma-ray emitting microquasar LS I +61°303* , High Energy Gamma-Ray Astronomy, 745, 311 [arXiv/0410504]

[7] Abdo, A. A., et al. 2009, *Fermi LAT Observations of LS I +61°303 : First Detection of an Orbital Modulation in GeV Gamma Rays*, ApJ, 701, L123 [arXiv/0907.4307]

[8] Massi, M., & Zimmermann, L. 2010, *Feasibility study of Lense-Thirring precession in LS I +61°303* , A&A, 515, A82 [arXiv/1003.3693]

[9] Massi, M. 2010, *The Two-Peak Model of LS I +61°303 : Radio Spectral Index Analysis*, Mem. S.A.It. Vol. 75, 282, in press [arXiv/1009.2016]

[10] Bondi, H. 1952, *On spherically symmetrical accretion*, MNRAS, 112, 195B

[11] Taylor, A. R., Kenny, H. T., Spencer, R. E., & Tzioumis, A. 1992, *VLBI observations of the X-ray binary LS I +61°303* , ApJ, 395, 268

[12] Bosch-Ramon, V., Paredes, J. M., Romero, G. E., & Ribó, M. 2006, *The radio to TeV orbital variability of the microquasar LS I +61°303* A&A, 459, L25

[13] Liu, Q. Z., & Yan, J. Z. 2005, *An additional H$\alpha$ emission component in LS I +61°303 : Further evidence for the H$\alpha$ emission related to the neutron star*, New Astronomy, 11, 130

[14] Grundstrom, E. D., et al. 2007, *Joint H$\alpha$ and X-Ray Observations of Massive X-Ray Binaries. II. The Be X-Ray Binary and Microquasar LS I +61°303* , ApJ, 656, 437 [arXiv/0610898]

[15] Smith, A., Kaaret, P., Holder, J., Falcone, A., Maier, G., Pandel, D., & Stroh, M. 2009, *Long-Term X-Ray Monitoring of the TeV Binary LS I +61°303 with the Rossi X-Ray Timing Explorer*, ApJ, 693, 1621 [arXiv/0809.4254]

[16] Chernyakova, M., Neronov, A., & Walter, R. 2006, *INTEGRAL and XMM-Newton observations of LS I +61°303* , MNRAS, 372, 1585 [arXiv/0606070]

PoS(INTEGRAL 2010)157

[17] Zhang, S., Torres, D. F., Li, J., Chen, Y. P., Rea, N., & Wang, J. M. 2010, *Long-term monitoring of LS I +61°303 with INTEGRAL*, MNRAS, 408, 642 [arXiv/1006.1427]

[18] Acciari, V. A., et al. 2009, *Multiwavelength Observations of LS I +61°303 with Veritas, Swift, and RXTE*, ApJ, 700, 1034 [arXiv/0904.4422]

[19] Albert, J., et al. 2009, *Periodic Very High Energy γ-Ray Emission from LS I +61°303 Observed with the MAGIC Telescope*, ApJ, 693, 303 [arXiv/0806.1865]

[20] Zamanov, R. K, & Martí, J. 2000, *First correlation between compact object and circumstellar disk in the Be/X-ray binaries*, A&A, 358, L55 [arXiv/0005201]

[21] Gregory, P. C., Neish, C. 2002, *Density and Velocity Structure of the Be Star Equatorial Disk in the Binary LS I +61°303 , a Probable Microquasar*, ApJ, 580, 1133

[22] Fender, R. P., Belloni, T. M., & Gallo, E. 2004, *Towards a unified model for black hole X-ray binary jets*, MNRAS, 355, 1105 [arXiv/0409360]

[23] McClintock, J. E., Remillard, R. A. 2004, *Black Hole Binaries*, [arXiv/0306213v4]

[24] McClintock, J. E., & Remillard, R. A. 2006, *Compact stellar X-ray sources*, Cambridge University Press, p. 157

[25] Hermsen, W., & Kuiper, L. 2007, *INTEGRAL deep observations on LS I +61°303* , in First GLAST Symposium

PoS(INTEGRAL 2010)157