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The two-peak model of LS I +61303: radio spectral index analysis

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Abstract. The most puzzling aspect of the radio emission from LS I +61°303 is that the large periodic radio outburst, with period equal to the orbital one, occurs very displaced from periastron passage, nearly at apoastron. In 1992, Taylor, one of the discoverers of this source, together with his collaborators proposed a model of a compact object in an eccentric orbit accreting from the equatorial wind of the Be star primary. The application of this model by Martí & Paredes (1995) predicts one ejection at periastron and a second more displaced ejection along the orbit. The first ejection should correspond to weak radio emission, because of strong inverse Compton losses of the emitting electrons due to the proximity to the hot Be star, whereas the second ejection, quite displaced from the star, would correspond to a strong radio outburst, that one indeed observed. Corroborated along the years by numerical computations, simulations and gamma-ray observations, until now this two-peak model could not be proved in the radio band, because of the negligible emission around periastron. We show here, that the radio spectral index based on the ratio of flux densities is the unique tool to monitor activity of LS I +61°303 in the radio band around periastron. The analysis of the radio spectral index over almost 7 years of Green Bank Interferometer data results in a clear double-peaked spectral index curve along the orbit. This result gives finally observational support at radiowavelengths to the two-peak accretion/ejection model for LS I +61°303. Moreover, the here shown comparison of the two-peak curves - the radio spectral index curve and the Fermi-LAT gamma-ray curve - indicates a new interesting hypothesis on the electron population responsible for the gamma-ray emission.

Key words. Radio continuum: stars – X-rays: binaries – gamma-rays: observations – X-rays: individual: LSI+61303

1. Introduction

The TeV-emitting source LS I +61°303 is a X-ray binary system where a compact object travels through the dense equatorial wind of a Be star. The most typical peculiarity of LS I +61°303 is a large periodic radio outburst toward apoastron. In Fig. 1 we see 6.7yr of Green Bank Interferometer data folded with the orbital period P_1=26.496 d (Φ: $\frac{(t-t_0)}{P_1}$, with t_0=JD 2443366.775) (Gregory 2002). Periastron passage corresponds to orbital phase Φ=0.23 for Casares et al. (2005) and to Φ = 0.275 for Aragona et al. (2009). As one can see in Fig. 1, the outburst is clustered around Φ $\simeq$0.6, i.e. almost apoastron. The broad shape of the light curve of Fig.1 is due to variations of the orbital phase and amplitude of the outburst, both changing with a

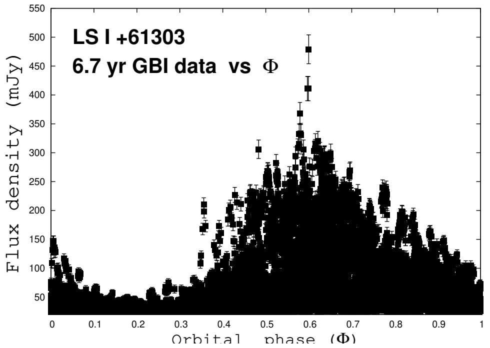

Fig. 1. Radio light curve of LS I +61303 (6.7 yr of Green Bank Interferometer data) vs orbital phase (Massi & Kaufman Bernadó (2009), reproduced by permission of the AAS).

long-term period P_2=1667 d (Gregory 2002) (Θ: $\frac{(t-t_0)}{P_2}$). Zamanov & Martí (2000) demonstrated a modulation on the same timescale in the H_α emission line. This latter result strongly suggests that the long-term modulation in the radio emission is related to changes in the Be star equatorial disk properties. In particular, Gregory & Neish (2002) suggest that the long-term modulation in radio properties may stem from periodic ejections of a shell (density enhancement) of gas in the equatorial disk of the Be star.

2. Two-peak accretion model

One of the fundamental questions concerning the strong periodic radio outbursts at $\Phi \simeq 0.6$ of LS I +61°303 has been: why are they shifted with respect to the periastron passage (i.e. $\Phi = 0.230 - 0.275$)?

The accretion rate $\dot{M} \propto \frac{\rho_{\rm wind}}{v^3_{\rm rel}}$, where $\rho_{\rm wind}$ is the density of the Be star wind and $v_{\rm rel}$ is the relative speed between the accretor and the wind, is in fact proportional to the density of the accreted material (Taylor et al. 1992). The highest density is obviously at the periastron. The explanation for the shift is that the orbit of LS I +61°303 is quite eccentric, e=0.54 – 0.7 (Aragona et al. 2009; Casares et al. 2005). In an eccentric orbit the different relationship for density and velocity (inversely proportional to the power of 3) creates two peaks in the accretion rate curve, one at periastron because of the highest density, and a second one when the drop in density is compensated by the decrease in velocity towards apastron. Taylor et al. (1992) computed the accretion rate curve for different eccentricities and showed that two peaks begin to appear for an eccentricity above 0.4. Whereas the first peak is always toward periastron, the orbital occurrence of the second accretion peak depends on variations of the wind of the Be star with the period P_2=1667 d. Martí & Paredes (1995) computed the accretion rate curve for different wind velocities and showed that for a stellar wind velocity of 20 km/sec the two peaks become rather close to each other, whereas for a wind velocity of 5 km/sec they have an orbital offset of $\Delta\Phi = 0.4$. For periastron at $\Phi \simeq 0.2$-0.3 the second peak may therefore appear at $\Phi \sim 0.6 - 0.7$, as indeed occurs. Martí & Paredes (1995) have shown that both peaks are above the Eddington limit and therefore one expects that matter is ejected twice within the 26.5 d interval. Romero et al. (2007) applied a smoothed particle hydrodynamics code to develop three-dimensional, dynamical simulations for LS I +61°303 and found that indeed the accretion rate has two peaks per orbit, i.e. a narrow peak at periastron, and a broad peak that lags the periastron passage by about 0.3 in phase.

Models and simulations predict therefore two peaks. Why do we observe only the second ejection? Martí & Paredes (1995) predicted that near periastron the ejected relativistic electrons are embedded in such a strong UV-radiation field that they loose their energy by the inverse Compton (EIC) process: no radio emission but high energy emission is predicted. Bosch-Ramon et al. (2006) computed the inverse compton losses and the related light curves of emission for LS I +61°303 in the radio band and at high energy. Bosch-Ramon et al. (2006) fixed the Be wind parameter to have the second accretion peak at Φ=0.5. Their results, are here shown in Fig. 2. In perfect correspondence to the accretion rate curve the radio light curve shows two peaks, one large outburst at Φ=0.5 and another smaller outburst at periastron. The high energy light curve shows

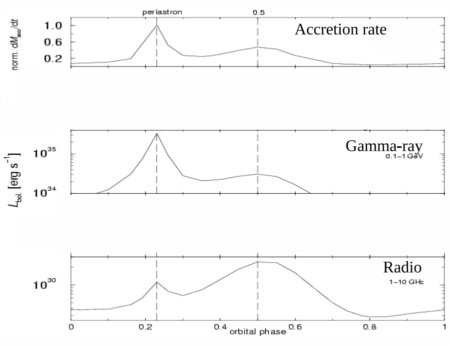

Fig. 2. Computed accretion rate and light curves by Bosch-Ramon et al. (2006) (from their Fig. 2, reproduced with permission ©ESO). Bosch-Ramon et al. fixed the Be wind parameter to have the second accretion peak at Φ=0.5.

exactly the contrary situation, again two peaks one at periastron and the other at Φ=0.5, but the dominant peak is at periastron. During the second accretion peak the compact object is at larger distance from the Be star and therefore inverse Compton losses are lower: the associated gamma-ray outburst is weaker and the electrons are able to emit stronger synchrotron radiation producing the larger radio outburst.

Gamma-ray observations confirm Martí & Paredes (1995) predictions and Bosch-Ramon et al. (2006) calculations. LS I +61°303 was detected by EGRET (Tavani et al. 1998). As discussed in Massi (2004), Massi et al. (2005) and Massi & Kaufman Bernadó (2009) these data well support the hypothesis of a high-energy outburst at periastron: EGRET observations at Θ=0.18 during a well sampled full orbit show a clear peak at periastron passage. EGRET observations at Θ=0.41, along with an increase of the emission again near periastron show even a second peak at $\Phi \simeq 0.5$ (see Fig. 3 in Massi et al. 2005). Fermi-LAT observations (Abdo et al. 2009) were performed at $\Theta = 0.788 - 0.927$. The Fermi light curve is characterized by a broad peak after periastron as well as a smaller peak just before apastron. Therefore, the first gamma-ray peak seems indeed to be persistent, whereas the second gamma-ray peak seems as predicted, to

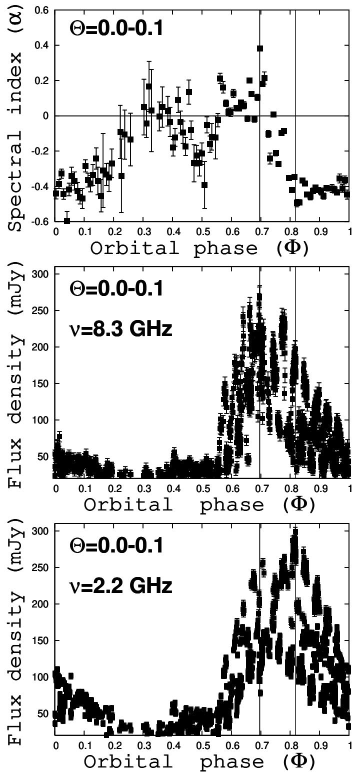

Fig. 3. LS I +61°303. Spectral index and flux density of Green Bank Interferometer data at 8.3 GHz and 2.2 GHz vs orbital phase, Φ, in the interval Θ=0.0-0.1. Note that the evolution from an optically thick to an optically thin spectrum occurs twice, giving the α vs Φ curve a double-peaked shape. (Massi & Kaufman Bernadó (2009), reproduced by permission of the AAS).

change as function of the long term variations of the Be star.

3. Radio spectral index analysis

From the previous section we see as the two-peak accretion model, including energetic losses, predicts at periastron a high energy outburst due to IC along with a small radio outburst, and associated to the second accretion peak a large radio outburst and possibly, depending on the stellar distance, a gamma-ray peak. The large radio outburst should follow the typical characteristics of microquasars: optically thick emission, i.e. $\alpha \geq 0$ (with flux density $S \propto \nu^{\alpha}$), followed by an optically thin outburst, i.e. $\alpha < 0$ (Fender et al. 2004). In microquasars the first type of emission, the optically thick radio emission, is related to a steady, low velocity, conical jet centered on the system. The following optically thin outburst, called "transient jet", is due to shocks caused by the travelling of new highly relativistic plasma, generated by a transient, through the underlying, slow, steady flow (Fender et al. 2004; review by Massi in this volume). In Fig.3 we see the spectral index and flux density, at 8.3 GHz and 2.2 GHz vs orbital phase, Φ, for the GBI data in the interval Θ=0.0-0.1 (see Massi & Kaufman Bernadó (2009) for details). Clearly associated with the large outburst of LS I +61°303 is the predicted evolution for microquasars, from an optically thick to an optically thin spectrum. At the bottom of Fig. 3, the light curve at 2.2 GHz reveals that the large outbust at $\Phi \sim 0.8$ is preceeded by another outburst at $\Phi \sim 0.7$. The spectral index at the top of Fig. 3, shows the different nature of the two outbusts: the minor outburst at $\Phi = 0.7$ is optically thick, whereas the larger peak around $\Phi = 0.8$ is an optically thin outburst. In particular, the outburst at $\Phi = 0.7$ is related to an optically-thick-emission interval creating a broad peak in the spectral index curve. In the context of microquasars this interval corresponds to the emission from a steady, low velocity conical jet. Around periastron in the light curves at 2.2 and 8.3 GHz one sees only very small, barely detectable outbursts at $\Phi \sim 0.3 - 0.4$. On the basis of the light curves alone one would never be able to associate these negligible peaks to the predicted small radio outburst at periastron by Martí & Paredes (1995) and Bosch-Ramon et al. (2006). When one, however, analyses the spectral index curve at the top of Fig. 3, one sees that $\Phi \sim 0.3 - 0.4$ indeed corresponds again to a broad peak in the spectral index curve. The evolution from an optically thick to an optically thin spectrum occurs clearly twice giving the α vs Φ curve a double-peaked shape, as expected from a two-peak accretion curve.

As shown in Fig. 5 of Massi & Kaufman Bernadó (2009) this shape is not constant but changes during the long 1667 d cycle in agreement with Martí & Paredes (1995) computations for variable parameters of the wind of the Be star. This variation of the accretion rate curve/spectral index curve with Θ implies that one can compare data of different epochs *only* when observed in the same Θ interval. As an example one sees that at the top of Fig. 3, for $\Theta = 0.0 - 0.1$, the spectral index curve at $\Phi = 0.5$ gives $\alpha < 0$ (i.e. corresponding to a transient jet); at the top of Fig. 4 for $\Theta = 0.788 - 0.927$, one sees that at the same orbital phase $\Phi = 0.5$, it results $\alpha > 0$ (i.e. corresponding to a steady slow conical outflow). We compare here in Fig. 4 the Fermi-LAT gamma-ray curve with the spectral index for GBI data at other epochs than Fermi-LAT observations but in the same phase $\Theta = 0.788 - 0.927$. It is worth noting that both Fermi-LAT gamma-ray peaks correspond to intervals where the radio emission is optically thin. This correspondence would imply that the electrons responsible for the inverse Compton process creating the gamma-ray emission are those of the fast transient jet and not those of the slow outflow.

4. Conclusions

We analyzed the radio spectral index using 6.7 years of GBI radio data of LS I +61°303. Our main conclusions are that the periodic ($P_1 = 26.5$d) large radio outburst of LS I +61°303 consists of two successive outbursts, one optically thick and the other optically thin. This creates one peak in the spectral index curve. In microquasars, the optically thick emission is associated to a steady jet and the optically thin outburst to the transient jet. We observe that along the 26.5 d orbit the evolution from an optically thick to an optically thin spectrum occurs also around periastron creating a second peak in the spectral index curve, giving the α vs Φ curve a double-peaked shape. This result agrees with the predictions of the two peak accretion/ejection model, with the results of three-dimensional dynamical simulations and finally with gamma-ray data. All these results indicate a scenario with a first ejection around the periastron passage with low radio emission, but high energy emis-

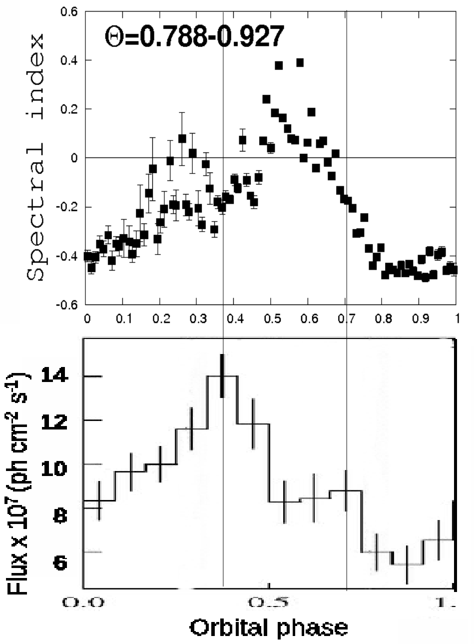

Fig. 4. Radio and gamma-ray data observed at different epochs but in the same interval Θ=0.788-0.927 of the 1667 d periodicity. Top: Spectral index of Green Bank Interferometer data at 8.3 GHz and 2.2 GHz. Bottom: Fermi-LAT data from Abdo et al. (2009), reproduced by permission of the AAS.

sion, due to inverse Compton losses caused by the proximity of the B0 star, and a second ejection far away from the Be star, with negligible losses and therefore with a well observable radio outburst. Finally, the here given comparison of radio (GBI) and gamma-ray (Fermi-LAT) data seems to imply that the electrons responsible for the inverse Compton process creating the gamma-ray emission are those of the fast transient jet and not those of the slow outflow.

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