Analysis of hard X-ray/high energy data from LS I +61°303 based on implications from its 4.6 yr periodicity

Zimmermann, L. and Massi, M.
Max Planck Institute for Radio Astronomy, Bonn, Germany

Grinberg, V. and Wilms, J.
Remeis Observatory/ECAP/FAU, Bamberg, Germany

The most peculiar radio characteristics of the TeV emitting high-mass X-ray binary LS I +61°303 are two periodicities: A large periodic outburst which exhibits the same period as the orbit (phase Φ) and a second periodicity of 1667 days (phase Θ) which modulates the orbital phase and amplitude of the large outburst. Recent analysis of the radio spectral index present strong evidence for the presence of the critical transition from optically thick emission (related to a steady jet) to an optically thin outburst (related to a transient jet) as in other microquasars. In parallel, a switch from a low/hard X-ray state to a transitional state (e.g. steep power law state) would be expected. We show how the critical transition from optically thick emission to an optically thin outburst is modulated by Θ. Folding over a too large Θ interval mixes up important information about the outbursts and can yield a false picture of the emission behaviour of the source along the orbit. We therefore analyse the implications of this long period for treatment of hard X-ray/high energy data obtained from LS I +61°303, e.g. with Fermi-LAT or INTEGRAL, taking into account this long-term periodicity.

I. 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, each peak in the radio spectral index 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 inverse Compton upscattering of the UV photons from the donor star by the relativistic electrons of the jet, 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 apastron [11, 12, 13, 14].

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, 5, 15, 16, 17, 18, 19, 20, 21]. 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 apastron, and in Fig. 4 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 [22]). It is suggested that this modulation could be due to periodic shell ejections from the circumstellar disk of the Be star [23].
II. HIGH ENERGY OBSERVATIONS AND THE RADIO SPECTRAL INDEX

The radio spectral index analysis by [5] have shown the importance of the large phase $\Theta$ 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 a transitional state, e.g., the steep power law state with $\Gamma > 2.4$ [21, 22, 23]. Furthermore, high energy and very high energy emission are directly connected to the transitional state (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 fitted with a power law with an index $\Gamma \geq 2.4$ [20, 21, 27, 28]. 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 transitional 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 necessary to take into account the long period $\Theta$. Therefore, to compare high energy data with the radio spectral index, it is necessary as well to take only data of the same $\Theta$ phase. [9] has done so e.g. for the first eight months of Fermi-LAT observations and the results (see Fig. 2) show that in this comparison the high energy peaks established by Fermi-LAT both correspond to the optically thin outbursts of LS I +61°303. One could then 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. Furthermore, in Fig. 3 are shown radio spectral index curves vs. the orbital phase for two different $\Theta$ intervals. In particular the orbital occurrence of the second peak is different in the different intervals. 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.

III. INTEGRAL OBSERVATIONS OF LS I +61°303 AND Θ

In Fig. 4 high energy and very high energy observations of LS I +61°303 with different instruments are shown with respect to the Θ intervals in which they have been carried out. Both, MAGIC and VERITAS probe the minimum and the maximum parts of Θ [21, 27, 28]. Due to the long integration times for the data, the sampling within these intervals is not very strong, although EGRET observed one complete orbital cycle at each of the two given intervals [6, 20, 21]. The latest published coverage by Fermi is of 2.5 years [30].

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 Θ by I1, I2 and I3, as noted in Fig. 4. 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 [18, 19, 31].

Following the radio spectral index though (see Fig. 4), folding over almost a complete Θ cycle would imply that even though the resulting light curves could show the overall periodicity of the source at these energies, a deeper insight about the ejections can be obscured by mixing different ejection processes (namely optically thick and thin ejections). The spectral analyses can then get corrupted, because of the same mixing of ejection processes.

I1 and I3 are covering most of the maximum of Θ (see Fig. 4). 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. In fact, [18], who used most of I3 and parts of I1, have found not only the modulation of the lightcurve with the orbital period, but also found that along the orbit the spectral index Γ changed from ≈1.5 around periastron to ≈3.2 around apastron. 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 apastron (see [2] and discussions therein) As mentioned above, in the unified X-ray states model with radio jets, a transient is associated with a transitional state, e.g. the steep power law, characterized by a spectral index Γ >2.4 [24, 25, 26].

IV. CONCLUSIONS AND DISCUSSION

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 [1, 23]. 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 two different kinds of outburst: optically thick (spectral index α > 0) and optically thin (α < 0). The first is attributed in the 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. In the first eight months observations with Fermi-LAT, 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 apastron (Φ=0.65-0.75). Furthermore, as discussed in [5].
the two peak shape of the $\alpha$ vs. $\Phi$ curve varies with $\Theta$, as does the distance of the two peaks (see also Fig. 2 here). The two-peak microquasar model of [12] predicts these variations in the accretion curve by incorporating changing wind velocities for the Be star (see their Fig.6). This behaviour should be seen at other wavelengths as well, due to the connected emission processes. In fact, after the first eight months, Fermi-LAT detected an increase in the overall flux level ($\Theta \approx 0.92$) and a broadening of the peak shape [30]. These variations are consistent with the observation that $\alpha$ varies with $\Theta$. Variations are also seen with VERITAS and MAGIC. LS I +61$^\circ$303 was detected around apastron until 2008 and then became quiescent between 2008-2010, where no detection was reported by VERITAS, while MAGIC reported only weak detection around apastron. Then in October 2010, VERITAS detected the source again, this time around periastron [21, 27, 28].

The strong connection between radio and HE/VHE emission underlines therefore the importance of the radio periods for the analysis of e.g. INTEGRAL data and can and should in principle be extended to other high energy instruments.

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