The apparent discontinuity in the periodicity of the GeV emission from LS I +61°303

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The γ-ray binary LS I +61°303 shows a discontinuity of the periodicity in its GeV emission. In this paper, we show that during the epochs when the timing analysis fails to determine the orbital periodicity, the periodicity is in fact present in the two orbital phase intervals \( \Phi = 0.0 - 0.5 \) and \( \Phi = 0.5 - 1.0 \). That is, there are two periodic signals, one towards periastron (i.e., \( \Phi = 0.0 - 0.5 \)) and another one towards apastron (\( \Phi = 0.5 - 1.0 \)).

The data analysis

2. Data analysis

For the present analysis \cite{2} we use Fermi LAT data from LS I +61°303 spanning the time range August 5, 2008 (MJD 54683) until June 30, 2014 with an energy range of 100 MeV to 300 GeV. For the computation of the light curves we used
3. Results: A periodic signal around apastron

3.1. Wavelet analysis

Our results are shown Fig. 2. The first plot of Fig. 2 presents the examined data set. The wavelet analysis was applied to the γ-ray data vs time, however, for a straightforward comparison with radio data, we express in the other plots of Fig. 2 the x-axis as the long-term phase \( \Theta \). The second plot of Fig. 2 shows the wavelet plot for the whole data set, i.e., the whole orbital period \( \Phi = 0.0 – 1.0 \). The absence of the orbital period around \( \Theta \approx 7.2 \) is consistent with the previous finding shown in Fig. 4 of [10]. When wavelet analysis is performed only on data from the orbital phase intervals \( \Phi = 0.0 – 0.5 \) (middle) and \( \Phi = 0.5 – 1.0 \) (bottom), it is revealed that there is always a periodic signal at \( \Phi = 0.0 – 0.5 \) (periastron). Moreover, there is a periodic signal at \( \Phi = 0.5 – 1.0 \) (apastron). The latter becomes particularly strong during the time when the orbital period is absent from the power spectra of \( \Phi = 0.0 – 1.0 \) [3].

3.2. Lomb-Scargle timing analysis

Figure 3 shows Lomb-Scargle periodograms of the γ-ray flux from LS I +61°303. The data have been selected from orbital phase intervals like in the previous section. In the periodogram for the entire orbit (Fig. 3a) the strongest feature is a peak which agrees well with the orbital period \( P_1 \) found by [17]. Figures 3d, e, and f refer to only data from \( \Phi = 0.5 – 1.0 \). In this orbital phase interval the peak at \( P_{long} \) is a very strong feature, in agreement with the findings of [10]. Moreover, the zoom of Fig. 3d, i.e., Fig. 3e, shows a second peak, \( P_2 = 26.99 \pm 0.08 \) d. This second peak becomes stronger and is almost as strong as the peak at \( P_1 = 26.48 \pm 0.08 \) d in the 5 day integrated data in Fig. 3f. The periods \( P_1 \), \( P_2 \) (see Fig. 4), and \( P_{long} \) here present are typical periodicities in radio data as shown in [15].

3.3. Folded Fermi LAT data: The apastron GeV peak and its orbital shift

Figure 5a and b show Fermi LAT data from the time (\( \Theta \approx 7.2 \)) of the disappearance of the orbital period from the power spectra folded with the orbital period. A second peak is evident at orbital phases \( \Phi = 0.8 – 1.0 \). Figure 5c shows Fermi LAT data for another \( \Theta \). It is now interesting to compare these plots with radio data. Because of the long-term periodicity we can compare γ-ray and radio data having the same fractional part of \( \Theta \). Figure 5d shows GBI radio data at 8 GHz [for details see 3].

4. Conclusions

During the intervals where the orbital periodicity is absent from the power spectra, wavelet and the folded light curves show two periodic signals, one at periastron and a second at apastron. The presence of the second periodic outburst disturbs the timing analysis and prevents it from finding the orbital periodicity. Comparison with the folded radio data (Fig. 4d) suggests that the apastron GeV peak follows the same orbital shift as the radio outbursts [3]. It is well-known the phenomenon of the orbital shift of the radio outburst in LS I +61°303: The largest outbursts occur at orbital phase 0.6, afterwards, with the long-term periodicity, the orbital phase of the peak of the outburst changes, as analysed by [16] in terms of orbital phase shift, by [17] in terms of timing residuals, and reproduced recently by the precessing jet model in [18], here shown in Fig. 5.

Our result of two GeV peaks along the orbit corroborates the two-peak accretion model for LS I +61°303. The hypothesis that a compact object that accretes material along an eccentric orbit undergoes two accretion peaks along the orbit was suggested and developed by several authors for the system LS I +61°303 [16, 20, 21, 22]. The first accretion peak is predicted to occur close to the Be star and to give rise to a major high-energy outburst. The second accretion peak is predicted to occur much farther away from the Be star, where the radio outburst occurs, and a minor
high-energy outburst is predicted there [21]. The predicted periastron event corresponds well to the observed GeV peak towards periastron, the second predicted high-energy outburst, corresponds well to the here discussed apoastron peak.

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Figure 2: Wavelet analysis of Fermi-LAT data. The strength of periodicity is colour coded as indicated in the bottom bar. (a) Fermi-LAT data with a time bin of 1 d. (b) Wavelet analysis for the whole orbital interval 0.0 – 1.0 (b–d use a time bin of one day). (c) Wavelet analysis for the orbital interval Φ = 0.5 – 1.0, i.e., around apoastron. (d) Wavelet for the orbital interval Φ = 0.0 – 0.5, i.e., around periastron.
Figure 3: Lomb-Scargle periodogram of the Fermi LAT data (with a time bin of one day). Figure 3 in [3]. (a) Data in the orbital phase $\Phi = 0.0 - 1.0$. (b) Zoom of Fig. 3a. (c) Same as 3b for data with a time bin of 5 d. (d) Data in the orbital phase $\Phi = 0.5 - 1.0$. The periods $P_2$ and $P_{\text{long}}$ here present are typical periodicities in radio data [15]. (e) Zoom of Fig. 3d. (f) Same as 3e for data with a time bin of 5 d. (g) Data in the orbital phase $\Phi = 0.0 - 0.5$. (h) Zoom of Fig. 3g. (i) Same as 3h for data with a time bin of 5 d.
Figure 4: (a)-(c) Folded Fermi LAT γ-ray data (100 MeV – 300 GeV). The blue curve in (c) is that of [9]. (d) Folded GBI 8 GHz radio data. The here discovered periodic apastron GeV peak follows the same timing characteristic (i.e., $P_1$ and $P_2$ are both present) as the periodic radio peak, which also occurs around apastron. During the time when the orbital period disappears from the power spectra of the γ-ray light curve (see Fig. 2 b, $\Theta \approx 0.86$) the apastron GeV peak becomes well visible in the folded light curve, because it is more displaced from the periastron peak (see [3] and here Sect. 4).

Figure 5: Left: Timing analysis of 6.7 years of GBI radio data at 2 and 8 GHz results in two periods, $P_1 = 26.49 \pm 0.07$ d, $P_2 = 26.92 \pm 0.07$ d. The long-term period $P_{\text{long}} = 1667 \pm 8$ d is consistent with the period $P_{\text{beat}} = 1/(\nu_1 - \nu_2) = 1667 \pm 393$ d resulting from the beating between the two close periodicities $P_1$ and $P_2$ [15]. Right: Orbital shift of the radio outburst of LS I +61°303 in the precessing jet model of [18]. At $\Theta = 0.86$ the outbursts peak at $\Phi \approx 0.6$. At $\Theta = 0.265$ the outbursts peak at $\Phi \approx 0.85$. 

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