Temporal features of LS I +61°303 in hard X-rays from the
Swift/BAT survey data

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ABSTRACT

We study the long-term spectral and timing behaviour of LS I +61°303 in hard X-rays (15–150 keV) using \sim 10 years of survey data from the \textit{Swift} Burst Alert Telescope (BAT) monitor. We focus on the detection of long periodicitites known to be present in this source in multiple wavelengths. We clearly detect three periods: the shorter one at 26.48 days is compatible with the orbital period of the system; the second, longer, periodicity at 26.93 days, is detected for the first time in X-rays and its value is consistent with an analogous temporal feature recently detected in the radio and in the gamma-ray waveband, and we associate it with a modulation caused by a precessing jet in this system. Finally, we find also evidence of the long-term periodicity at \sim 1667 d, that results compatible with a beat frequency of the two close, and shorter, periodicities. We discuss our results in the context of the multi-band behaviour of the physical processes of this source.

Key words: X-rays: binaries – X-rays: individual: LS I +61°303. Facility: \textit{Swift}

1 INTRODUCTION

LS I +61°303 is an accreting binary system well-known for exhibiting an exceptional broadband spectrum from radio to TeV energies (\textit{Albert et al.} 2008). The system consists of a main sequence star of type B0 Ve (\textit{Hutchings & Crampton} 1984), with an estimated mass 10–15 M\odot, and a compact object (it is still debated if a black-hole or a neutron star) orbiting with a period \textit{P}\textsubscript{\textit{orb}} = 0.537 ± 0.0028 d in a highly eccentric orbit (\textit{e} = 0.537 ± 0.034), at a distance from us of 2 kpc (\textit{Aragona et al.} 2009).

The system is characterized by different long periodicities: the shortest one is associated with the above-mentioned orbital period and it is detected in all bands of the electromagnetic spectrum, from radio, where it was first noticed (\textit{Taylor & Gregory} 1982) up to \gamma-rays (\textit{Abdo et al.} 2009). The longest periodicity, also first noted in the radio band (\textit{Gregory et al.} 1999), is clearly super-orbital at a period \sim 4.6 years (\textit{P}\textsubscript{\textit{so}}), and because of the larger time-span required to detect it, it has been only recently detected at higher frequencies (see \textit{Li et al.} 2014 and reference therein). In the X-ray band, the modulation appears phase shifted of \sim 0.2 with respect to the radio one (\textit{Li et al.} 2012). In between there is a periodicity very close to the known orbital period at \textit{P}\textsubscript{2} = 26.99 ± 0.08 d, that has been more recently observed only in the radio and in the \gamma-ray bands (\textit{Massi & Jaron} 2013; \textit{Jaron & Massi} 2014) and, finally, a periodicity that appears as an averaged value between \textit{P}\textsubscript{2} and \textit{P}\textsubscript{\textit{orb}} at \textit{P}\textsubscript{av} = 26.704 ± 0.004, that has been exclusively attributed to the radio outburst recurrence time (\textit{Ray et al.} 1997; \textit{Jaron & Massi} 2013).

According to \textit{Massi & Torricelli-Ciamponi} (2014) \textit{P}\textsubscript{2} is caused by a precession of a conical jet, as also revealed by the periodic change of the associated extended radio structure (\textit{Massi et al.} 2012), while the \textit{P}\textsubscript{\textit{so}} is the result of the beat between the two shorter periods, \textit{P}\textsubscript{\textit{orb}} and \textit{P}\textsubscript{2} (\textit{Massi & Jaron} 2013): namely, its value (within the statistical uncertainties) results compatible with this hypothesis (\textit{P}\textsubscript{\textit{so}} = (\textit{P}\textsubscript{\textit{orb}}\textsuperscript{-1} – \textit{P}\textsubscript{2}\textsuperscript{-1})\textsuperscript{-1}). Other authors suggest instead a possible connection with the time-scales of the Be stellar activity (\textit{Ackermann et al.} 2013), or the precession of the Be companion star’s decretion disk (\textit{Lipunov & Nazin} 1994).

In this paper, we exploit the continuous hard X-ray coverage of this source made in the last \sim 10 years by the \textit{Swift}/BAT monitor, to assess the presence and the spectral characteristics of these periodicities in the hard X-ray band.

2 DATA REDUCTION AND ANALYSIS

We retrieved the survey data for LS I +61°303 collected with \textit{Swift}/BAT between 2004 December 09 (MJD 53348) and 2015 March 10 (MJD 56827) from the HEASARC public archive\footnote{\url{http://heasarc.gsfc.nasa.gov/docs/archive.html}} and processed them using a software package dedi-
cated to the analysis of the data from coded mask telescopes (Segreto et al. 2010). The BAT light curve consists of 55,312 entries and the source was in the BAT field-of-view (Segreto et al. 2010). The BAT light curve consists of 55,312 entries and the source was in the BAT field-of-view (Segreto et al. 2010). The BAT light curve consists of 55,312 entries and the source was in the BAT field-of-view (Segreto et al. 2010). The BAT light curve consists of 55,312 entries and the source was in the BAT field-of-view (Segreto et al. 2010). The BAT light curve consists of 55,312 entries and the source was in the BAT field-of-view (Segreto et al. 2010). The BAT light curve consists of 55,312 entries and the source was in the BAT field-of-view (Segreto et al. 2010). The BAT light curve consists of 55,312 entries and the source was in the BAT field-of-view (Segreto et al. 2010). The BAT light curve consists of 55,312 entries and the source was in the BAT field-of-view (Segreto et al. 2010).

Data analysis was performed using the HEASARC/FTOOLS v. 6.16, the RStudio software (RStudio Team 2015) and the specific Lomb-Scargle R package (Ruf 1999). We report errors at one sigma confidence level, unless stated otherwise.

2.1 Temporal analysis: detection of the $P_{\text{so}}$

We first studied the long-term light curve of the BAT data, looking for the $P_{\text{so}}$ presence. Because the data cover approximately slightly more than two complete orbits, we tried to directly fit the light curve using as a best-fitting model the sum of a constant emission and a sine function, assuming the shape of the periodicity is sinusoidal. Data were re-binned using a time-bin of 80 days, corresponding to about three complete orbital periods. The values for the constant rate, the sine amplitude, the period and the phase were initially all left as free parameters.

We found an averaged flux of $(4.9 \pm 0.2) \times 10^{-5}$ counts s$^{-1}$ pixel$^{-1}$, a semi-amplitude of $(1.2 \pm 0.3) \times 10^{-5}$ counts s$^{-1}$ pixel$^{-1}$ a super-orbital period $P_{\text{so}} = 1689 \pm 122$ d. We show in the upper and lower panel of Fig. 2 the BAT light curve with super-imposed the best-fitting model and the folded profile at $P_{\text{so}}$ respectively. The F-test that compares this model with the null-hypothesis of no modulation in the data gives $\sim 1\%$ probability that the improvement is obtained only by chance. The sinusoid peaks at the super-orbital phase $\sim 0.2$, compatible with the phase shift ($\Delta \phi = 0.17 \pm 0.02$) observed in soft X-rays and in hard X-ray with INTEGRAL/ISGRI data (Li et al. 2012, 2014).

We then extracted two, statistically similar, energy-selected light curves in the 15-35 keV (source significance $\sim 20\sigma$) and in the 35-150 keV (significance $\sim 16\sigma$) bands to check the amplitude dependence on energy. To this aim, we obtained the values for best-fitting function composed of a constant and a sinusoidal component as previously described. We found that the modulation is statistically detected in the softer band at $> 3\sigma$ ($P_{\text{so}} = 1715 \pm 140$ and amplitude fraction $\sim 0.3$) while only marginal detection ($\sim 2\sigma$) is obtained for the harder band.

2.2 Temporal analysis: Lomb-Scargle periodograms

We searched for any periodicity in the 22–32 d period range using the Lomb-Scargle periodogram (LSP) technique (Lomb 1976). We consider that the error on the detected periods is the half-width of the bin period, that is for the BAT data-set and periods of interest $\sim 0.10$ d. A preliminary search using the whole dataset in the 15-150 keV band did not result in any significant detection. In fact, LSP method is insensitive to the statistical error associated to each measure, while the BAT survey data are characterized by a wide spread of non-Gaussian statistical errors that depend on several factors (mainly the reduction of the coded fraction when
the source is observed at large off-axis angles). In this case, a filtering method may help a weak feature to emerge over the noise. We therefore began to gradually remove data with the largest associated rate uncertainty. We noted that by filtering out from the original dataset the 23% of the data with the largest uncertainty, a periodicity at 26.47 ± 0.10 d starts to be significantly detected, while removing the 35% of the noisiest data, resulted in the detection of a second period of slightly higher value at 26.93 ± 0.10 d, compatible with the $P_2$ period that had been reported in radio and in the gamma band (see Fig. 3).

We repeated the same procedure for the two energy-filtered datasets (15–35 keV and 35–150 keV bands). We noted again that it was necessary to remove part of the noisiest entries to obtain statistically significant detections. As for the entire energy range the orbital period is the first feature to emerge, followed by the $P_2$ detection. In particular, for the softest band both periods are detected when 36% of the data are removed, while for the hardest energy band this happens after 24% of the data are removed.

Following Jaron & Massi (2014), we then passed to study the power of the two signals for different orbital phase intervals (where the phase is calculated assuming as time of reference $T_0 = 43.366275$ MJD and $P_{\text{orb}} = 26.496$ d), using a moving window of constant phase width of 0.5, with no selection on energy, and filtering out the noisiest data when needed. We found that the intensity of both features strongly depends on the orbital phase selection: this is more clearly seen in the upper panel of Fig. 5 we show the BAT data folded to assess the presence and the spectral characteristics of its periodicities (when 35% of noisiest data are removed). We note that the power associated to the $P_2$ periodicity becomes sensibly stronger with respect to $P_{\text{orb}}$, in analogy with what observed also in the GeV band (Jaron & Massi 2014).

Finally, we studied the temporal evolution of the signals according to the super-orbital phase. To this aim, we selected 5 phase intervals, choosing the boundaries so to keep the same number of data for each interval (i.e. 0, 0.15, 0.31, 0.54, 0.79, 1). We found that both the $P_2$ and the $P_{\text{orb}}$ periods could be well detected in the LSP only for the super-orbital phase interval 0.15–0.31, whereas marginal significant detection is obtained for the other phase-intervals.

3 ORBITAL MODULATION OF THE SPECTRAL SHAPE

We studied the spectral shape of the hard X-ray emission as a function of the orbital, $P_{\text{orb}}$, and jet precession $P_2$ phase. In the upper panel of Fig. 6 we show the BAT data folded at $P_{\text{orb}}$ for three energy bands: 15–35 keV, 35–150 keV, and 15–150 keV. The emission peaks at phase $\sim 0.3$, while the phase of minimum emission appears more structured around the apoastron passage. The observed maximum flux ratio is $\sim 6$. The folded profile is similar in the two energy-selected bands, although it is to be noted that the soft emission is enhanced over the hardest band in the first half of the orbital cycle. This is most easily observed through a direct spectral fit of the phase-selected spectra. We choose 10 equally spaced phase selected spectra and fitted them using a simple power-law model. We show in the lower panel of Fig. 6 the dependence of the photon-index as a function of the orbital phase. We observe a clear trend as a function of the phase that gives an account of the overall modulation of the energy-selected folded profiles.

We show in Fig. 6 two folded profiles at $P_2$ using the same epoch of reference of the folded $P_{\text{orb}}$ and a period of 26.93 d, that is the our best value according to the LSP of Fig. 4. The profile in blue is averaged over all orbital phases, whereas the profile in black is obtained when the signal becomes enhanced in the orbital phase interval 0–0.5.

4 DISCUSSION

We examined the Swift/BAT light curve of LS I +61°303 to assess the presence and the spectral characteristics of its

\[ \text{Figure 3. LSP of the filtered BAT data-set in the 22–32 d period region of interest. False alarm probability (horizontal dotted line) is set at 0.01. Blue (red) line is the LSP for the BAT dataset with 23% (35%) of noisiest data removed.} \]

\[ \text{Figure 4. LSP of two phase-selected datasets. Blue (red) line is the LSP for the orbital phase interval 0–0.5 (0.5–1.0). False alarm probability (horizontal dotted line) set at 0.01.} \]
During the first half of the super-orbital cycle, we confirm a higher X-ray emission. The overall emission (synchrotron emission emitted by relativistic electrons in the magnetized jet) is the highest when the jet forms the minimum angle with our line of sight and its emission becomes Doppler boosted. We estimated the expected beat period ($\nu_{\text{beat}} = \nu_2 - \nu_1$) of these two periodicities to be $1560 \pm 480$ d, consistent with our measure of the long-term modulation ($P_{\text{iso}}$), although we note the rather large uncertainties on $P_2$ and $P_{\text{orb}}$. We found that the power of the two signals depends on the super-orbital phase, and it is maximum in both cases for the super-orbital phase 0.15–0.31, that corresponds to the peak of the $P_{\text{iso}}$ folded profile (lower panel of Fig. 2).

We also studied the spectral shape in hard X-rays as a function of the orbital phase ($P_{\text{orb}}$) for the whole BAT time-span. The folded, time-averaged over the whole BAT observing window, X-ray profile peaks close to the periastron passage, and it shows two dips, before and after the apastron, that hint for a secondary peak at this phase (Fig. 5, lower panel). Although the ISGRI folded profile and the photon-index of the power-law that best fits the data in the 15–150 keV range as a function of the orbital phase, that shows a significant amplitude in the flux emission, comparable to that of the two signals depends on the super-orbital phase, and it is maximum in both cases for the super-orbital phase 0.15–0.31, that corresponds to the peak of the $P_{\text{iso}}$ folded profile (lower panel of Fig. 2).

Finally, we also reported for the first time the folded X-ray profile at the presumed jet periodicity, that shows a significant amplitude in the flux emission, comparable to that

![Figure 5. Upper panel: folded BAT light curve (15–110 keV range) at $P_{\text{orb}} = 26.49$ d. Time zero of reference MJD 43366.275. Red, blue, and black curves are data selected in the 15–35 keV, 35–150 keV and 15–150 keV ranges, respectively. Magenta dotted lines indicate the periastron and apoastron phase passages (Aragona et al. 2009). The BAT rate is in units of $10^{-3}$ counts s$^{-1}$ pixel$^{-1}$; lower panel: the photon-index of the power-law that best fits the data in the 15–150 keV range as a function of the orbital phase. We also show for comparison the values obtained with INTEGRAL/ISGRI data (red triangles) according to Li et al. (2014). Two periods shown for clarity.](image1)

![Figure 6. Folded BAT light curve (15–110 keV range) at $P_2 = 26.93$ d. Time zero of reference MJD 43366.275. Profile in blue is phase averaged (see LSP of Fig. 3), while profile in black is from data selected in the $P_{\text{orb}}$ phase ($\Phi > 0.5$, see LSP of Fig. 4). The BAT rate is in units of $10^{-3}$ counts s$^{-1}$ pixel$^{-1}$.](image2)
shown in the orbital period, when phase-selected around the
apoastron passage.

5 ACKNOWLEDGEMENTS

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