SPECTRAL ANALYSIS IN ORBITAL/SUPERORBITAL PHASE SPACE AND HINTS OF SUPERORBITAL VARIABILITY IN THE HARD X-RAYS OF LS I +61°303

JIAN LI1, DIEGO F. TORRES1,2, AND SHU ZHANG3
1 Institute of Space Sciences (IEEC-CSIC), Campus UAB, Torre C5, 2a planta, E-08193 Barcelona, Spain; jian@ieec.uab.es
2 Institució Catalana de Recerca i Estudis Avançats (ICREA), E-08010 Barcelona, Spain
3 Laboratory for Particle Astrophysics, Institute of High Energy Physics, Beijing 100049, China
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ABSTRACT

We present an INTEGRAL spectral analysis in the orbital/superorbital phase space of LS I +61°303. A hard X-ray spectrum with no cutoff is observed at all orbital/superorbital phases. The hard X-ray index is found to be uncorrelated with the radio index (non-simultaneously) measured at the same orbital and superorbital phases. In particular, the absence of an X-ray spectrum softening during periods of negative radio index does not favor a simple interpretation of the radio index variations in terms of a microquasar’s changes of state. We uncover hints of superorbital variability in the hard X-ray flux, in phase with the superorbital modulation in soft X-rays. An orbital phase drift of the radio peak flux and index along the superorbital period is observed in the radio data. We explore its influence on a previously reported double-peak structure of a radio orbital light curve, and present it as a plausible explanation.

Key words: methods: observational – X-rays: binaries – X-rays: individual (LS I +61°303)

Online-only material: color figures

1. INTRODUCTION

LS I +61°303 is a high-mass X-ray binary hosting a B0 V star with an equatorial outflowing disk. A compact object with an orbital period of 26.496 days (e.g., Casares et al. 2005) orbits the companion. LS I +61°303 is detected up to GeV and TeV γ-rays (Albert et al. 2006; Abdo et al. 2009; Acciari et al. 2009; Hadasch et al. 2012), and the non-thermal spectral energy distribution is dominated by high-energy photons. Two short (<0.1 s) and highly luminous (>10^{37} erg s^{-1}) thermal flares were recently detected from the direction of LS I +61°303 (Barthelmy et al. 2008; Burrows et al. 2012), giving support to the hypothesis that the compact object in LS I +61°303 is a (at least internally) highly magnetized neutron star (Torres et al. 2012; Papitto et al. 2012).

Besides the orbital period of 26.496 days and other short timescale variability (see, e.g., Paredes et al. 2007), LS I +61°303 is known to have a long-term (1667 days) superorbital modulation. The latter was first discovered in radio (Paredes 1987; Gregory et al. 1989, Gregory 1999, 2002), and then observed in the Hα emission line (Zamanov et al. 1999), X-rays (Li et al. 2012; Chernyakova et al. 2012), GeV (Ackermann et al. 2013), and hinted at TeV (Li et al. 2012; Torres et al. 2012). The possible origin of this 1667 day superorbital modulation could be the precession of the Be disk (Lipunov & Nazin 1994), the beat frequency between the orbital and precessional rates in a microquasar scenario (Massi & Jaron 2013), or the cyclic variability in the Be star envelope. The last interpretation seems to be the most likely, since the Hα emission line varies on the same period and it is well known, for Be stars, that the size of the circumstellar disk grows as the equivalent width of Hα increases (e.g., Hanuschik et al. 1988). In the maximum of the equivalent width of Hα, the X-ray and γ-ray emission are enhanced (Li et al. 2012; Ackermann et al. 2013). The orbital phase of the X-ray peaks from LS I +61°303 varies from 0.35 to 0.75 along the superorbital period, consistently leading the radio peaks by 0.2 orbital phases (Chernyakova et al. 2012). The different origin regions of X-ray and radio emission could lead to the observed phase lag. The observed multiwavelength variabilities in the superorbital timescale were discussed in the scenarios proposed by Torres et al. (2012) and Papitto et al. (2012), in which a neutron star switches between ejector and propeller states.

Black-hole (BH) composed microquasars manifest themselves in five classical spectral X-ray states (van der Klis 1994; Tanaka & Lewin 1995; Tanaka & Shibazaki 1996; Esin et al. 1997): the high/soft (HS) state, the low/hard (LH) state, the quasi-silent state, the very high state, and the intermediate state. These spectral states were reclassified by McClintock & Remillard (2006) as thermal–dominant, hard X-ray, quiescent, steep power law (SPL), and intermediate states. From an observational perspective, an optically thick steady jet with a flat (radio spectral index α ≈ 0) or inverted (α > 0) radio component is usually seen in the hard X-ray state (a power-law spectrum with index 1.5 < Γ < 2.1 in X-rays, McClintock & Remillard 2006), and an optically thin transient jet (α < 0) is associated with the overall hard to soft state transition (Fender et al. 2004, Fender et al. 2009).

In the hypothesis in which LS I +61°303 is a microquasar, the short thermal flares that have been detected from the region of LS I +61°303 must be explained by the spatial superposition of a magnetar with a γ-ray binary, although this is unlikely. In this hypothesis, Zimmermann & Massi (2012) expected a steady jet (α > 0) in the hard X-ray state of the source, and thus characterized by a power law with an index of 1.5 < Γ < 1.8 and a cutoff at high energies. A transient jet (α < 0) would, on the contrary, be expected in the SPL state of LS I +61°303, showing an X-ray slope of Γ > 2.4. These assumptions seem to be very simplified, given that such an SPL state is poorly characterized. McClintock & Remillard (2006) note that many BH binaries could be radio-quiet during this phase, and moreover, such a state is often characterized by high X-ray luminosity (>0.2 times the Eddington level) and the detection of a thermal component or quasi-periodic oscillations, all of which are clearly not the case for LS I +61°303 (Li et al. 2011).
Although Green Bank Interferometer (GBI) radio data showed spectral index transitions (Massi & Kaufman Bernadó 2009), the photon index of INTEGRAL observations was found to be compatible with an LH state (Chernyakova et al. 2006; Zhang et al. 2010) at all times. The photon index was $\Gamma = 3.6^{+1.5}_{-1.1}$ (Chernyakova et al. 2006) only on one occasion. However, the large error bars (due to little exposure) introduced a large uncertainty. Zimmermann & Massi (2012) demonstrated that averaging the INTEGRAL data over orbital and superorbital phase ranges that are too large can result in a dominant LH state and cancel out the SPL state. Zimmermann & Massi (2012) suggested that this effect explains the hard spectra all along the orbit in the LS $I +61^\circ303$ system, and which led to the inconsistency between the data and their predictions. Here, using INTEGRAL observations that double the size of our previous analysis (Zhang et al. 2010) and two more years of data than in Chernyakova et al. (2012), we can separate the orbital and superorbital phases and test these ideas.

2. OBSERVATIONS AND DATA ANALYSIS

INTEGRAL (Winkler et al. 2003) is a γ-ray mission covering the energy range 15 keV–10 MeV. Observations are carried out in individual Science Windows (ScW), which have typical duration times of about 2000 s. We use all public IBIS/ISGRI data for which LS $I +61^\circ303$ has an offset angle less than 14°. Our data set comprises about 2006 ScWs. The data cover revolutions 6–1317, from 2002 November 1 to 2013 July 27 (MJD 52,579–56,500), adding up to a total effective exposure time of 928 ks in IBIS/ISGRI. The data reduction is performed using the standard ISDC offline scientific analysis (OSA 10.0). IBIS/ISGRI images for each ScW are generated in the energy band of 18–60 keV. The count rates at the position of the source are extracted from all individual images to produce the long-term light curve on the ScW timescale. The spectra of LS $I +61^\circ303$ are produced for each of the ScW following the standard steps as stated in the IBIS Analysis User Manual, running the pipeline from the raw data to SPE level. All of the spectral analysis is performed using XSPEC 12.8.1; uncertainties are given at the 1 confidence level for one single parameter of interest.

We have also considered radio data from the NASA/NRAO GBI database. The radio data set, the same as the one used by Massi & Kaufman Bernadó (2009) and Zimmermann & Massi (2012), covers LS $I +61^\circ303$ at $1 = 2.25$ GHz and $2 = 8.3$ GHz for 6.7 yr, covering three periods, MJD 49,379.975–50,174.710, MJD 50,410.044–51,664.879, and MJD 51,798.333–52,833.441. The radio spectral index $\alpha$ and its error $\alpha$ are calculated as $\alpha = \log(S_1/S_2)/\log(1/2)$ and $\alpha = (0.434/\log(1/2))\sqrt{(S_1/S_2)^2 + (S_1/S_2)^2}$, where $S_1$ and $S_2$ are the corresponding radio fluxes at the two frequencies of interest.

3. RESULTS

3.1. INTEGRAL Spectral Analysis in the Orbital/Supernbital Phase Space

The orbital phase of an X-ray binary system represents a unique location of the compact object in the orbit. The compact object will encounter a similar physical environment (e.g., magnetic field, mass density, accretion rate, etc.) in the same orbital phase if the properties of the companion star are stable, which will presumably lead to a repetitive pattern of orbital emissions.

The long-term stability of the X-ray orbital light curve is observed in LS 5039 (Kishishita et al. 2009). Unlike LS 5039, which is hosting an O star with a relative stable stellar wind, LS $I +61^\circ303$'s companion is a Be star with circumstellar disk variability, which presumably gives rise to the superorbital period. Because the circumstellar disk is configured differently along the superorbital period, the physical environment in each orbit is different even for the same orbital phase. Consequently, we observe variable orbital emission from LS $I +61^\circ303$ along the superorbital period in all frequencies (Paredes 1987; Gregory et al. 1989; Torres et al. 2010; Li et al. 2012; Chernyakova et al. 2012; Ackermann et al. 2013). Averaging data from orbital and superorbital phase ranges that are too large mixes different physical conditions and cancels out information (Zimmermann & Massi 2012). In order to expect a similar physical configuration in the LS $I +61^\circ303$ system, similar orbital and superorbital phases should be required.

With all INTEGRAL data combined, LS $I +61^\circ303$ is detected with a significance of 10.59 in the 18–60 keV band (Figure 1, left panel). INTEGRAL hard X-rays and GBI radio data distribution in the orbital/supernbital phase space are shown in Figure 2 (left panels). This is similar to Figure 4 in Gregory (2002) and Figure 2 in Chernyakova et al. (2012) for their respective data sets. The number of observations at each position in the phase space is given by the color scale. Although the radio (MJD 49,379.975–51,823.441) and hard X-ray (MJD 52,579–56,500) data do not overlap in time, some are co-located at the same orbital and superorbital phases. Figure 2 (upper right panel) shows the overlapped INTEGRAL and GBI observations in phase space. The radio index for the phase space when hard X-rays and radio observations are both available (Figure 2, left panels) is shown in the bottom right panel of Figure 2 (light blue represents $\alpha < 0$; dark blue represents $\alpha > 0$).

LS $I +61^\circ303$ should be in the SPL state/LH state with photon indices $\Gamma > 2.4$ and $1.5 < \Gamma < 1.8$, respectively, according to Zimmermann & Massi (2012). To test this, we have extracted the INTEGRAL spectra in the expected SPL state ($\alpha < 0$, light blue region) and LH state ($\alpha > 0$, dark blue region). X-ray spectra are well fitted with a simple power law without high-energy cutoffs. The results are shown in Table 1. The X-ray photon index is hard ($\Gamma = 1.45^{+0.21}_{-0.19}$) when the radio index $\alpha < 0$, which occurs for most of the observations. This is not consistent with the predictions mentioned. In the case of the radio index $\alpha > 0$, the X-ray photon index results in $\Gamma = 2.59^{+0.83}_{-0.36}$, the large error bars are expected from the much less effective exposure (see Table 1). Due to this large uncertainty, no significant difference could be drawn between the two X-ray spectra.

3.2. Hints of Superorbital Variability of LS $I +61^\circ303$ in Hard X-Ray

The INTEGRAL observations cover LS $I +61^\circ303$ for more than 10 yr. The long-term light curve in the 18–60 keV band binned in 200 days is shown in Figure 1 (right panel). A constant fit to the light curve yields an average flux of $0.34 \pm 0.03$ counts s$^{-1}$ and a reduced $\chi^2$ of 50.92/16, which indicates variability at the 4.3 level. The light curve can be fitted by a sinusoidal function with fixed period at 1667 days, yielding a reduced $\chi^2$ of 13.42/14 (Figure 1, right panel). An F-test shows that the possibility of wrongly refusing the sinusoid is $8.83 \times 10^{-5}$.
We fold the INTEGRAL ScW light curve at 1667 days superorbital period with $T_0$ at MJD 43,366.275. A clear modulation profile is seen (Figure 3, top left panel). A constant fit to the light curve yields a reduced $\chi^2$ of 36.8/7, indicating variability at the 4.6 level. The superorbital light curve of LS 1+61°303 in hard X-rays peaks around the superorbital phase $\sim$0.2, which is in phase with the superorbital modulation in the soft X-ray (the red points in the top left panel of Figure 3 show the modulated fraction in the 3–30 keV band from Li et al. 2012). The exposure time and significance of the corresponding superorbital phase are shown in the middle and bottom panels of Figure 3. The large error bar of the superorbital light curve peak occurs as a result of the low exposure time (7.4 ks) it has compared to other phases (hundreds of ks). We extract spectra for different superorbital and orbital phases. All spectra are well fitted by a simple power law. The fitting parameters are shown in Table 1.

3.3. Orbital Phase Drift of the Radio Peak Flux and Index

In the X-ray and radio bands, the superorbital modulation manifests itself not only in the peak flux or the modulated fraction variation (Gregory 2002; Li et al. 2012), but also in a systematic drift of the orbital phase of the peak flux and the spectral index (Ray et al. 1997; Gregory 2002; Chernyakova et al. 2012). We have detected the drift of the peak flux and spectral index in radio data, consistent with the results of Gregory (2002) and Chernyakova et al. (2012). From superorbital phases $\sim$0.6 to $\sim$1.5, the orbital phase of the radio peak flux (both 2.25 GHz and 8.3 GHz data show a similar evolution; see Figure 3) is linearly drifting from the orbital phase $\sim$0.5 to $\sim$0.95. The linear drift of the spectral index is less evident, but clearly shifted earlier—by $\sim$0.1 in the orbital phase—compared to the flux (Figure 3, bottom right panel). Because of the scarce orbital coverage of INTEGRAL along the superorbital period (Figure 2, bottom left panel), we are, as of yet, unable to explore the presence of a peak flux drift in hard X-rays.

Massi & Kaufman Bernadó (2009) claimed that the periodic radio orbital outbursts consisted of two peaks. We propose here that the two-peak structure is related to the drift of the radio peak flux along the superorbital period. Figure 3 of Massi & Kaufman Bernadó (2009) shows the radio orbital light curve.
Figure 3. Left: superorbital light curve of LS I +61°330 in 18–60 keV, as observed by INTEGRAL. The red points show the modulated fraction in the 3–30 keV band from Li et al. (2012). Middle and bottom: exposure and significance for the corresponding superorbital phase, respectively. Right: radio flux intensity at 2.25 GHz (top) and spectral index (bottom) as a function of the orbital and superorbital phases. (A color version of this figure is available in the online journal.)

Table 1
X-Ray Spectra Parameters Associated with Observations Providing a Radio Index $\alpha < 0$ and $\alpha > 0$ and Superorbitally/Orbitally Separated Spectra from INTEGRAL/ISGRI Observations

| Radio Index | X-Ray Photon Index (T) | Flux (18–60 keV) \(10^{-11}\) erg cm\(^{-2}\) s\(^{-1}\) | Reduced \(^2\) \(\text{dof}\) | Effective Exposure (ks) |
|-------------|------------------------|-----------------------------------|-----------------|---------------------|
| $\alpha < 0$ | 1.49\(_{+0.21}^{-0.23}\) | 1.67 ± 0.19 | 0.86 (4) | 508.0 |
| $\alpha > 0$ | 2.59\(_{+1.01}^{-1.13}\) | 2.10\(_{+0.58}^{-0.59}\) | 0.57 (5) | 42.8 |
| Superorbital Phase | X-Ray Photon Index (T) | Flux (18–60 keV) \(10^{-11}\) erg cm\(^{-2}\) s\(^{-1}\) | Reduced \(^2\) \(\text{dof}\) | Effective Exposure (ks) |
| 0.1–0.2 | 1.06\(_{+0.22}^{-0.23}\) | 2.14 ± 0.23 | 0.254 (5) | 238.9 |
| 0.2–0.3 | 1.79\(_{+0.23}^{-0.24}\) | 3.65 ± 0.36 | 0.330 (7) | 133.1 |
| 0.3–0.5 | 1.66\(_{+0.31}^{-0.32}\) | 1.87 ± 0.29 | 1.00 (4) | 182.3 |
| 0.5–0.8 | 1.27\(_{+0.40}^{-0.38}\) | 1.31 ± 0.29 | 0.975 (3) | 241.0 |
| 0.8–1.1 | 1.27\(_{+0.64}^{-0.63}\) | 1.57\(_{+0.62}^{-0.60}\) | 0.688 (4) | 134.4 |
| Orbital Phase | X-Ray Photon Index (T) | Flux (18–60 keV) \(10^{-11}\) erg cm\(^{-2}\) s\(^{-1}\) | Reduced \(^2\) \(\text{dof}\) | Effective Exposure (ks) |
| 0.0–0.4 | 1.90\(_{+0.67}^{-0.40}\) | 1.63 ± 0.29 | 0.256 (4) | 219.3 |
| 0.4–0.5 | 1.60\(_{+0.23}^{-0.21}\) | 2.84 ± 0.30 | 0.763 (5) | 162.3 |
| 0.5–0.6 | 1.54\(_{+0.28}^{-0.33}\) | 2.84 ± 0.39 | 0.358 (8) | 118.2 |
| 0.6–0.7 | 1.44\(_{+0.32}^{-0.30}\) | 2.24 ± 0.35 | 0.424 (4) | 154.2 |
| 0.7–1.0 | 0.70\(_{+0.33}^{-0.34}\) | 0.98\(_{+0.28}^{-0.27}\) | 0.26 (3) | 273.7 |

during the superorbital phase from 0.0–0.1, in which the authors noted two peaks at orbital phases 0.69 and 0.82. However, in our Figure 3 (top right panel), it is clear that the orbital phase of the radio peaks drifts from $\sim$0.7 to $\sim$0.8 during the superorbital phase from 0.0–0.1. Thus, to explore these drifts in detail, in Figure 4 we display the light curves of 2.25 GHz (top panel), 8.3 GHz (middle panel), and the radio index (bottom panel) during the superorbital phase from 0.0–0.1, where each orbit is noted with a different color. The radio data cover more than one superorbital period, from superorbital phases $\sim$3.6 to $\sim$5.1; the data in the superorbitally folded bin 0.0–0.1 was gathered in two passages corresponding to superorbital phases 4.0–4.1 and 5.0–5.1. These results are shown in Figure 4. In the right panel of Figure 4, we show the corresponding folded orbital light curve in the superorbital phase 0.0–0.1, similar to Figure 3 of Massi & Kaufman Bernadó (2009), but retaining the different colors for the different orbits. The phases of the two reported peaks (Massi & Kaufman Bernadó 2009) are indicated with dashed black lines. In Figure 4, right (top right and middle panels), it is apparent that the phase of the peak flux in 2.25 GHz and 8.3 GHz is drifting in each orbit. The orbital light curve depicted in green peaks around the orbital phase $\sim$0.69, which is the first peak reported in Massi & Kaufman Bernadó (2009). Several orbits later, the black light curve peaks at the orbital phase $\sim$0.82, which is near the second peak reported. Thus, folded in the superorbital phase (0.0–0.1), the two peaks in Figure 3 of Massi
& Kaufman Bernadó (2009) may actually be a superposition of single peaks from different orbits. Similarly, the drifting of orbital peaks may also have effects on Figure 5 of Massi & Kaufman Bernadó (2009), where the data is also folded over a bin of 0.1 superorbital phase. Thus, only the light curve of each individual orbit, or the orbital light curve folded in a narrower superorbital phase that avoids the orbital peak-drifting effect, is suitable for exploring the reality of the double-peak structure, which is questioned here.

4. DISCUSSION

We have tested one of the methods proposed to identify the microquasar nature of the LS I +61°303 system: namely, that it is in the SPL state when the radio index $\alpha < 0$ and in the LH state when $\alpha > 0$, and that using large orbital and superorbital phase ranges mixes these states, canceling out the state transition signatures (Zimmermann & Massi 2012). The latter has been claimed to be the reason for the non-detection of significant spectral variations in the INTEGRAL data analyzed so far. Here, with a significantly larger data set, we have introduced the orbital/superorbital phase space and extracted the X-ray spectrum for the corresponding specific cuts, avoiding averaging data over a superorbital range that is too large. LS I +61°303 shows a hard spectrum (single power law with no cutoff, $\Gamma = 1.49^{+0.21}_{-0.16}$; see Table 1) when $\alpha < 0$, which is inconsistent with the SPL state interpretation of Zimmermann & Massi (2012) stated above.

As noted in the Introduction, such a clear distinction between states based on the radio index seems unlikely. The SPL state itself is not an “intermediate state” that lies between soft and hard states, though transitions pass through SPL frequently (McCintock & Remillard 2006; Zhang 2013). It may also be unrealistic to consider that optically thin radio emission is confined to the SPL state only. If a hard to soft state transition does not pass through an SPL state (e.g., the 2011 outburst of H II 1743–322 during which the photon index is always below 2.4; Zhou et al. 2013) or optically thin radio flares appear in other intermediate states but not in the SPL state, the X-ray photon index will not go above 2.4 during the optically thin radio emission. Thus, the X-ray spectrum during $\alpha < 0$ might be a mixture of an SPL state or transitions to SPL states (e.g., see the case of XTE J1650–500, Corbel et al. 2004; GX 339–4, Gallo et al. 2004; XTE J1859+266, Brocksopp et al. 2002, Corbel et al. 2004), and intermediate states when optically thin radio emissions locate out of SPL states. Nevertheless, the fact that most of the observation time in INTEGRAL indeed has a concurrent $\alpha < 0$ (at the same orbital and superorbital phase) indicates that the most likely alternative is simply that there is no state transition at all, something which has also been supported by the consistent low X-ray flux.

We also showed hints that the superorbital variability of LS I +61°303 in hard X-rays, and that the appearance of a double-peak structure in the radio light curve of superorbital folded data can be accommodated by a drift of a single peak on an orbital basis.

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