VARIABILITY IN THE ORBITAL PROFILES OF THE X-RAY EMISSION OF THE $\gamma$-RAY BINARY LS I +61° 303

Diego F. Torres$^{1,2}$, Shu Zhang$^3$, Jian Li$^3$, Nanda Rea$^1$, G. Andrea Caliandro$^1$, Daniela Hadasc$^1$, Yupeng Chen$^3$, Jianmin Wang$^{3,4}$, and Paul S. Ray$^5$

1 Institut de Ciències de l’Espai (IEEC-CSIC), Campus UAB, Torre C5, 2a planta, 08193 Barcelona, Spain
2 Institut Català de Recerca i Estudis Avançats (ICREA), 08010 Barcelona, Spain; dtorres@ieec.uab.es
3 Laboratory for Particle Astrophysics, Institute of High Energy Physics, Beijing 100049, China
4 Theoretical Physics Center for Science Facilities (TPCSP), CAS, Beijing 100049, China
5 Space Science Division, Naval Research Laboratory, Washington, DC 20375-5352, USA

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ABSTRACT

We report on the analysis of Rossi X-Ray Timing Explorer Proportional Counter Array (PCA) monitoring observations of the $\gamma$-ray binary system LS I +61° 303, covering 35 full cycles of its orbital motion. This constitutes the largest continuous X-ray-monitoring data set analyzed to date for this source. Such an extended analysis allows us to report (1) the discovery of variability in the orbital profiles of the X-ray emission, (2) the existence of a few (recent) short flares on top of the overall behavior typical of the source, which, given the PCA field of view, may or may not be associated with LS I +61° 303, and (3) the determination of the orbital periodicity using soft X-ray data alone.

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

Online-only material: color figures

1. INTRODUCTION

LS I +61° 303 is one of the few high-mass X-ray binaries that have been recently detected at TeV (Albert et al. 2006) and GeV energies (Abdo et al. 2009). Indeed, LS I +61° 303 shows periodic TeV emission modulated by the orbital motion (Anderhub et al. 2009), with a TeV peak out of phase with that observed at GeV energies, variable X-ray emission, and a radio counterpart (see below). In the last few years, there has been a burst of activity trying to understand the nature of this source, particularly whether it is a pulsar or a black hole system, and which are the mechanisms that lead to the multi-wavelength behavior (e.g., Bednarek 2006; Dubus 2006; Gupta & Bottcher 2006; Sierpowska-Bartosik & Torres 2009). In part, these efforts were prompted by the results of a large very long baseline interferometry campaign (Dhawan et al. 2006), which discovered rapid changes along the orbit in the multi-wavelength behavior (e.g., Bednarek 2006; Dubus 2006; Gupta & Bottcher 2006; Sierpowska-Bartosik & Torres 2009). However, the changing morphology of the radio emission along the orbit would require a highly unstable jet, and the shape of this structure would not be expected to be reproduced orbit after orbit (Albert et al. 2008; see however Massi & Kaufman Bernadó 2009 for an alternative explanation). The repeatability of the orbital modulation and simultaneous multiwavelength studies are thus crucial for constraining models.

However, soft X-ray pointed observations of LS I +61° 303 have in general been too limited to cover full orbits of the system, which has a period of $\sim$26.5 days, or to study long-term evolution of the X-ray orbital profile. As an example, the observations at soft X-rays conducted by XMM-Newton (Neronov & Chernyakova 2006; Chernyakova et al. 2006; Sidoli et al. 2006), Chandra (Paredes et al. 2007; Rea et al. 2010), ASCA (Leahy et al. 1997), ROSAT (Goldoni & Mereghetti 1995; Taylor et al. 1996), and Einstein (Bignami et al. 1981) were all too short to cover even a single full orbit. Longer term observations of LS I +61° 303 were performed using instruments such as the Rossi X-Ray Timing Explorer (RXTE) All Sky Monitor (ASM; see Leahy 2001) and Swift-XRT (Esposito et al. 2007) and, at harder X-rays, by INTEGRAL-IBIS/SGRI (Chernyakova et al. 2006; Zhang et al. 2010). The most aggressive monitoring campaign at soft X-rays done so far was with the Proportional Counter Array (PCA) on RXTE. Intensive monitoring during the month of 1996 March were analyzed by Harrison et al. (2000) and Greiner & Rau (2001). Smith et al. (2009) recently analyzed about five months of RXTE/PCA observations covering the period 2007 August 28 to 2008 February 2, reporting the discovery of several flares but only a marginal detection of orbital modulation. Furthermore, their orbital profile hinted at a two-peak light curve in the 2–10 keV band (see their Figure 2). Hint of a similar two-peak feature was reported by Paredes et al. (1997) with 10 months of RXTE/ASM data, covering 1996 February to December. Although the two, as yet unconfirmed, X-ray peaks are not located at the expected phases according to earlier proposed two-peak accretion models (e.g., Taylor et al. 1992; Martí & Paredes 1995), such models do predict two local maxima in the radio and X-ray light curves.

An alternative approach to the study of LS I +61° 303 has been to focus on possible correlated variability, particularly after the system has been detected at higher energies (Albert et al. 2006; Abdo et al. 2009). The first strictly simultaneous observations at TeV and X-rays of LS I +61° 303 have recently been presented by the MAGIC collaboration (Anderhub et al. 2009). Using observations by XMM-Newton, Swift, and MAGIC during $\sim$60% of an orbit, it was found that there is a correlation between the X-ray and TeV emission at the time where the latter was measurable. Other campaigns, e.g., Acciari et al. (2009), fall short of achieving such a result, probably because of non-simultaneity or being based on short snapshots of the system. But, given that the soft X-ray and the TeV emission themselves can be highly variable individually, a simultaneous correlation may only be indicative of local physical conditions, and not taken as a proof of a persistent correlation between energy bands, orbit after orbit. Indeed, at several recent conferences where results from the VERITAS array have been presented
In this Letter, we report on several years of sensitive X-ray monitoring of LS I +61° 303 obtained by the RXTE satellite (see Gruber et al. 1996). The observations covered 35 full cycles of the 26.496 day binary period and constitute the largest continuous pointed X-ray-monitoring data set on LS I +61° 303 to date.

2. OBSERVATIONS AND DATA ANALYSIS

Our data set covers the period between 2006 October and 2010 March, and includes 326 RXTE/PCA pointed observations identified by proposal numbers 92418, 93017, 93100, 93101, 93102, 94102, and 95102. These observations provide a total of 483 ks of exposure time on the source. Here, we focus on the data since 2007 September, which constitute the majority of the data (473 ks) and have smaller time gaps between observations.

The analysis of PCA data was performed using HEASoft 6.6. We filtered the data using the standard RXTE/PCA criteria. To be precise, only PCU2 (in the 0–4 numbering scheme) has been used for the analysis, because it is the only Proportional Counter Unit (PCU) that was 100% on during the observations. We select time intervals where the source elevation is >10° and the pointing offset is <0.02°. The background file used in the analysis of PCA data is the most recent available one from the HEASARC Web site for faint sources, and detector breakdown events have been removed.6

To search for a periodic signal in the light curve data, we used the Lomb–Scargle periodogram method. Power spectra were generated for the light curve using the PERIOD subroutine (Press & Rybicki 1989), and checked using the powspec tool of the XRONOS software package. The oversampling and high-frequency factors which set the period resolution and range (Press & Rybicki 1989) were set to search for periodic variability in the 1–1000 day range. The Lomb–Scargle technique allows us to sample below the average Nyquist period (with reduced sensitivity) due to the unevenly sampled nature of the data, without creating problems due to aliasing. The 99% white noise significance levels were estimated using Monte Carlo simulations (see, e.g., Kong et al. 1998). The 99% red noise significance levels were estimated using the REDFIT subroutine, which can provide the red-noise spectrum via fitting a first-order autoregressive process to the time series (Schulz & Mudelsee 2002).7

3. RESULTS

The upper panel of Figure 1 represents the light curve (in 64 s time bins in the 3–30 keV band) of the whole extent of the observations analyzed. This data set significantly extends (more than by a factor of 5) that considered by Smith et al. (2009), which covers only the 2007–2008 campaign, from MJD 54340 to 54498. From this light curve one can see that, on top of the overall behavior typical of the source, there are several short flares. A few of these short flares were also observed by Smith et al. (based on the same data). We observe additional flares at about MJD 54670.84 and at MJD 54699.65 (the latter was first

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6 The background file is pca_bkgd_confaint7_eMv20051128.mdl and see the Web site http://heasarc.gsfc.nasa.gov/docs/xte/recipes/pca_breakdown.html for more information on the breakdowns. The data have been barycentered using the FTOOLS routine faxbary using the JPL DE405 solar system ephemeris.

7 See ftp://ftp.ncdc.noaa.gov/pub/data/paleo/softlib/редfit
reported by Ray et al. 2008). A detailed study of these flares will be provided elsewhere. These short flares would significantly affect the study of the orbital profile of LS I +61° 303; hence we decided to remove them from the current analysis. To cut them out, clipped all observations with count rates above three times the mean value of 1.551 ± 0.008 counts s^{-1} (see the horizontal line on the top panel of Figure 1). We tested that our results were not sensitive to changing the cut to 5σ above the mean, or cutting based on fitting a Gaussian standard deviation σ. With this flux cut, we folded the data modulo the radio period of 26.4960 ± 0.0028 days (Gregory 2002) with the orbital zero phase taken at JD 2443366.775 (Gregory & Taylor 1978). The result can be seen in the second panel of Figure 1. A clear orbital modulation can be seen in the X-ray data, with a peak rising up around phase 0.45. This phase is shortly after the periastron passage, which is between phases 0.23 and 0.30 (Casares et al. 2005; Aragona et al. 2009; Grundstrom et al. 2007).

The third panel of Figure 1 shows the power spectrum analysis of the unfolded light curve. A peak is found at 26.68 ± 0.58 days, matching the orbital period of the system and presenting a power density of ~160. This is the first time that such an X-ray orbital periodicity is clearly shown in PCA data. The white noise and the red noise, both at 99% confidence level, are marked in the same figure, and present a much smaller power. A second peak is visible in the power spectrum, corresponding to the first harmonic, with periodicity at 13.36 ± 0.12 days.

We investigated whether the orbital light curve is stable in time. To that aim, we divided our data into five periods of six-months each, which provided good statistics at all the phases of the orbit. Figure 2 shows the folded light curve in each of the six-month periods, ordered by time. Figure 3 (left panel) shows a superposition of the folded light curves obtained in each six-month period. Significant (more than 7σ) variations in the flux at a fixed phase value appear with the largest differences being located in the phase range around the global peak seen in the middle panel of Figure 1. In Figure 3 (right panel), we plot the modulated flux fraction (obtained as (c_{\text{max}} - c_{\text{min}})/(c_{\text{max}} + c_{\text{min}})), where c_{\text{max}} and c_{\text{min}} are the maximum and minimum count rates found in each six-month orbital profile after background subtraction; see Figure 2 as a function of time (one point for each of the six-month period considered). It is immediately obvious that, while the orbital average value of the count rate remains similar, the modulated signal significantly varies with time, increasing monotonically during the observations.

From the individual six-month orbital profiles (shown in Figure 2), and the example of month-by-month variability (shown in Figure 4), one can conclude that the X-ray profile is not stable at any of these timescales. We find the phase of X-ray maximum anywhere from phase 0.3 to 0.9 in both the single orbit and six-month averages. Looking at the light curves, one sees changes both in flux level and shape, starting with the appearance of a weakly modulated double-peaked structure and evolving into a more clearly visible, broad single-peaked light curve at later times. However, fitting one and two sine functions having the orbital and half the orbital periods, respectively, we find large χ²-values compared to the number of degrees of freedom (dof). Then, in both cases, the fits are not good enough to make claims, indicating that more harmonics are needed, which cannot be well tested with the current data given the low dof. In addition, the power spectrum remains featureless in most of these shorter six-month periods due to limited statistics (i.e., periodicity hints remain below the red noise in most of the individual six-month data sets). In one of the six-month periods though (the third one) the X-ray periodicity is significantly seen in the power spectrum. We also noted signals appearing between one and ~two days, which result from the spacing of the observations and are thus unrelated to the physical behavior of the source.

We also report on several flares (see also Smith et al. 2009) observed in this long-term monitoring. However, caution should be exercised—the PCA field of view is about 1° (FWHM) so there is no direct evidence for the relation of this flaring phenomenology with LS I +61° 303. Since none of these short flares were observed by any instrument with a better spatial resolution, we cannot exclude that they were generated in a nearby (in sky projection) source.

Similarly, on 2008 September 10, Swift-BAT triggered on a short soft gamma repeater (SGR) like burst from the direction of LS I +61° 303 (de Pasquale et al. 2008). The Burst Alert Telescope (BAT) location of the burst had an uncertainty of 2.2 arcmin (all at 90% confidence level; Barthelmy et al. 2008), centered 88 arcsec away from the sub-arcsecond accurate
Figure 3. Left: superposition of folded 3–30 keV light curves obtained in each of the five separate six-month periods considered. Right: evolution of the modulated flux fraction in each of the five separate six-month periods considered. The corresponding dates are as in Figure 2.

(A color version of this figure is available in the online journal.)

Figure 4. As an example of shorter timescale variability, each panel shows the 3–30 keV light curve evolution along each of the months the first six-month period of data we analyzed, from 28/8/2007–28/2/2008, MJD 54340-54524. Variability in the folded profiles is also visible at these scales. See the text for details.

(A color version of this figure is available in the online journal.)

position of LS I +61° 303. The other telescope on board Swift-XRT did not detect the burst because it started observing 921 s after the BAT trigger (Evans et al. 2008). The X-Ray Telescope (XRT) did detect LS I +61° 303 (being the brightest source in the field) at a flux level and a spectrum consistent with what was previously observed by other missions and Swift-XRT itself (Leahy et al. 1997; Greiner & Rau 2001; Sidoli et al. 2006; Esposito et al. 2007). Following these notices Dubus & Giebels (2008) noted that the burst location, light curve, duration, fluence, and spectra were fully consistent with a soft γ-ray repeater/anomalous X-ray pulsar short duration burst originating from LS I +61° 303. They then considered this to be the first manifestation of magnetar-like activity in a high-mass X-ray binary, concluding that LS I +61° 303 was likely to host a young, but highly magnetized pulsar. This is a tantalizing hypothesis for which, like the association of the PCA flares with LS I +61° 303, there is yet no proof. Rea & Torres (2008) and Muñoz-Arjonilla et al. (2008) analyzed archival Chandra ACIS-I observation of LS I +61° 303 performed on 2006 April 7 (50 ks; Paredes et al. 2007), showing that many faint sources are detected in the field of view. Thus, any of the several X-ray sources without a radio counterpart within the field of view could be the origin of the magnetar-like burst. The RXTE PCA observation nearest to the burst is ObsID 93102-01-32-01, MJD 54719 at 18:17 UT, about 6 hr after the burst. The total exposure time is 1492 s. No flares are detected in this observation. The max count rate is 1.86 counts s⁻¹ and the average count rate is 1.09 counts s⁻¹. This latter result is consistent with the report by Ray et al. (2008), made immediately after the Swift burst was announced.

4. DISCUSSION

The discovery of high and very high energy (VHE) gamma-ray-emitting X-ray binaries triggered an intense effort to understand the particle acceleration, absorption, and emission mechanisms in these binary systems. The eccentricity and relatively small orbital periods provide significant changes in physical conditions along the orbit. Despite this effort, the nature of the compact object and emission mechanisms powering these systems is not settled. Because of this, multifrequency observations and long-term monitoring campaigns such as the one reported here are essential. Multifrequency observations can provide knowledge of the dominance of single or multiple
particle populations, and of the nature of these particles. For instance, if the radiation mechanisms are dominated by a single particle population, an X-ray/VHE correlation with similar fluxes would favor leptonic models over hadronic ones, where the luminosity in X-rays should be less, given their origin in secondary particles. On the other hand, long-term monitoring provides information on possible trends in the overall behavior of the source, and gives perspective as to the steadiness or variability of the former conclusions. Such monitoring can also catch unusual events or source states that could provide the key to the nature of the source. There are a few potential observations that would conclusively demonstrate the true nature, such as the discovery of pulsations at any frequency or the detection of clear accretion signals, both of which are for the moment still elusive (see, e.g., Rea et al. 2010).

This Letter shows that the soft X-ray emission from LS I +61° 303 presents a periodic behavior (visible only for long integration times) at the orbital period, whose shape varies at all timescales explored. Profile variability is seen from orbit to orbit all the way up to multi-year timescales. The phase of the profile maximum also changes. It is then possible that the X-ray emission is orbitally modulated due to the interaction of a stellar wind flow with a pulsar wind (e.g., Dubus 2006; Sierpowska-Bartosik & Torres 2008) or a jet (e.g., Gupta & Böttcher 2006; Bosch-Ramon et al. 2006), but the details of such variability may strongly depend on the intrinsic behavior of the Be stellar wind present in the system. Our results imply the following.

1. The study of short-term, simultaneous multifrequency observations such as the one made by the MAGIC Collaboration (Anderhub et al. 2009) produce local-in-time information useful for determining the process or the primaries responsible for the radiation detected, but do not establish a steady overall behavior. The fact that the X-ray and the TeV emission from LS I +61° 303 are correlated in a single short observation cannot be used to claim that the position in phase of the maxima in the light curves is maintained on timescales longer than the simultaneous observations themselves. In fact, given the variable nature of the X-ray emission, a correlation found in a short observation might not be a sufficient proof that this correlation maintains with time.

2. Long-term variability in X-rays does occur on timescales of years. Thus, if the TeV and X-ray emission are indeed always correlated, the TeV maximum should also vary in phase. In addition, the relative strengths of the emission in these bands can be affected by the level of absorption at which the maximal photon production happens (e.g., see Sierpowska-Bartosik & Torres 2009), varying from orbit to orbit.

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