Massi, M.; Jaron, F.; Hovatta, Talvikki

Long-term OVRO monitoring of LS I +61°303: confirmation of the two close periodicities

Published in:
ASTRONOMY AND ASTROPHYSICS

DOI:
10.1051/0004-6361/201525643

Published: 01/01/2015

Please cite the original version:
Letter to the Editor

Long-term OVRO monitoring of LS I +61°303: confirmation of the two close periodicities

M. Massi\(^1\), F. Jaron\(^1\), and T. Hovatta\(^{2,3}\)

\(^1\) Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany
\(^2\) Aalto University Metsähovi Radio Observatory, Metsähoviintie 114, 02540 Kylmälä, Finland
\(^3\) Cahill Center for Astronomy and Astrophysics, California Institute of Technology, Pasadena CA, 91125, USA

Received 12 January 2015 / Accepted 26 January 2015

ABSTRACT

Context. The gamma-ray binary LS I +61°303 shows multiple periodicities. The timing analysis of 6.7 yr of GBI radio data and of 6 yr of Fermi-LAT GeV gamma-ray data both have found two close periodicities $P_{1,\text{GBI}} = 26.49 \pm 0.07 \text{d}$, $P_{2,\text{GBI}} = 26.92 \pm 0.07 \text{d}$ and $P_{1,\text{OVRO}} \approx 26.5 \pm 0.1 \text{d}$ and $P_{2,\text{OVRO}} \approx 26.9 \pm 0.1 \text{d}$.

Aims. The system LS I +61°303 is the object of several continuous monitoring programs at low and high energies. The frequency difference between $\nu_1$ and $\nu_2$ of only 0.0006 d\(^{-1}\) requires long-term monitoring because the frequency resolution in timing analysis is related to the inverse of the overall time interval. The Owens Valley Radio Observatory (OVRO) 40 m telescope has been monitoring the source at 15 GHz for five years and overlaps with Fermi-LAT monitoring. The aim of this work is to establish whether the two frequencies are also resolved in the OVRO monitoring.

Methods. We analysed OVRO data with the Lomb-Scargle method. We also updated the timing analysis of Fermi-LAT observations.

Results. The periodograms of OVRO data confirm the two periodicities $P_{1,\text{OVRO}} \approx 26.5 \pm 0.1 \text{d}$ and $P_{2,\text{OVRO}} \approx 26.9 \pm 0.1 \text{d}$.

Conclusions. The three independent measurements of $P_1$ and $P_2$ with GBI, OVRO, and Fermi-LAT observations confirm that the periodicities are permanent features of the system LS I +61°303. The similar behaviours of the emission at high (GeV) and low (radio) energy when the compact object in LS I +61°303 is toward apastron suggest that the emission is caused by the same periodically ($P_1$) ejected population of electrons in a precessing ($P_2$) jet.

Key words. radio continuum: stars – X-rays: binaries – X-rays: individuals: LSI +61°303 – gamma rays: stars

1. Introduction

The stellar system LS I +61°303 is formed by a compact object and a Be star in an eccentric orbit ($e = 0.72 \pm 0.15$, Casares et al. 2005). Fermi-LAT observations (Abdo et al. 2009) reveal a large outburst toward periastron ($\Phi_{\text{periastron}} = 0.23 \pm 0.02$, Casares et al. 2005) along with a smaller outburst toward apastron (Jaron & Massi 2014). Radio observations of the system show a large radio outburst toward apastron exhibiting a modulation of $\approx 1667$ days (Paredes et al. 1990; Gregory 2002; Massi & Kaufman Bernadó 2009, and here Fig. 1).

Two distinct outbursts along the orbit are well understood in the context of accretion along an eccentric orbit (Bondi & Hoyle 1944). The expression of the accretion rate is

$$M = \frac{4\pi v_{\text{wind}}(GM_*)^2}{\dot{v}_{\text{rel}}^3},$$

where $v_{\text{wind}}$ is the density, and $\dot{v}_{\text{rel}}$ is the relative velocity between the compact object and the Be equatorial wind. As shown by several authors for the eccentric orbit of LS I +61303, two peaks result: one peak corresponds to the periastron passage because of the highest density; the second peak occurs in the phase interval (toward apastron) where the reduced velocity of the compact object compensates for the decrease in density (Taylor et al. 1992; Mari & Paredes 1995; Bosch-Ramon et al. 2006; Romero et al. 2007). At each accretion peak, matter is assumed to be ejected outward in two jets perpendicular to the accretion disk plane as for microquasars, but for the two ejections different energetic losses for the particles occur. Ejected relativistic electrons around periastron suffer severe inverse Compton losses because of the proximity to the Be star (Bosch-Ramon et al. 2006); the electrons upscatter stellar photons to higher energies, and by doing so, they loose their energy and become unable to generate synchrotron emission in the radio band. The consequence is that around periastron a high-energy outburst caused by inverse Compton process results, but no or negligible radio emission (Bosch-Ramon et al. 2006). This first predicted gamma-ray outburst has been confirmed by Fermi-LAT observations (Abdo et al. 2009; Hadasch et al. 2012; Ackermann et al. 2013; Jaron & Massi 2014). During the second accretion peak, the compact object is much farther away from the Be star, and inverse Compton losses are lower: the electrons can propagate out of the orbital plane and generate synchrotron emission in the radio band and a minor gamma-ray outburst (see the predicted outbursts in Fig. 2 of Bosch-Ramon et al. 2006). Indeed, as quoted above, radio and gamma-ray observations confirm the predicted radio and minor gamma-ray outburst toward apastron. The spectrum of the radio outburst has been reported to be flat from 1.5 to 22 GHz by Gregory et al. (1979), and recently, Zimmermann (2013) observed a flat spectrum up to 33 GHz. These radio observations corroborate the microquasar hypothesis for LS I +61°303 because a flat radio spectrum is indeed associated with the conical
Recently, a Lomb-Scargle analysis of Fermi-LAT data resulted in a precessing period of 27–28 days (Massi et al. 2012). This important result must be confirmed by simultaneous observations. In particular, a much larger population of electrons in a precessing jet. This important result would imply that the emission is caused by the same region of the system and with the predicted periodicity of 27 days and a fractional part of 0.084 and 0.084 (Jaron & Massi 2014). The importance of using a Monte Carlo randomization test is that it is distribution-free and not constrained by any specific noise models (Poisson, Gaussian, etc.). The fundamental assumption is that if there is no periodic signal in the time series, then the probability of permutations that give a peak randomized and could have occurred in any other order. A test for periodic signals is to calculate the proportion of permutations that give a peak higher than that of the original time series would then provide an estimate of the probability that such a peak could have occurred. To search for possible periodicities, we used the Lomb-Scargle randomization test (1985), which is very efficient for Testing a period among a set of candidate periods. The fundamental assumption is that if there is no periodic signal in the time series, then the probability of permutations that give a peak randomized and could have occurred in any other order. A test for periodic signals is to calculate the proportion of permutations that give a peak higher than that of the original time series would then provide an estimate of the probability that such a peak could have occurred. To search for possible periodicities, we used the Lomb-Scargle randomization test (1985). The advantages of using a Monte Carlo randomization test is that it is distribution-free and not constrained by any specific noise models (Poisson, Gaussian, etc.). The fundamental assumption is that if there is no periodic signal in the time series, then the probability of permutations that give a peak randomized and could have occurred in any other order. A test for periodic signals is to calculate the proportion of permutations that give a peak higher than that of the original time series would then provide an estimate of the probability that such a peak could have occurred. To search for possible periodicities, we used the Lomb-Scargle randomization test (1985). The advantages of using a Monte Carlo randomization test is that it is distribution-free and not constrained by any specific noise models (Poisson, Gaussian, etc.). The fundamental assumption is that if there is no periodic signal in the time series, then the probability of permutations that give a peak randomized and could have occurred in any other order. A test for periodic signals is to calculate the proportion of permutations that give a peak higher than that of the original time series would then provide an estimate of the probability that such a peak could have occurred. To search for possible periodicities, we used the Lomb-Scargle randomization test (1985). The advantages of using a Monte Carlo randomization test is that it is distribution-free and not constrained by any specific noise models (Poisson, Gaussian, etc.). The fundamental assumption is that if there is no periodic signal in the time series, then the probability of permutations that give a peak randomized and could have occurred in any other order. A test for periodic signals is to calculate the proportion of permutations that give a peak higher than that of the original time series would then provide an estimate of the probability that such a peak could have occurred.

A timing analysis of the GBI radio data of LS I +61° 303 was carried out by Richards et al. (2011). The GBT radio telescope is part of the Owens Valley Radio Observatory (OVRO) 40 m telescope monitoring at 15 GHz between March 2009 and 2015. In this Letter, we present a timing analysis of these data. Section 2 describes the data reduction and the results. Section 3 presents our conclusions.

2.1. OVRO observations

To search for possible periodicities, we used the Lomb-Scargle randomization test (1985). The advantages of using a Monte Carlo randomization test is that it is distribution-free and not constrained by any specific noise models (Poisson, Gaussian, etc.). The fundamental assumption is that if there is no periodic signal in the time series, then the probability of permutations that give a peak randomized and could have occurred in any other order. A test for periodic signals is to calculate the proportion of permutations that give a peak higher than that of the original time series would then provide an estimate of the probability that such a peak could have occurred.
result in the randomization test with a false-alarm probability of $p < 1\%$.

2.3. Fermi-LAT

The timing analysis in Jaron & Massi (2014) for the whole data set gave $P_2$ as significant ($p < 1\%$) in the randomization tests even if it is a rather weak feature in the periodograms of their Fig. 3a–c. In other words, the timing analysis performed on the whole Fermi data set yields that $P_2$ is significant even if the spectral feature is much lower than that at $P_1$. When the timing analysis is performed for emission in the orbital phase $\Phi = 0.5–1.0$, as described in Jaron & Massi (2014), the spectral feature at $P_2$ is comparable with that at $P_1$, but the randomization tests find a probability of false detection of $p = 4\%$. The $\gamma$-ray data used in that analysis did span the time period MJD 54 683 (August 05, 2008) to MJD 56 838 (June 30, 2014). Now we have five more months of Fermi-LAT observations. The data reduction was performed as reported in Jaron & Massi (2014). The periodogram for data in the orbital phase $\Phi = 0.5–1.0$ shown in Fig. 2 has the same periodicities as in Jaron & Massi (2014), but with the important difference that now the randomization test gives both frequencies as significant, with a false-alarm probability of $p < 1\%$.

2.4. 385 days of GBI data vs. RATAN results

The frequency resolution in a periodogram is related to the inverse of the overall time interval of observations. The resolution for GBI of $\Delta \nu = 0.0001 \, \text{d}^{-1}$ covers six times the difference in frequency between $v_1 = 0.03775 \pm 0.00010 \, \text{d}^{-1}$ and $v_2 = 0.03715 \pm 0.00010 \, \text{d}^{-1}$ determined by Massi & Jaron (2013). Indeed, the two spectral features are evident in the GBI periodogram shown here in Fig. 2. Very recently, Trushkin et al. (2014) reported that the timing analysis of RATAN-600 radio telescope data did not find the two frequencies. The reported daily monitoring with the RATAN-600 radio telescope includes the time from 16 November 2013 (MJD 56 612) to 6 December 2014 (MJD 56 997), that is, 385 days. This corresponds to a frequency resolution of $0.00065 \, \text{d}^{-1}$ that is even higher than the difference in frequency between $v_1$ and $v_2$ of $0.00060 \, \text{d}^{-1}$. We tested the insufficient frequency resolution by performing the timing analysis on 385 days of GBI data. The resulting periodogram, shown in Fig. 3, is well comparable with that of Trushkin et al. (2014). The two frequencies $v_1$ and $v_2$ are plotted in Fig. 3 by arrows. The low spectral resolution is still unable to resolve the frequency separation.

![Fig. 2. Lomb-Scargle periodograms of three independent long-term monitorings of LS I +61°303. Top: OVRO at 15 GHz. Centre: Fermi-LAT in the energy range 100 MeV to 300 GeV using only data from the orbital phase interval $\Phi = 0.5–1.0$ (see Jaron & Massi 2014). Bottom: GBI at 2 GHz (empty circles) and 8 GHz (filled squares) (see Massi & Jaron 2013). In all periodograms there are two periodicities with a false-alarm probability of between 0.00 and 0.01 (see Sect. 2). The ratio ($R$) between the intensity of the two spectral features at $P_1$ and $P_2$ is different in the different periodograms and is $R = 1.9$ at 2 GHz and $R = 1.5$ at 8 GHz for GBI data, $R = 1.4$ at 15 GHz and $R = 1.3$ for GeV data.](image1)

![Fig. 3. Lomb-Scargle periodograms of 385 days of GBI radio data at 2 GHz to be compared with the periodogram in Trushkin et al. (2014) also of 385 days. The spectral resolution of only 0.00065 d$^{-1}$ cannot resolve the separation of 0.0006 d$^{-1}$ between $v_1 = 0.03775 \pm 0.00010 \, \text{d}^{-1}$ and $v_2 = 0.03715 \pm 0.00010 \, \text{d}^{-1}$ determined by Massi & Jaron (2013) with 6.7 yr of GBI data.](image2)
3. Conclusions and discussion

The spectral resolution in the timing analysis of OVRO data is able to distinguish the two spectral features found in GBI and Fermi-LAT data (Table 1).

These two periodicities are physically related to the periodical ejection ($P_1$) of electrons in a particular orbital phase toward apastron and to the precession ($P_2$) of the jet. The beating of these two periodicities probably causes the so-called long-term modulation. The peak flux density of the periodical radio outburst exhibits in fact a modulation of 1667 ± 8 d (Gregory 2002).

Massi & Jaron (2013) have shown the consistency between the two periodicities probably causes the so-called long-term modulation and the beating of the two frequencies determined in the GBI timing analysis, that is, $P_{\text{beat}} = (P_1^{-1} - P_2^{-1})^{-1}$ (Table 1). Moreover, Massi & Torricelli-Ciamponi (2014) have shown that a physical model for LS I +61°303 of synchrotron emission from a precessing ($P_2$) jet, periodically ($P_1$) refilled with relativistic particles, produces a maximum when the jet electron density is at its maximum and the approaching jet forms the smallest possible angle with the line of sight. This coincidence of the highest number of emitting particles and the strongest Doppler boosting of their emission occurs with a period of $P_1^{-1} - P_2^{-1}$, that is, $P_{\text{beat}}$, or the long-term periodicity.

The open question now is: why is the precession so close to the orbital period? While the microquasar SS433 and several known precessing X-ray binaries (Larwood 1998) have a precession period longer by an order of magnitude than the orbital period (as predicted for a tidally forced precession by the companion star), the different case of the microquasar GRO J1655–40 was discovered in 1995 (Hjellming & Rupen 1995). This system has an orbital period of 2.601 ± 0.027 days (Bailyn et al. 1995). Hjellming & Rupen (1995) discovered a radio jet in this object with a precessional period of 3.0 ± 0.2 days (Hjellming & Rupen 1995). LS I +61°303 seems to be the second case of this new class of objects with orbital and precession periods that are rather close to each other.

Acknowledgements. The OVRO 40 M Telescope Monitoring Program is supported by NASA under awards NNX08AW31G and NNX11A043G, and by the NSF under awards AST-0808050 and AST-1109911. We would like to thank Jürgen Neidhöfer, Giammarco Quaglia, and Eduardo Ros for helpful comments. This work has made use of public Fermi data obtained from the High Energy Astrophysics Science Archive Research Center (HEASARC), provided by NASA Goddard Space Flight Center. The Green Bank Interferometer is a facility of the National Science Foundation operated by the NRAO in support of NASA High Energy Astrophysics programs.

References
Dhawan, V., Modaszewski, A., & Rupen, M. 2006, Proc. of the VI Microquasar Workshop, 52.1
Reig, P. 2011, ApSS, 332, 1
Trusshkin, S. A., Nizhelskii N. A., & Tsymbul P. G. 2014, ATEF, 6786