Radio QPO in the $\gamma$-ray-loud X-ray binary LS I $+61^\circ303$

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ABSTRACT

LS I $+61^\circ303$ is a $\gamma$-ray emitting X-ray binary with periodic radio outbursts with time scales of one month. Previous observations have revealed microflares superimposed on these large outbursts with periods ranging from a few minutes to hours. This makes LS I $+61^\circ303$, along with Cyg X-1, the only TeV emitting X-ray binary exhibiting radio microflares. To further investigate these microflaring activity in LS I $+61^\circ303$ we observed the source with the 100-m Effelsberg radio telescope at 4.85, 8.35, and 10.45 GHz and performed timing analysis on the obtained data. Radio oscillations of 15 hours time scales are detected at all three frequencies. We also compare the spectral index evolution of radio data to that of the photon index of GeV data observed by Fermi-LAT. We conclude that the observed QPO could result from multiple shocks in a jet.

Key words: Radio continuum: stars – X-rays: binaries – X-rays: individual (LS I $+61^\circ303$)

1 INTRODUCTION

It is a known fact that a subclass of X-ray binaries and a subclass of Active Galactic Nuclei (AGN) are sources of radio emission. There is evidence that radio outbursts in these systems are superimposed by microflaring activity of lower amplitude and short time scales. These short timescale variations, characterised as Quasi Periodic Oscillations (QPO) (Fender et al. 1997), may change periods. These short timescale variations, characterised as Quasi Periodic Oscillations (QPO) (Fender et al. 1997), may change periods. These short timescale variations, characterised as Quasi Periodic Oscillations (QPO) (Fender et al. 1997), may change periods. These short timescale variations, characterised as Quasi Periodic Oscillations (QPO) (Fender et al. 1997), may change periods. These short timescale variations, characterised as Quasi Periodic Oscillations (QPO) (Fender et al. 1997), may change periods. These short timescale variations, characterised as Quasi Periodic Oscillations (QPO) (Fender et al. 1997), may change periods. These short timescale variations, characterised as Quasi Periodic Oscillations (QPO) (Fender et al. 1997), may change periods. These short timescale variations, characterised as Quasi Periodic Oscillations (QPO) (Fender et al. 1997), may change periods. These short timescale variations, characterised as Quasi Periodic Oscillations (QPO) (Fender et al. 1997), may change periods.
As a third explanation, QPO have been related to discrete ejections of plasma. Multi-wavelength QPO observations of GRS 1915+105 (see references in Mirabel & Rodríguez 1999) have been interpreted as periodic discrete ejections of plasma, with a mass of about $10^{39}$ g and at relativistic speeds, with subsequent replenishment of the inner accretion disk.

Testing possible models for the origin of QPO is still complicated because of insufficient statistics. Remaining open questions include: How stable are these “quasi” periodic oscillations? Why are QPO present in the radio spectral index? Why does the radio spectrum oscillate between optically thin and thick emission in GRS 1915+105 and Cyg X-3, and is that a general property of QPO? Do the “flat” radio spectra in microquasars and AGN indeed arise from the combination of emission from optically thick and thin regions as suggested in Fender et al. (2002)? In order to answer these questions, it is requisite to increase the sample of X-ray binaries exhibiting radio QPO. For this purpose we investigate on LS I +61°303 which is one of the few radio emitting X-ray binaries which also emits in γ-rays (GeV, Abdo et al. 2009, and TeV, Albert et al. 2006, Acciari et al. 2008). Moreover, LS I +61°303 is periodic at all wavelengths on the orbital time scale (26.5 d) and has revealed microflaring activity ( Sect. 2).

Aimed at investigating QPO in LS I +61°303 we performed new observations with the Effelsberg 100-m radio telescope. Our new radio observations and data analysis are described in Sect. 3 along with the along with the Fermi-LAT data reduction. In Sect. 4 we present our results and in Sect. 5 our conclusions.

## 2 THE BINARY SYSTEM LS I +61°303

The X-ray binary LS I +61°303 is composed of a Be star (Casares et al. 2005) and a black hole (Massi et al. 2017), exhibiting radio outbursts (Gregory 2002; Jaron & Massi 2013) occurring periodic, related to the orbital period of ~26.5 days. With an SED peaking above 1 GeV, LS I +61°303 can further be classified as a γ-ray binary (see Table 2 in Dubus 2013). Among the black hole binaries discussed above, only LS I +61°303 and Cyg X-1 have the peculiarity of emitting at TeV, this, however, being a transient phenomenon for Cyg X-1 (Albert et al. 2006), and also LS I +61°303 has episodes of TeV non-detection (Acciari et al. 2011).

Two magnetar-like signals were detected from a large region of sky crowded by other potential sources beside LS I +61°303 (Rea & Torres 2008). On that basis Torres et al. (2012) put forward their working hypothesis that LS I +61°303 could be the first magnetar detected in a binary system, and studied the implications. In the magnetar scenario, as well as for the pulsar scenario (see, e.g., Dubus 2013), variability of the Be star would trigger and explain observed long-term variability in the emission of LS I +61°303 at all wavelengths (Gregory 2002; Li et al. 2014; Ackermann et al. 2013; Ahnen et al. 2016). However, following the well-studied (i.e., over 100 years) case of the binary system ε Tau, i.e., also a Be star in a binary system (Sect. 4 in Massi & Torricelli-Ciamponi 2016 and references therein), Be star variations last 2-3 cycles only and are of different lengths (Rivinius et al. 2013). Timing analysis of 37 years of radio data performed by Massi & Torricelli-Ciamponi (2016) reveals that LS I +61°303 does not show merely 2-3 cycles which are of different lengths but a repetition of 8 full cycles of an identical length of 1628 days, well in agreement with the scenario of a microquasar with a precessing jet (Massi & Torricelli-Ciamponi 2014; Jaron et al. 2016). In addition, as discussed in Jaron et al. (2016), the orbital shift in the equivalent width of the Hz emission line (Paredes-Fortuny et al. 2015), points to variations caused by a precessing jet.

Optical polarization observations determined a rotational axis for the Be star of 25 degrees (Nagae et al. 2008). For parallel orbital and Be spin axes and the mass function determined through orbital motions measurements (Casares et al. 2005) a 25 degree inclination implies a black hole of 4 solar masses, as argued by Massi et al. (2017, and references therein), who further probe from X-ray observations that the photon index vs. luminosity trend of LS I +61°303 is very different from that of the non-accreting pulsar binary PSR B1259-63, whereas this trend agrees with that of moderate-luminosity regime black holes in general and with the two black holes in the same X-ray luminosity range: Swift J1357.2-0933 and V404 Cygni, in particular.

The source is well-known for its strong radio outbursts with orbital periodicity monitored for ~40 years (Massi & Torricelli-Ciamponi 2016). Along with this strong radio outburst there is also evidence of occurrence of microflaring activity with time scales of minutes to hours. During the decaying phase of one of the radio outbursts of LS I +61°303, a step-like pattern was observed for the first time with the Westerbork Synthesis Radio Telescope (WSRT) with a characteristic timescale of ~10$^5$s (Taylor et al. 1992). Peracaula et al. (1997) performed the first systematic study of this short-term radio variability and found a period of 1.4 hours for these microflares with an amplitude of ~4 mJy in VLA observations related to the decay of one radio outburst. Recently, Zimmermann et al. (2015) observed during the decay of one outburst of LS I +61°303 sub-flares with a characteristic time-scale of two days (see their Fig. 1). Furthermore, the radio spectral index oscillated in a quasi-regular fashion and the local peaks in spectral index roughly coincide with the peaks of the sub-flares seen in the total intensity light curves. Finally, at higher energy, Harrison et al. (2000) discovered a periodicity of ~40 minutes in an X-ray ASCA observation associated to the onset of a radio outburst.

## 3 OBSERVATION AND DATA ANALYSIS

### 3.1 Effelsberg radio telescope

Our multi-frequency flux density measurements were performed about every 45 minutes for almost 100 hours on April 17–21, 2014 (MJD 56764.726 until MJD 56768.763). The orbital phase $\Phi$ is defined as $\Phi = \frac{t - t_0}{P_{\text{orb}}} \mod 1$, where, $t_0$ = MJD 43366.275, orbital period $P_{\text{orb}} = 26.4960 \pm 0.0028$ d (Gregory 2002), giv-
The data reduction, from raw telescope data to calibrated flux densities/spectra, was done in the standard manner as described in Angelakis et al. (2015). Problems with the 8.35 GHz receiver caused the large flagging of data at this frequency. The best data set for sampling rate and SNR is that at 4.85 GHz. The light curves obtained for all three frequencies are shown in Figure 2 (a, c, e) along with their spectral index computed as $\alpha = \log(S_1/S_2)/\log(\nu_1/\nu_2)$ for Fig 2 b, and as a linear fit to the fluxes vs. frequency in double logarithmic scale for every time bin of 45 minutes, shown in Fig. 2 d.

In order to analyse short-term periodicities, we removed the long-term trend from the light curves by subtracting a quadratic function

$$f_1(t) = a_1 (t - t_0)^2 + b_1,$$

with best-fit parameters listed in Table 1. The rectified data were then analyzed using wavelet analysis (Torrence & Compo 1998), auto-correlation function and Lomb-Scargle periodogram (Lomb 1976; Scargle 1982). We test the significance of found periodic signals by employing the Fisher randomisation test (Linnell Nemec & Nemec 1985) where the flux is permuted a thousand times during $\Phi = 0.68 - 0.83$ for our observations. The secondary focus receivers of the Effelsberg 100-m telescope were used at three frequencies, namely 4.85, 8.35, and 10.45 GHz (6.0, 3.6, 2.8 cm wavelengths respectively). Flux density measurements were performed using the “cross-scan” technique, i.e., progressively slewing over the source position in azimuthal and elevation direction with the number of sub-scans matching the source brightness at a given frequency (typically 4 to 12). At 4.85 and 10.45 GHz, the “beam switch”, realised through multiple-feed systems, removed most of the tropospheric variations, allowing for more accurate measurements. The cross-scan technique on the other hand allows instantaneous correction of small, remaining pointing offsets.

Table 1. Best-fit parameters of the parabola used for subtracting the long-term trend from the lightcurves.

| Frequency | $a_1$       | $t_0$ (MJD) | $b_1$       |
|-----------|-------------|-------------|-------------|
| 4.85 GHz  | $-0.009 \pm 0.001$ | 56766.6 \pm 0.1 | 0.16 \pm 0.02 |
| 8.35 GHz  | $-0.008 \pm 0.001$ | 56766.3 \pm 0.1 | 0.13 \pm 0.05 |
| 10.45 GHz | $-0.009 \pm 0.001$ | 56766.4 \pm 0.1 | 0.12 \pm 0.03 |

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Table 2. Best-fit parameters as a result of fitting a sine function to the folded data with period of 15.4 h.

| Frequency (GHz) | A (mJy) | B (mJy) | $\phi_0$ | $\chi^2$ |
|----------------|---------|---------|---------|---------|
| 4.85           | 9.3 ± 1.2 | -0.2 ± 0.8 | 0.7 ± 0.1 | 0.9 |
| 8.35           | 8.9 ± 0.9 | 2.1 ± 0.8  | 0.7 ± 0.1 | 0.8 |
| 10.45          | 6.7 ± 0.7 | 0.5 ± 0.6  | 0.7 ± 0.1 | 1.3 |

and thousand new randomised time series are created and their periodograms calculated. The proportion of randomised time series that contain a higher peak in the periodogram than the original periodogram at any frequency then gives the false alarm probability $p$ of the peak. If $p < 0.01$, the period is significant, and if 0.01 < $p$ < 0.1 the period is marginally significant. The data were then folded on the resulting significant period, and the folded data were fitted with a sine-function

$$f_2(\phi) = A \sin 2\pi(\phi - \phi_0) + B,$$

with its best-fit parameters in Table 2.

3.2 Fermi-LAT data reduction

We compare our radio data with GeV $\gamma$-ray data. For this purpose we use the GeV data from the Fermi-LAT in the energy range 0.1–3.0 GeV from MJD 56764.125 until MJD 56768.875. For the analysis of Fermi-LAT data we used version v10r0p5 of the Fermi ScienceTools\(^1\). We used the instrument response function p8r2_SOURCE_V6 and the corresponding model gll_iem_v06.fits for the Galactic diffuse emission and the template iso_p8r2_SOURCE_V6_v06.txt. Model tiles were created automatically with the script makeFGLxml.py\(^2\) from the third Fermi-LAT point source catalog (Acero et al. 2015). The spectral shape of LS I +61°303 in the GeV regime is a power law with an exponential cut-off at 4–6 GeV (Abdo et al. 2009; Hadasch et al. 2012). Here we restrict our analysis to the power law part of the GeV emission by fitting the source with

$$\frac{dn}{dE} = n_0 \left( \frac{E}{E_0} \right)^{-\alpha} \text{counts cm}^2\text{sec} \text{eV}$$

with all parameters left free for the fit, and including data in the energy range $E = 0.1 – 3$ GeV. All other sources within a radius of 10° and the Galactic diffuse emission were left free for the fit. All sources between 10° – 15° were fixed to their catalog values. The light curves were computed performing this fit for every time bin of width half a day for a data run from 2014 April 17 (MJD 56764.125) till 2014 April 21 (MJD 56768.875). On average, the test statistic for LS I +61°303 was 40, which corresponds to a detection of the source at the 6.3$\sigma$ level on average in each time bin.

4 RESULTS

The light curves at all three frequencies (Fig. 2 a, c, e) show small-scale oscillations. Amplitude and width seem to vary from one peak to the other. The higher sensitivity of 4.85 GHz data give rise to significant timing analysis results: the wavelet analysis in the top panel of Fig. 3 shows that the oscillations at 4.85 GHz have a periodicity of about 16 hours. The auto-correlation coefficient in the middle panel of Fig. 3 shows peaks at 15 hours, 30 hours and at about 55 hours. Lomb-Scargle analysis in the bottom panel of Figure 3 gives a dominant and significant feature at 15.4 ± 0.6 h. Indeed, data at all three frequencies fold with the 15.4 hours period (see Fig. 4 and fitting parameters in Table 2) with significance of the oscillations clearly above 8$\sigma$. Oscillations are also present in the radio spectral index $\alpha$ (Fig. 2 d) corroborating the observed spectral index oscillations by Zimmermann et al. (2015, see the bottom panel of their Fig. 1). The oscillations create a sort of flattening of the spectral index, and a zoom-in centered at MJD 56766.3 clearly shows $\alpha = 0$ (Fig. 2 f).

5 CONCLUSIONS AND DISCUSSION

We observed one radio outburst of LS I +61°303 with the Effelsberg 100-m telescope in April 2014 for approximately 100 h at 4.85, 8.35, and 10.45 GHz. We analysed these data along with simultaneous Fermi-LAT GeV data. Our results reveal the following:

(i) QPO previously observed in LS I +61°303 showed time scales of minutes, hours and days (Taylor et al. 1992; Peracaula et al. 1997; Zimmermann et al. 2015). Our study determines periodicitites of ~ 15 h. There are three hypotheses to explain the physical mechanism behind the occurrence of these periodicities. The first is associated to the geometry of the jet (Rani et al. 2010), the second one to multiple shocks (Klein-Wolt et al. 2002, and references therein), and the third one implies discrete plasma ejections (Mirabel & Rodríguez 1999, and references therein). In the first scenario the reason for oscillations is the helical topology of the magnetic field in the jet associated to Doppler boosting effects. Since in a conical jet of a microquasar the 10 GHz emission originates from a jet-segment nearer to the central engine of the system than the 5 GHz jet-segment (Kaiser 2000), this scenario implies a longer period for 5 GHz oscillations. This is not compatible with

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1 available from http://fermi.gsfc.nasa.gov/ssc/data/analysis/software/
2 available from http://fermi.gsfc.nasa.gov/ssc/data/analysis/user/
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REFERENCES

Abdo A. A., et al., 2009, ApJ, 701, L123
Acciari V. A., et al., 2008, ApJ, 679, 1427
Acciari V. A., et al., 2011, ApJ, 738, 3
Acero F., et al., 2015, ApJS, 218, 23
Ackermann M., et al., 2013, ApJ, 773, L35
Ahnen M. L., et al., 2016, A&A, 591, A76
Albert J., et al., 2006, Science, 312, 1771
Angelakis E., et al., 2015, A&A, 575, A55
Casares J., Ribas I., Paredes J. M., Martí J., Allende Prieto C., 2005, MNRAS, 360, 1105
Dubus G., 2013, A&A Rev, 21, 64
Espaillat C., Bregin J., Hughes P., Lloyd-Davies E., 2008, ApJ, 679, 182
Fender R. P., Pooley G. G., 1998, MNRAS, 300, 573
Fender R. P., Pooley G. G., Robinson C. R., Harmon B. A., Zhang S. N., Canosa C., 1997, inwickramasinghe D. T., Bicknell G. V., Ferrario L., eds, Astronomical Society of the Pacific Conference Series Vol. 121, IAU Colloq. 163: Accretion Phenomena and Related Outflows. p. 701 (arXiv:astro-ph/9612292)
Fender R. P., Rayner D., Trushkin S. A., O’Brien K., Sault R. J., Pooley G. G., Norris R. P., 2002, MNRAS, 330, 212
Gierlinski M., Middleton M., Ward M., Done C., 2008, Nature, 455, 369
Gregory P. C., 2002, ApJ, 575, 427
Hadasch D., et al., 2012, ApJ, 749, 54
Han X., Hjellming R. M., 1992, ApJ, 400, 304
Harrison F. A., Ray P. S., Leahy D. A., Waltman E. B., Pooley G. G., 2000, ApJ, 528, 454
Jaron F., Massi M., 2013, A&A, 559, A129
Jaron F., Torricelli-Ciamponi G., Massi M., 2016, A&A, 595, A92
Kaiser C. R., 2006, MNRAS, 367, 1083
Klein-Wolt M., Fender R. P., Pooley G. G., Belloni T., Migliari S., Morgan E. H., van der Klis M., 2002, MNRAS, 331, 745
Li J., Torres D. F., Zhang S., 2014, ApJ, 785, L19
Linnell Nemec A. E., Nemec J. M., 1985, AJ, 90, 2317
Lomb N. R., 1976, ApSS, 39, 447
Marscher A. P., Gear W. K., 1985, ApJ, 298, 114
Martí J., Mirabel I. F., Rodrigo L. F., 2001, Information Bulletin on Variable Stars, 3127
Massi M., Torricelli-Ciamponi G., 2014, A&A, 564, A23
Massi M., Torricelli-Ciamponi G., 2016, A&A, 585, A123
Massi M., Migliari S., Chernyakova M., 2017, preprint, (arXiv:1704.01335)
Mirabel I. F., Rodrigo L. F., 1999, ARA&A, 37, 409
Nagar O., Kawabata K. S., Fukazawa Y., Okazaki A., Isogai M., 2008, in Yuan Y.-F., Li X.-D., ed., American Institute of Physics Conference Series Vol. 968, Astrophysics of Compact Objects. pp 328–330, doi:10.1063/1.2840421
Paredes-Fortuny X., Ribó M., Bosch-Ramon V., Casares J., Fors O., Núñez J., 2015, A&A, 575, L6
Perecaula M., Martí J., Paredes J. M., 1997, A&A, 328, 283
Plotkin R. M., et al., 2017, ApJ, 834, 104
Pooley G. G., Fender R. P., 1997, MNRAS, 292, 925
Rani B., Gupta A. C., Joshi U. C., Ganesh S., Wiita P. J., 2010, ApJ, 719, L153
Rea N., Torres D. F., 2008, The Astronomer's Telegram, 1731
Rivinius T., Carciofi A. C., Martayan C., 2013, A&ARv, 21, 69
Rodríguez L. F., Mirabel I. F., 1997, ApJ, 474, L123
Scargle J. D., 1982, ApJ, 263, 835
Taylor A. R., Kenny H. T., Spencer R. E., Tzioumis A., 1992, ApJ, 395, 268
Torrence C., Compo G. P., 1998, Bulletin of the American Meteorological Society, 79, 61
Torres D. F., Rea N., Esvin P., Li J., Chen Y., Zhang S., 2012, ApJ, 744, L153
Van der Laan H., 1966, Nature, 211, 1131
Valtaoja E., Terasranta H., Urpo S., Nesterov N. S., Lainela M., Valtonen M., 1992, A&A, 254, 71
Van der Laan H., 1966, Nature, 211, 1131
Zimmermann L., Fuhrmann L., Massi M., 2015, A&A, 580, L2

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