Search for radio pulsations in LS I +61 303

A. Cañellas[1], Bhal Chandra Joshi[2], J.M. Paredes[1], C.H. Ishwara-Chandra[2,3], J. Moldón[1], V. Zabalza[1], J. Martí[4], M. Ribó[1]

[1] Departament d'Astronomia i Meteorologia and ICCUB, Universitat de Barcelona (IEEC-UB)
[2] National Centre for Radio Astrophysics, TIFR
[3] Inter-University Centre for Astronomy and Astrophysics
[4] Departamento de Física (EPSJ), Universidad de Jaén (Spain)

Abstract

LS I +61 303 is a radio emitting high-mass X-ray binary that shows periodic emission from radio to TeV energies with its orbital period of 26.5 days. This is one of the three X-ray binaries detected up to now at TeV energies and, as it is the case for LS 5039, the nature of the compact object is unknown. We have searched for pulsed radio emission from LS I +61 303 using the phased array mode of GMRT. Simultaneous data from the multi-bit phased array (PA) back-end and the polarimeter (PMTR) were taken at 1280 MHz. Three runs of data were performed lasting 3, 2 and 1 hours, respectively. No pulses have been found, what places a sub-mJy upper limit for a possible millisecond pulsed emission from LS I +61 303.

Introduction

Located at a distance of 2.0±0.2 kpc (Frail & Hjellming 1991), LS I +61 303 contains a rapidly rotating B0 Ve star with a stable equatorial shell, and a compact object of unknown nature with a mass between 1 and 5 $M_\odot$, orbiting it every 26.5 days (Hutchings & Crampton 1981, Casares et al. 2005). Quasi-periodic radio outbursts monitored during 23 years have provided an accurate orbital period value of 26.4960±0.0028 d (Gregory 2002). The orbit is eccentric (e = 0.72) and periastron takes place at phase 0.23±0.02, assuming T_0= JD 2,443,366.775 (Casares et al. 2005). The maximum of the radio outbursts varies between phase 0.45 and 0.95. X-ray outbursts, starting around phase 0.4 and lasting up to phase 0.6, have also been detected (Harrison et al. 2000 and references therein). Orbital X-ray periodicity has also been found using *RXTE*/ASM data (Paredes et al. 1997), which currently reveal a broad maximum. Similar results have been obtained at higher energies with *INTEGRAL* data (Hermsen et al. 2006).

LS I +61 303 is also spatially coincident with a source above 100 MeV detected by EGRET (Kniffen et al. 1997). The MAGIC Cerenkov telescope discovered LS I +61 303 at very high energy gamma rays (E >100 GeV; Albert et al. 2006), and further observations by the MAGIC collaboration have led to the discovery of the orbital variability of TeV emission with a period of 26.8±0.2 d (Albert et al. 2009).

Massi et al. (2004) reported the discovery of an extended jet-like and precessing radio emitting structure at angular extensions of 10–50 milliarcseconds. Due to the presence of apparently relativistic radio emitting jets, LS I +61 303 was proposed to be a microquasar. However, VLBA images obtained during a full orbital cycle show a rotating elongated morphology (Dhawan et al. 2006), which may be consistent with a model based on the interaction between the relativistic wind of a young non-accreting pulsar and the wind of the donor star (Dubus 2006). On 2008 September 10th, the *Swift* Burst Alert Telescope (BAT) detected a burst in the direction of LS I +61 303, a magnetar-like activity that has been proposed to be linked to the presence of a young highly magnetized pulsar in the binary system (Dubus & Giebels 2008). In any case, from an observational point of view it is not clear yet if LS I +61 303 contains an accreting black hole, an accreting neutron star or a non-accreting neutron star.

The source does not appear as a radio pulsar in any of the public catalogs built after performing blind pulsar searches. On the other hand, there are no targeted pulsational searchs on LS I +61 303 in the literature.

LS I +61 303: a scaled down version of the pulsar PSR B1259−63?

LS I +61 303 has been compared to PSR B1259−63, the first variable galactic source of VHE gamma-rays. This is a binary system containing a B2Ve donor and a 47.7 ms radio pulsar orbiting it every 3.4 years in a very eccentric orbit with e = 0.87. Both systems are γ-ray binaries, being PSR B1259−63 the only γ-ray binary with a confirmed pulsar (Johnston et al. 1992, Connors et al. 2002, Johnston et al. 2005). The radio light curve of the unpulsed emission of PSR B1259−63 is well explained by the adiabatic expansion of a synchrotron bubble, which is similar to the behaviour found in LS I +61 303. In PSR B1259−63 the radio pulses detected vanished near periastron, probably due to free-free absorption by the stellar wind and interaction with the Be disk wind. Well after the periastron passage, pulses are detected at all observing frequencies having the lower frequency (1.4 GHz) the highest flux density, and with an spectral index around −0.6 (Connors et al. 2002, Johnston et al. 2005).

In the case of LS I +61 303 the apastron separation is smaller than the periastron separation for PSR B1259−63.

Minimising absorption

Since we wanted to observe at the orbital phase with a minimum absorption, we computed the optical depth towards the compact object at different orbital phases and for different frequencies (0.60, 1.28, 2.30 and 5.00 GHz) using

$$\tau \simeq 0.3\ \dot{M}^2_{\rm w,8}\ v^{-2}_{\rm w,2000}\ T_4^{-3/2}\ \nu^{-2}_{\rm GHz}\ \int_{l_0}^{\infty} r^{-4} dl$$

and a mass-loss rate of 10^{-8} $M_\odot$ yr^{-1}, a wind speed of 2000 km s^{-1}, a temperature of 10^4 K and a density of $n \propto r^{-2}$, integrating along the line-of-sight path from the position of the compact object (l_0) up to the observer at ∞. With these opacities we have estimated the observed pulsed flux densities, $S_\nu = S_0\ \nu^{\alpha} e^{-\tau}$, at different frequencies and for several values of the spectral index (α = −0.5,−1.0,−2.0), and assuming an unabsorbed pulsed flux density S_0 at 1.28 GHz. In Fig. 1 we show the expected pulsed flux densities for α = −1.0, which can be considered a typical spectral index for pulsars. The pulsed flux density orbital variability at a given frequency is entirely due to the variability of the optical depth along the orbit. We concluded that the best option to try to detect pulsations in LS I +61 303 is to observe at 1.28 GHz around phase 0.6.

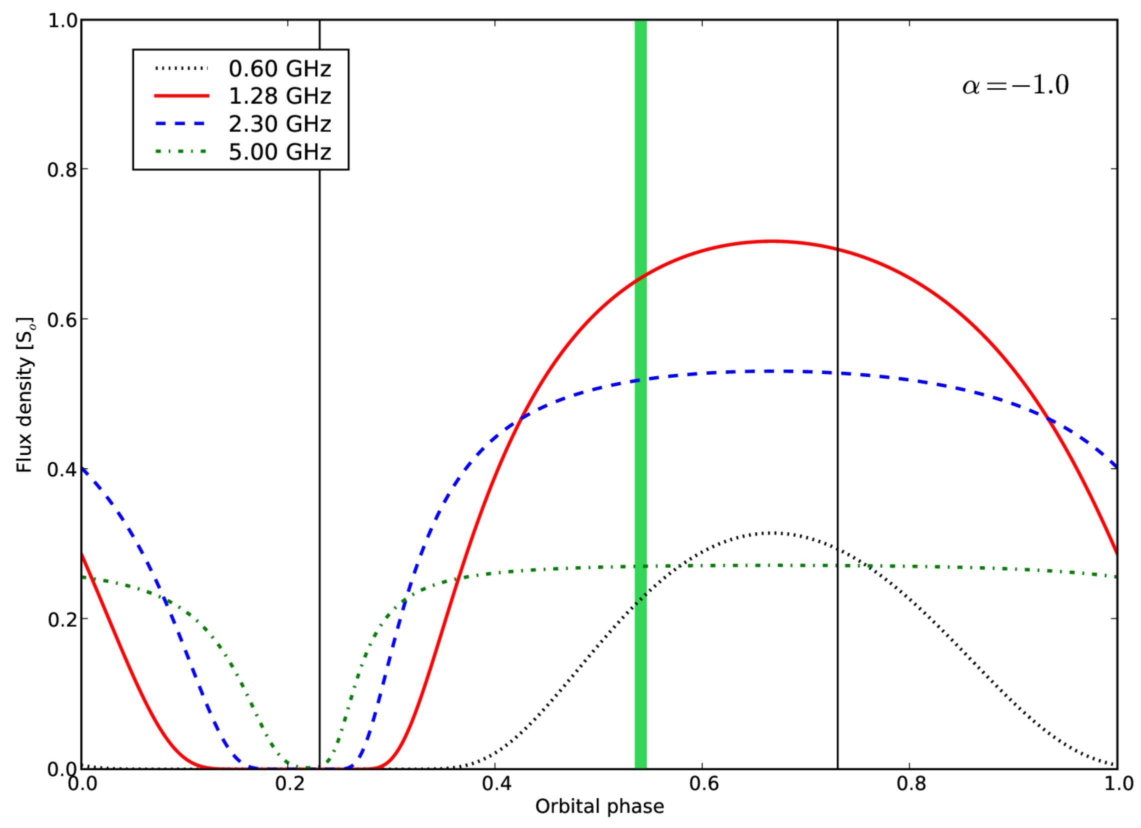

Fig. 1. The expected LS I +61 303 pulsed flux density along the orbit at different frequencies for α =−1.0 assuming that the intrinsic pulsed flux density at 1.28 GHz is S_0 and considering free-free absorption effects. Periastron and apastron are indicated by the vertical black lines at phases 0.23 and 0.73, respectively. The highest observable flux density is expected to occur at 1.28 GHz at orbital phase ~0.6, three days before apastron. The actual observation phase range is indicated by the vertical green stripe centred at 0.54.

References

Albert, J., et al. 2006, Science, 312, 1771
Albert, J., et al. 2009, ApJ, 693, 303
Casares, J., et al. 2005, MNRAS, 360, 1105
Connors, T. W., et al. 2002, MNRAS, 336, 1201
Dhawan, V., et al. 2006, PoS, Proc. of the VI Microquasar Workshop, ed. T. Belloni, p.52.1
Dubus, G. 2006, A&A, 456, 801
Dubus, G. & Giebels, B. 2008, ATel, 1715
Frail, D. A., & Hjellming, R. M. 1991, AJ, 101, 2126
Gregory, P. C. 2002, ApJ, 575, 427
Grundstrom, E. D., et al. 2007, ApJ, 656, 437
Harrison, F. A., et al. 2000, ApJ, 528, 454
Hermsen, W., & Kuiper, L. 2006, In: The keV to TeV connection, Rome, Italy, 17–19 October 2006
Hutchings, J. B., & Crampton, D. 1981, PASP, 93, 486
Johnston, S., et al. 1992, ApJ, 387, L37
Johnston, S., et al. 2005, MNRAS, 358, 1069
Kniffen, D. A., et al. 1997, ApJ, 486, 126
Massi, M., et al. 2004, A&A, 414, L1
Paredes, J.M., et al. 1997, A&A, 320, L25

Observations

Phased array observations were performed with the Giant Metrewave Radio Telescope (GMRT) on 2009 July 2[nd] and 3[rd] (UT), centred at phase 0.54. Data from two polarizations were taken in a bandwidth of 32 MHz centred at 1280 MHz divided into two subbands (USB and LSB), each split in 256 channels. Three back-ends were used simultaneously: multi-bit phased array (PA) back-end at USB, the polarimeter (PMTR) at USB and the PMTR at LSB; PA sampling time was chosen to be $t_{\rm samp}$= 128 µs, and $t_{\rm samp}$= 256 µs for both PMTRs. This redundancy is convenient for cross-checking, but only PA data results will be mentioned hereafter. PA data has less noise and better sampling, therefore is the best suited for detection and puts a more strict upper limits.

Three observations of LS I +61 303 were carried out, lasting ~3 hours (21:31:45–00:32:14 UT), ~2 hours (00:52:04–03:01:02 UT) and ~30 minutes (03:09:35–03:40:44 UT).

With the aim of checking the data quality, we observed four know pulsars as well: B0329+54, B1937+21, B2022+50 and B2035+36. This group of pulsars cover a wide range of the parameters (see Table 1). All four pulsars were easily detected with the signal-to-noise ratios (*S/N*) shown in Table 2.

It is convenient to define a parameter, *K*, which averages the expected over search *S/N* ratios. B0329+54 and B2035+36 were excluded from the average; the former due to its high brightness (not expected in this case) and the later because W10 is unknown for this pulsar. The result is *K* = 3.6±1.4 for PA.

pulsar name	P (ms)	DM (cm^{-3}pc)	$W50$ (ms)	$W10$ (ms)	$S1400$ (mJy)	α
B0329+54	714.519699726	26.833	6.6	31.4	203	-1.6
B1937+21	1.557806472448817	71.0398	0.063	0.19	10	*
B2022+50	372.619054536	33.021	4.7	14.9	2.2	-0.8
B2035+36	618.71508419	93.56	10.7	*	0.8	-1.6

Table 1. Parameters on the four known pulsars from ATNF when available (* when not). P is the period, DM is the dispersion measure, W50 and W10 are the width of pulse at 50% and 10% of peak respectively, S1400 is the mean flux density at 1400 MHz and α is the spectral index defined as $S \propto \nu^{\alpha}$.

pulsar name	expected S/N	search S/N	expected S/N over search S/N
B0329+54	9241.2	179.1	51.60
B1937+21	155.25	31.3	4.96
B2022+50	64.737	28.9	2.24
B2035+36	32.219$^{(*)}$	18.3	1.76

$^{(*)}$ obtained with $D = W50/P$

Table 2. Expected over obtained signal-to-noise ratios for the four known pulsars. In general the duty cycle was computed using *W10* (*D*=*W10*/*P*), but in the case of B2035+36 *W50* was used instead.

Analysis and results

The data on LS I +61 303 were analysed using publicly available pulsar analysis package SIGPROC (http://sigproc.sourceforge.net) adapted for GMRT data format. The data were first examined for Radio Frequency Interference (RFI) by estimating the distribution of powers over the whole time series. Any outliers to the expected Gaussian distribution were clipped. The resulting 256 channel data for a sideband was dedispersed to 256 trial dispersion measures (DM-integrated electron column density in the line of sight) ranging from 0 to 1000 pc cm^{-3}. The Fourier transform of the dedispersed time series for each trial DM was then computed and up to 32 harmonics in the resultant spectrum were summed. Any periodicity above 8 times the signal to noise ratio in the summed spectrum was recorded. After ignoring the known interference periodicities, the data were folded at candidate periodicities to produce eight 2-MHz subbands and eight subintegration over the entire observations as well as the total average profile, which were plotted as a composite plot. These plots were manually examined for all candidate periodicities.

All of the candidate periodicities were rejected as astronomical signals, what places a strict upper limit on the absorbed pulsed emission from LS I +61 303.

The minimum pulsar mean flux density detectable within a data set is

$$S^{\rm mean}_{\rm min} = K \times (S/N)_{\rm min} \frac{\beta T_{\rm sys}}{G N_{\rm a} \sqrt{N_{\rm p} t \Delta\nu}} \sqrt{\frac{D}{1-D}}$$

Considering *K* = 3.6, *t* = 3 hours, a minimum *S/N* of 8 and a canonical duty cycle of 10% we obtain an **upper limit of 0.34 mJy for the radio pulses flux density from a putative pulsar with *P*>2 ms in the direction of LS I +61 303** for the PA. If LS I +61 303 had the same duty cycle than PSR B1259−63 (63%), the upper limit would be 1.3 mJy. See Figure 2 for other values of the duty cycle and the range of possible values for the parameter *K*.

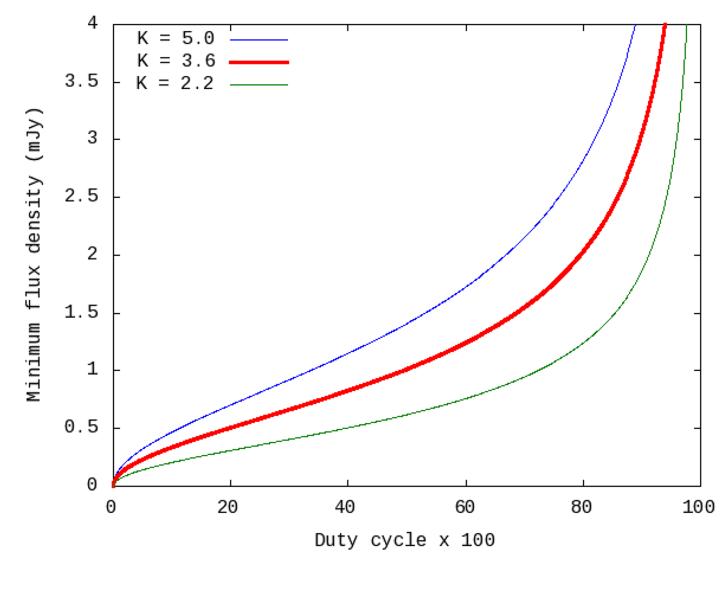

Fig. 2. Flux density upper limits in mJy for LS I +61 303 obtained with for increasing values of the duty cycle for the PA back-end data.

Aknowledgements

We thank the staff of the GMRT who have made these observations possible. GMRT is run by the National Centre for Radio Astrophysiscs (NCRA) of the Tata Institute of Fundamental Research (TIFR).

A.C., J.M.P., J.M., V.Z. and M.R. acknowledge support by DGI of the Spanish Ministerio de Educación y Ciencia (MEC) under grant AYA2007-68034-C03-01 and FEDER funds.

A.C. is supported by a fellowship FI from the Comissionat per a Universitats i Recerca of the DIUE of the Generalitat de Catalunya and the European Social Fund.

J.Moldón acknowledges support by Ministerio de Ciencia e Innovación under grant BES-2008-004564.

J.Martí acknowledges support by grant AYA2007-68034-C03-02 from the Spanish government, research group FQM-322 and excellence grant FQM-5418 from the Consejería de Innovación, Ciencia y Empresa (CICE) of Junta de Andalucia and FEDER funds.

M.R. acknowledges financial support from MEC and European Social Funds through a *Ramón y Cajal* fellowship.