Variable Very Low Frequency Emission from the Gamma-Ray Binary LS I +61 303

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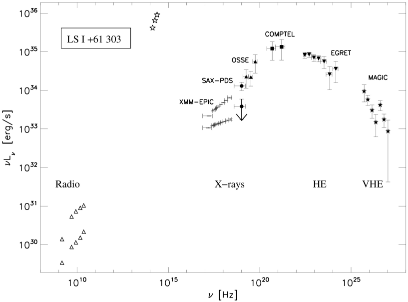
Outline

1. Introduction
   - Radio emission from gamma-ray binaries
   - The gamma-ray binary LS I +61 303
   - Goals of the project
2. Radio observations (GMRT & LOFAR)
3. Results
4. Conclusions

Gamma-Ray Binaries

Binary systems which host a compact object orbiting a high mass star that have the non-thermal maximum of the Spectral Energy Distribution in γ-rays (Paredes et al. 2013, Dubus 2013)

System	Main star	P/ days
Cygnus X-3	WR	0.2
Cygnus X-1 ??	O9.7Iab	5.6
MWC 656 ??	Be	60.4
PSR B1259–63	09.5Ve	1236.7
HESS J0632+057	B0 Vpe	315.0
LS I +61 303	B0 Ve	26.5
1FGL J1018.6–5856	O6V	16.6
LS 5039	O6.5V	3.9



Green: X-ray binaries with gamma-ray emission

Red: known gamma-ray binaries

SED of the gamma-ray binary LS I +61 303. Sidoli et al. (2006)

Gamma-Ray Binaries

Young non-accreting pulsar scenario

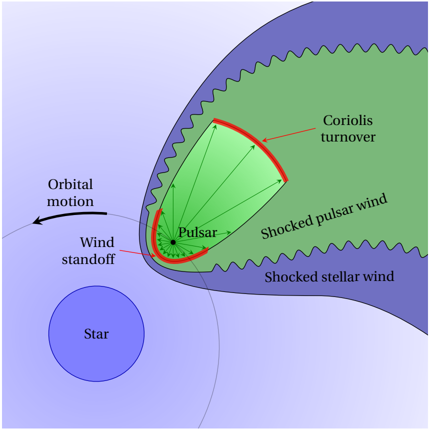
Strong shock between both winds:

- Relativistic pair plasma wind from the pulsar
- Stellar wind from the massive companion star

Originally proposed by Maraschi & Treves (1981),

re-proposed by Dubus (2006)

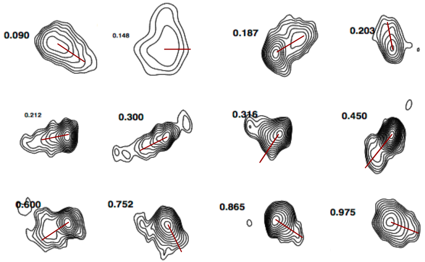
Radio flux dominated by the synchrotron emission



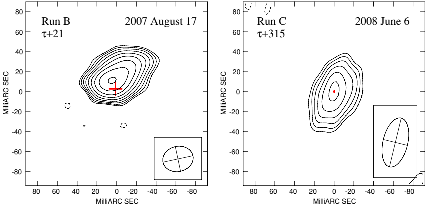
Model for LS 5039 from Zabalza et al. (2012)

Extended radio emission

Using VLBI observations, we resolve the radio emission for all the gamma-ray binaries which have been explored.



LS I +61 303. Adapted from Dhawan et al. (2006)



PSR B1259–63 Moldón et al. (2011)

The gamma-ray binary LS I +61 303

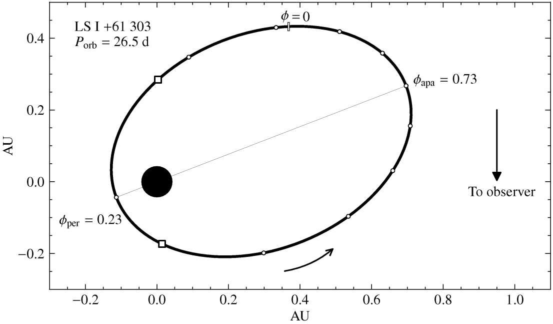
LS I +61 303

B0 Ve star ($12.5 \pm 2.5\ M_\odot$)
$d = 2.0 \pm 0.2$ kpc
$e = 0.72 \pm 0.15$

$P_{orb} = 26.496 \pm 0.003$ d
$P_{super} = 1667 \pm 8$ d

Variability at all frequencies
X-ray–TeV: correlated(?)
Radio–TeV: correlated
Optical–Radio: correlated
GeV–TeV: anticorrelated

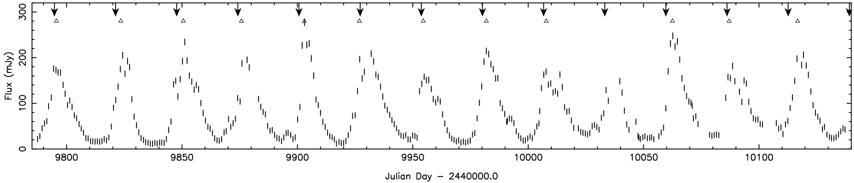
Frail & Hjellming (1991), Casares et al. (2005), Gregory (2002)



Radio emission of LS I +61 303

LS I +61 303 exhibits a large variability at radio frequencies.

Emission orbitally modulated ($P_{\rm orb} \approx 26.5$ d)



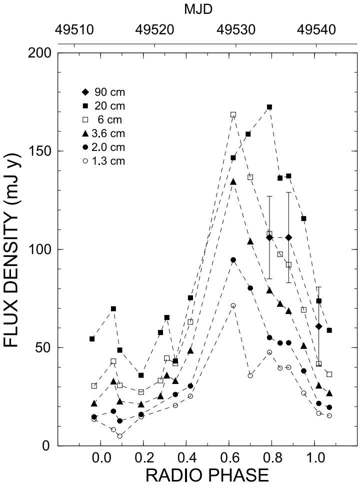
Ray et al. (1997)

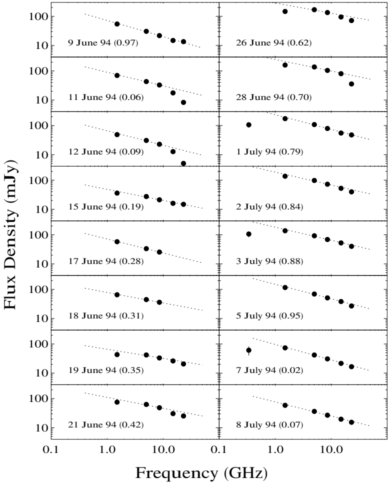
The outbursts are not equal from cycle to cycle

Radio pulsar searches have been conducted without success
(McSwain et al. 2011, Cañellas et al. 2012)
Therefore, the observed radio emission is not pulsed.

Radio emission of LS I +61 303

Focusing on one single outburst…

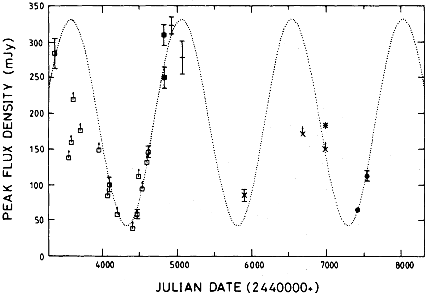


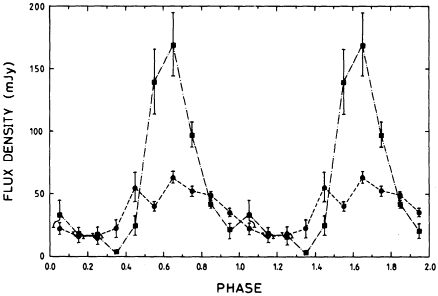


Strickman et al. (1998)

Superorbital modulation

LS I +61 303 also exhibits a periodic modulation of the amplitude and the phases of these outbursts.
The period of this superorbital modulation is 1667 d ($\approx$ 4.4 yr)





Paredes et al. (1990)

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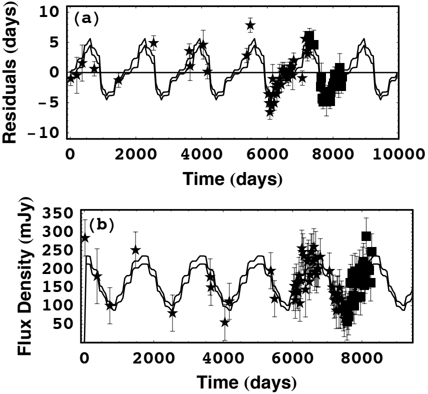
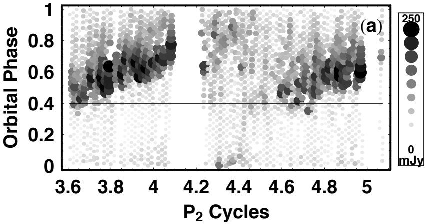
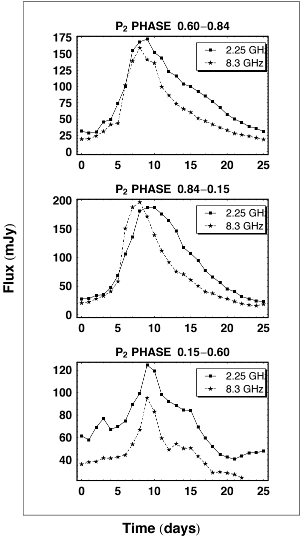
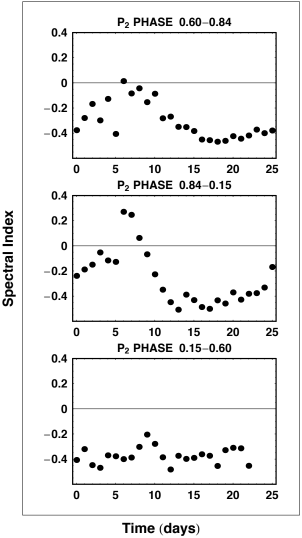




Gregory (2002)

Superorbital modulation





Gregory (2002)

Goals

At $\nu \ll 1$ GHz LS I +61 303 and all the gamma-ray binaries have been poorly explored.

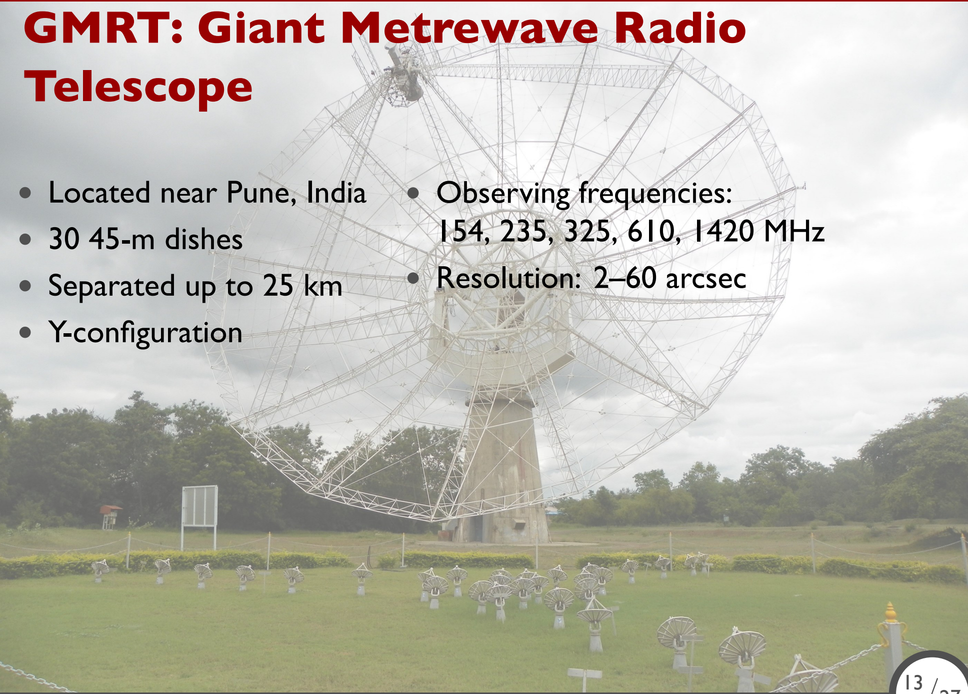
We expect...

- Absorption mechanisms arising from the spectrum (Bosch-Ramon 2009)
- A large extended structure, "*nebula*" at arcsec-arcmin scales (Bosch-Ramon et al. 2011)
- A more steady emission along the time (Durant et al. 2011)

Goals of this work

- Determine the low-frequency spectrum of LS I +61 303
- Study its variability
- Search for absorption mechanisms
- Detect for first time the predicted extended emission

GMRT: Giant Metrewave Radio Telescope



- Located near Pune, India
- 30 45-m dishes
- Separated up to 25 km
- Y-configuration

- Observing frequencies: 154, 235, 325, 610, 1420 MHz
- Resolution: 2–60 arcsec

LOFAR: The Low Frequency Array

- New generation (digital) radio interferometer
- The Netherlands (core), France, Germany, Sweden, United Kingdom, Poland
- 24 core, 14 remote and 8 international stations
- 48 HBAs and 96 LBAs each
- LBA: 30–80 MHz & HBA: 110–250 MHz
- Baselines: 100 m–1500 km

LOFAR: The Low Frequency Array

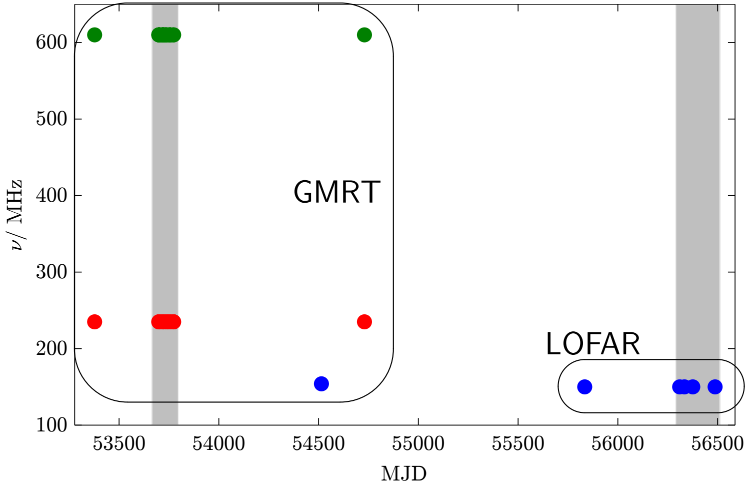
We started a collaboration with the Transient Key Project (TKP) of LOFAR.

We have access to the following data for LS I +61 303 at 150 MHz:

- One deep observation during the commissioning phase (2011)
  - Testing of the current status of LOFAR
  - Still high noise (rms = 40 mJy)
- Regular short observations with the Radio Sky Monitor (RSM)
  - 6 pointings in 2013. 4 are already analyzed
  - More pointings in the coming months

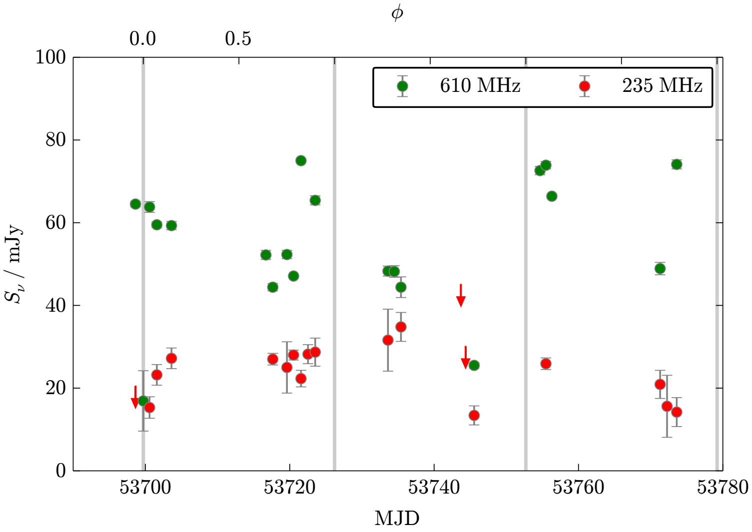
Studying LS I +61 303 at $\nu < 1$ GHz

We have analyzed $\sim$30 unpublished archival GMRT observations at 235/610 MHz in 2005–2008 and one observation at 150 MHz in 2008



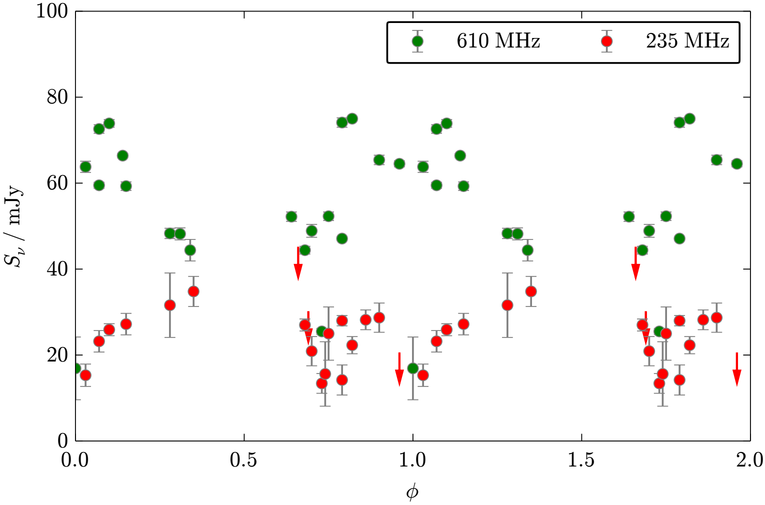
Results from the GMRT observations

GMRT data from Nov. 2005 to Feb. 2006



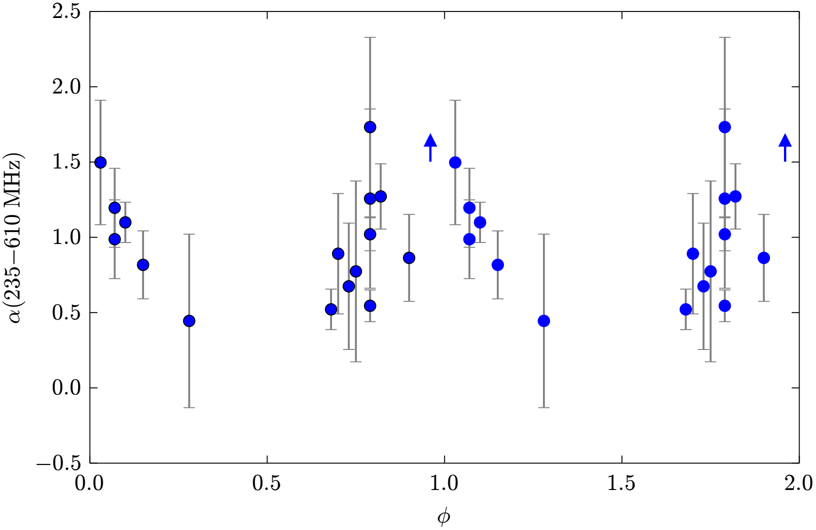
Results from the GMRT observations

GMRT data from Nov. 2005 to Feb. 2006



Results from the GMRT observations

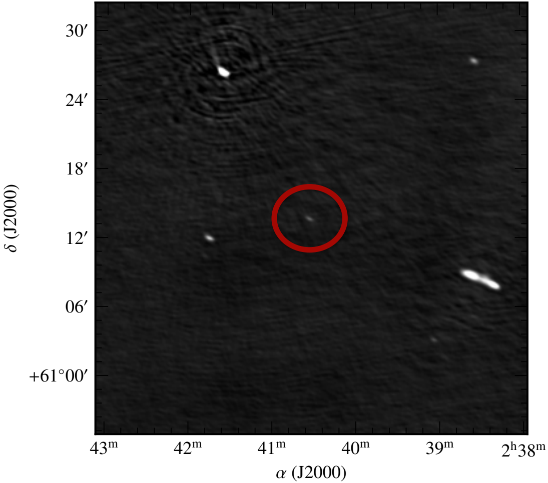
GMRT data from Nov. 2005 to Feb. 2006



Results at very low frequencies

With the GMRT observation at 154 MHz we detected for first time a gamma-ray binary at these very low frequencies.

- $\nu = 154$ MHz
- Bandwidth 32 MHz
- Beam:
  30×14 arcsec
- Point-like source
- $S_\nu = 37 \pm 2$ mJy

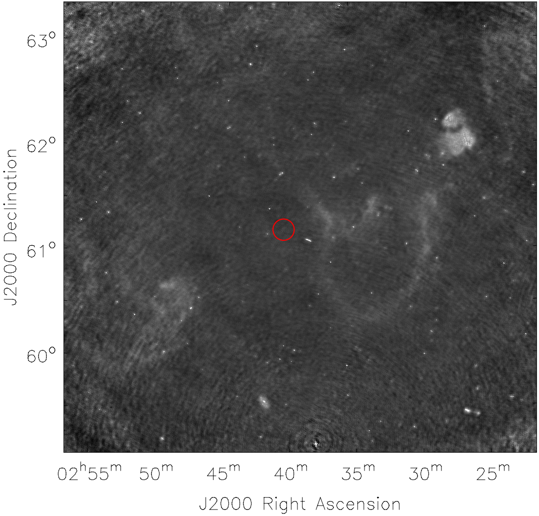


Results at very low frequencies

6 RSM pointings to LS I +61 303 with LOFAR up to now.

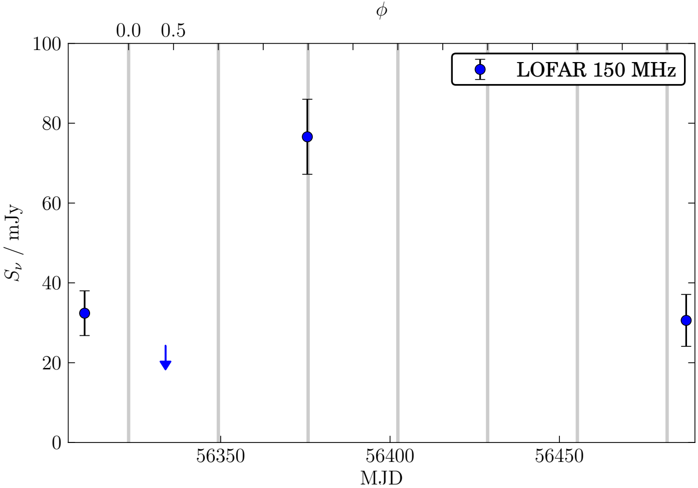
- $\nu = 149$ MHz
- Bandwidth 78 MHz
- Beam: 27×15 arcsec

- 4 analyzed obs.
- 3 detections $> 3\sigma$
- Point-like source



Results at very low frequencies

Preliminary results from the RSM LOFAR observations
Detection of LS I +61 303 in three of four analyzed observations
The behavior of the source is variable along the time



Discussion

Unresolved questions

Variability at 150 MHz, orbitally modulated?

We observe a large variability at 610 MHz but a more constant emission at 235 MHz. What is the origin of this behavior?

- Outbursts absorbed at 235 MHz?
  Emitting region becomes optically thick at the very low frequencies?
- Changes in the electron density of the surrounding plasma with produces different absorption mechanisms?
- Changes in the emitting region?

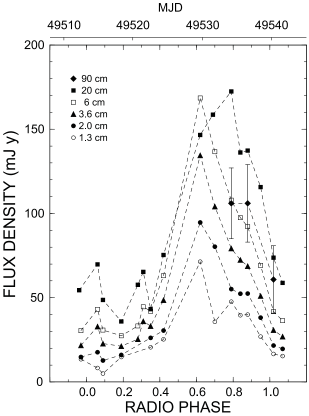
$$\ell K_0 \rightsquigarrow 1.08\,\ell K_0, \qquad B \rightsquigarrow 0.75\,B$$

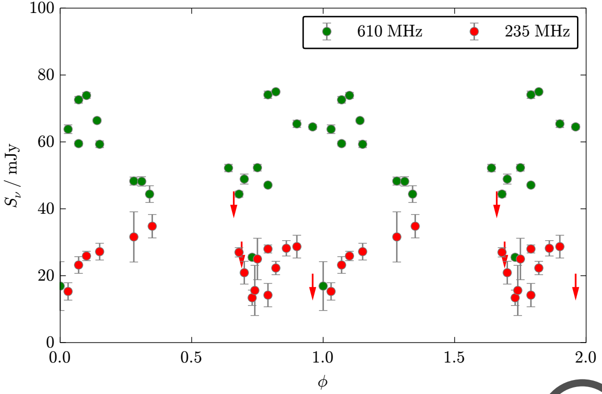
Consistency of the results

Comparing these results with the ones from Strickman et al. (1998)
We need to take into account the superorbital period:

$$\phi^{\rm super}_{\rm Strickman} \approx 0.7 \qquad \phi^{\rm super}_{\rm GMRT} \approx 0.2 \qquad \phi^{\rm super}_{\rm LOFAR} \approx 0.8$$

$$S_{2.2} \sim 175~{\rm mJy} \qquad S_{2.2} \sim 120~{\rm mJy} \qquad S_{2.2} \sim 175~{\rm mJy}$$





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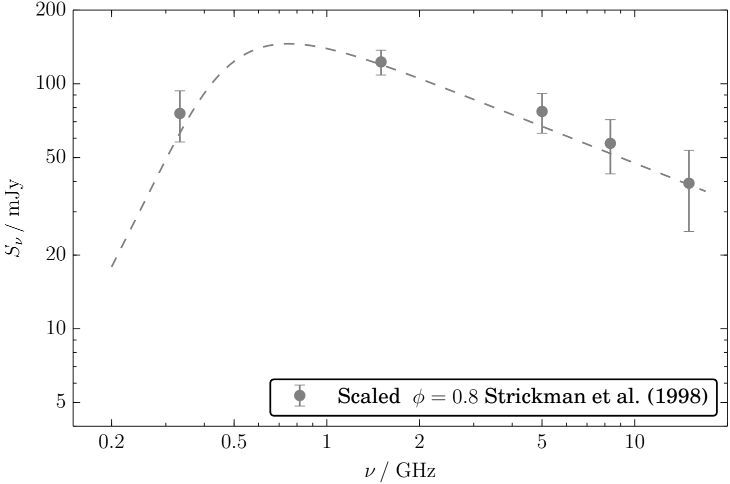
Considering the estimations from Gregory (2002), we extrapolate the fluxes from Strickman et al. (1998) to the ones expected at the superorbital phase observed in the GMRT data.



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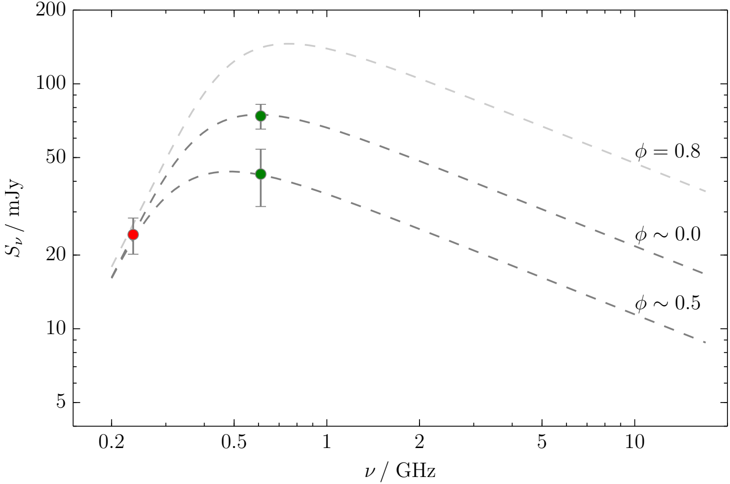

Conclusions

- Detection for the first time of a gamma-ray binary at 150 MHz
- Claiming of variability at this frequency
- The outbursts are not present at 235 MHz but still visible at 610 MHz. The origin of this behavior is still unclear
- The extended emission at very low frequency is not detected in the LOFAR and GMRT images
  Sensitivities $\lesssim 1$ mJy and/or resolutions of $\approx$ arcsec are necessary
- More data at 150 MHz could resolve the origin of the observed variability
- The characterization of the behavior of LS I +61 303 at low frequencies still requires deeper studies in combination with high-frequency observations