Studies on high-energy binary sources through radio observations

Benito Marcote

ASTRON

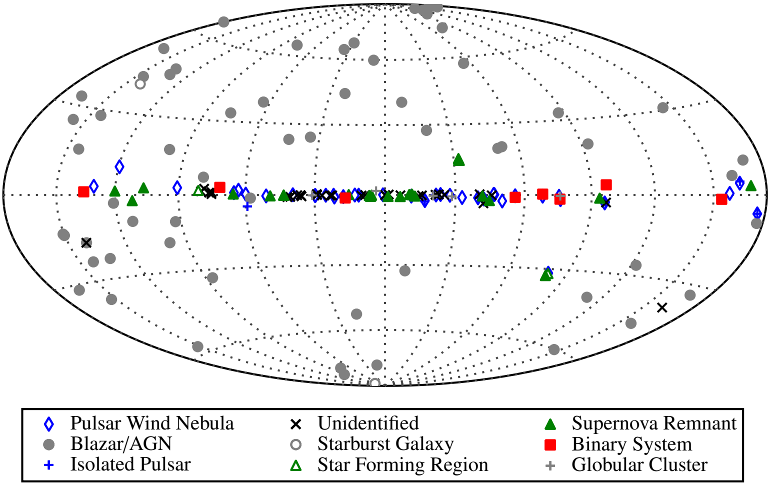
November 3, 2015

Universitat de Barcelona

ICCUB Institut de Ciències del Cosmos

Introduction

The gamma-ray sky



Very high-energy γ-ray all-sky map showing the 161 sources discovered up to now emitting at TeV energies. TevCat catalog (`tevcat.uchicago.edu`)

Introduction

Binary systems with persistent γ-ray emission

γ-ray emitting sources associated to Galactic binary systems usually display non-thermal emission from radio to γ-rays

All these binaries are composed of, at least, one **massive early-type star**

$$M \sim 10 \text{ to} \sim 150\ \mathrm{M}_{\odot}, \qquad v_{\infty} \sim 10^3\ \mathrm{km\ s^{-1}}, \qquad T_{\mathrm{eff}} \sim 20\,000\text{–}50\,000\ \mathrm{K}$$

Three different types, as a function of the companion and the nature of the emission:

- Colliding wind binaries
- High-mass X-ray binaries
- Gamma-ray binaries

Introduction

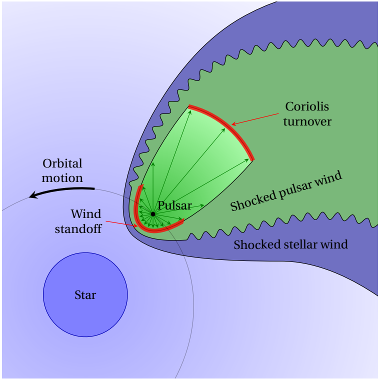
Gamma-Ray Binaries

Massive star and compact object (NS or BH)
Non-thermal SED dominated by the γ-ray emission probably produced by the presence of shocks between the non-relativistic stellar wind and the relativistic wind from the compact object

The whole population of gamma-ray binaries consists currently of five systems:

System	Main star	$P/$ days
LS 5039	O6.5 V	3.9
1FGL J1018.6–5856	O6 V	16.6
LS I +61 303	B0 Ve	26.5
HESS J0632+057	B0 Vpe	315.0
PSR B1259–63	O9.5 Ve	1236.7

Radio: synchrotron emission by a population of accelerated electrons
HE: Inverse Compton scattering of stellar UV photons by the same population of electrons



Model for LS 5039 (Zabalza et al. 2012)

Motivation and performed studies

- HE binaries are good laboratories that accelerate particles up to relativistic energies, connecting particle physics to astrophysics
- γ-ray emission produced by the same electron population that generates the emission from radio to X-rays
- Radio observations emerge thus as a powerful tool to study in detail physical properties of the emitting regions in these HE systems
- In particular, the low frequencies remain unexplored and can provide important clues about the absorption processes and their physical parameters
- VLBI observations can resolve the radio emission and distinguish the different regions that produce the emission

First detailed studies at low-frequencies of gamma-ray binaries:

LS 5039 (VLA, WSRT and GMRT observations)
LS I +61 303 (GMRT and LOFAR observations)

The gamma-ray binary LS 5039

LS 5039

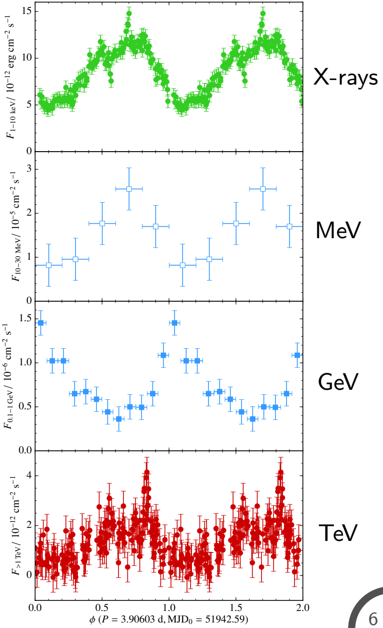
$\alpha_{J2000} = \ 18^h\ 26^m\ 15.06^s$
$\delta_{J2000} = -14^\circ\ 50'\ 54.3''$

O6.5 V star ($23 \pm 3\ M_\odot$)
Compact object, NS or BH (1–5 $M_\odot$)

$P \approx 3.9$ d
$e = 0.35 \pm 0.04$
$d = 2.5 \pm 0.5$ kpc

X-rays: periodic
GeV light-curve: periodic (anticorrelated)
TeV light-curve: periodic
Radio: persistent, small variability without orbital modulation

Aharonian et al. (2005), Casares et al. (2005), Kishishita et al. (2009), Abdo et al. (2009), Casares et al. (2012), Zabalza et al. (2013), Collmar & Zhang (2014)



The gamma-ray binary LS 5039

LS 5039

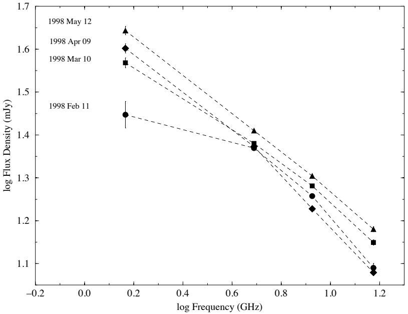
$\alpha_{\mathrm{J2000}} = \ 18^{\mathrm{h}}\ 26^{\mathrm{m}}\ 15.06^{\mathrm{s}}$
$\delta_{\mathrm{J2000}} = -14^{\circ}\ 50'\ 54.3''$

O6.5 V star ($23 \pm 3\ \mathrm{M}_{\odot}$)
Compact object, NS or BH (1–5 $\mathrm{M}_{\odot}$)

$P \approx 3.9\ \mathrm{d}$
$e = 0.35 \pm 0.04$
$d = 2.5 \pm 0.5$ kpc

X-rays: periodic
GeV light-curve: periodic (anticorrelated)
TeV light-curve: periodic
Radio: persistent, small variability without orbital modulation

Aharonian et al. (2005), Casares et al. (2005), Kishishita et al. (2009), Abdo et al. (2009), Casares et al. (2012), Zabalza et al. (2013), Collmar & Zhang (2014)



Radio spectra from 1.4 to 15 GHz

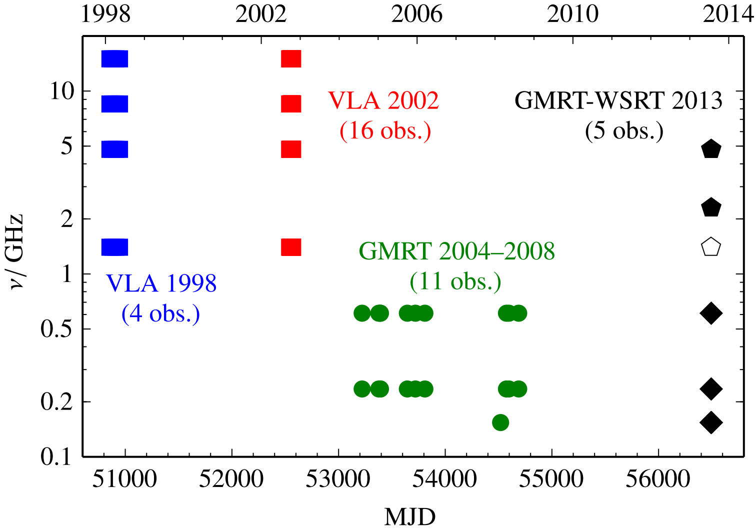
Spectral index $\alpha = -0.46 \pm 0.01$, where $S_{\nu} \propto \nu^{\alpha}$

Variability $< \pm 25$ %.

Martí et al. (1998)

No radio pulses founded (McSwain et al. 2011)

Summary of the observations analyzed in this work

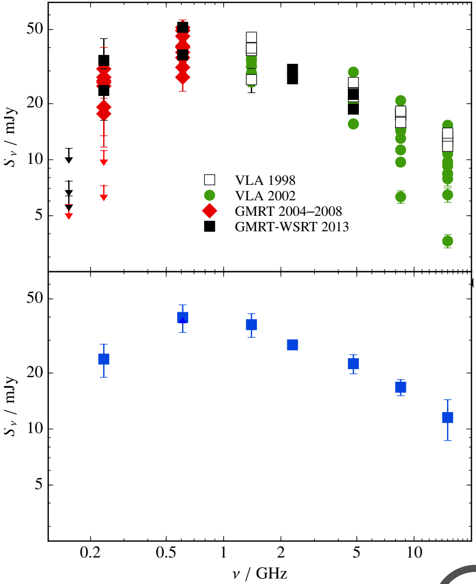


VLA and GMRT archival observations analyzed in this work
GMRT-WSRT observations proposed and analyzed as PI in 2013

Non-simultaneous spectrum of LS 5039

Combining data from 1998 to 2013

- Small variability along the years ($< 25\,\% \quad \forall\ \nu$)
- “Similar” profile in average
- Turnover at ~ 0.5 GHz
- Source undetected at 150 MHz



- Only two data points at 2.3 GHz (not representative)
- The mean square errors have been used in the average data

Modeling the LS 5039 spectrum

A first approximation (toy model)

Most of the radio emission comes from a compact core $\lesssim 1$ mas or ~ 3 AU (semi major axis: 0.19 AU) (Moldón et al. 2012)

We have built a very simple model to understand the spectrum:

- Compact core $\rightsquigarrow$ one-zone model
- No orbital modulation $\rightsquigarrow$ symmetric emitting region (spheric)
- For simplicity $\rightsquigarrow$ isotropic and homogeneous
- We consider the presence of a synchrotron emitting plasma
- Turnover produced by either SSA, FFA or Razin effect (and combinations of them)

Modeling the LS 5039 spectrum

A first approximation (toy model)

We have built a very simple model to understand the spectrum:

- **Synchrotron emission**, with a particle injection:

$$n(E)\mathrm{d}E = KE^{-p}\mathrm{d}E$$

- **Synchrotron self-absorption** (SSA), from relativistic plasma:

$$\kappa_{\mathrm{SSA}} \propto KB^{(p+2)/2}\nu^{-(p+4)/2}$$

- **Free-free absorption** (FFA), from thermal plasma:

$$\kappa_{\mathrm{FFA}} \propto n_{\mathrm{e}}^2 T_{\mathrm{w}}^{-3/2}\nu^{-2}$$

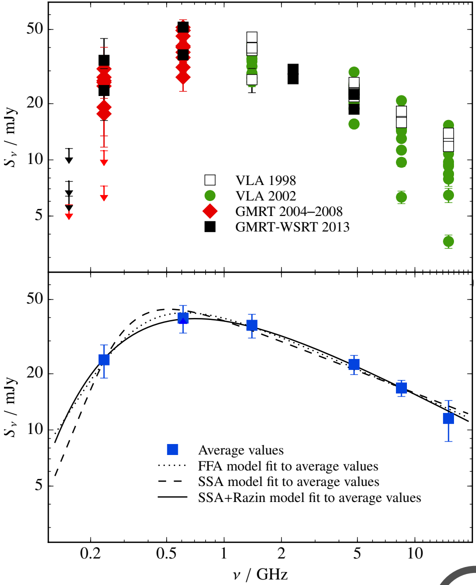
- **Razin effect**, from thermal plasma:

$$S_\nu \rightsquigarrow S_\nu e^{-\nu_{\mathrm{R}}/\nu}, \qquad \nu_{\mathrm{R}} \equiv 20 n_{\mathrm{e}} B^{-1}$$

Non-simultaneous spectrum of LS 5039

Combining data from 1998 to 2013

- The average spectrum can be fitted by typical models:
  - SSA
  - Synchrotron + FFA
  - SSA + Razin
  - FFA + Razin
  - SSA + FFA
- Small differences between fits
- SSA+Razin is the best fit
- But the other fits are not statistically rejected

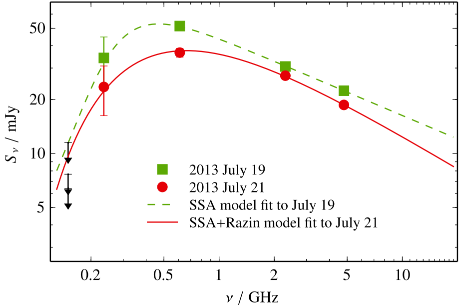


Quasi-simultaneous spectrum of LS 5039

GMRT & WSRT campaign in 2013 July 19 and 21

Two 0.15–5 GHz spectra at orbital phases $\phi \approx 0.9$ and 0.4

- Similar spectra, but subtle differences between the two epochs
- Persistent turnover at ~ 0.5 GHz
- Stronger emission on 2013 July 19
- 2013 July 19: pure SSA spec.
- 2013 July 21: SSA+Razin spec.
- FFA provides poor fits



GMRT data: 235 and 610 MHz
WSRT data: 2.3 and 5.0 GHz

154 MHz GMRT data taken every other day (on 2013 July 18, 20 and 22)

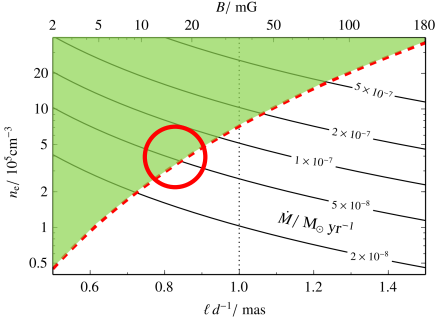
Modeling the LS 5039 spectrum

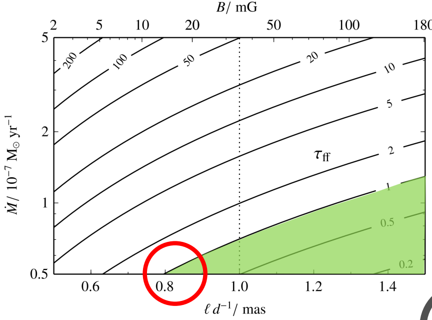
Coherent picture from fits and τ_ν^{FF}

- Avg. spectrum: SSA+Razin
- July 19 spectrum: SSA
- July 21 spectrum: SSA+Razin

- Coherent picture with:

$$\ell \sim 0.85\ \mathrm{mas}\ (\sim 2.5\ \mathrm{AU})$$
$$B \sim 20\ \mathrm{mG}$$
$$n_e \sim 4 \times 10^5\ \mathrm{cm}^{-3}$$
$$\dot{M} \sim 5 \times 10^{-8}\ \mathrm{M}_\odot\ \mathrm{yr}^{-1}$$





Conclusions

Marcote, B., Ribó, M., Paredes, J. M., Ishwara-Chandra, C. H., 2015, MNRAS, 451, 4578

- **Significant mixing** of the non-relativistic wind inside the synchrotron radio emitting relativistic plasma, even close to $\sim 100\%$ (consistent with recent simulations, e.g. Bosch-Ramon et al. 2012,2015)

- The derived mass-loss rate (model dependent, but in agreement with recent results from Casares et al., in prep.) implies that the **wind is clumpy**

- Presence of **Razin effect**, widely observed in Colliding Wind Binaries, that gives further support to the scenario of the **young non-accreting pulsar**

- Variability $< \pm 25$ % from 0.2 to 15 GHz on day, month and year timescales
- Persistent turnover at ~ 0.5 GHz

The gamma-ray binary LS I +61 303

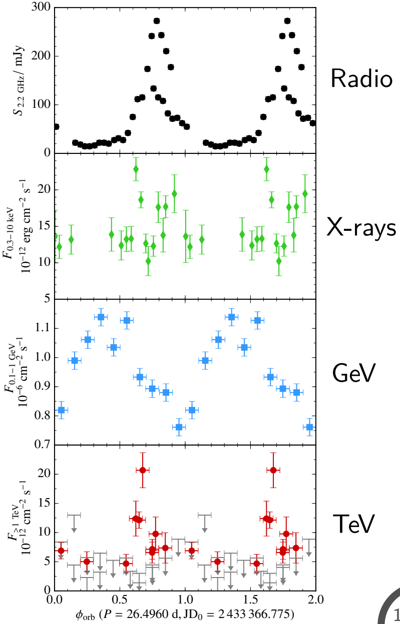
LS I +61 303

B0 Ve star ($12.5 \pm 2.5\ \mathrm{M}_\odot$)
$d = 2.0 \pm 0.2$ kpc
$e = 0.72 \pm 0.15$

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

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

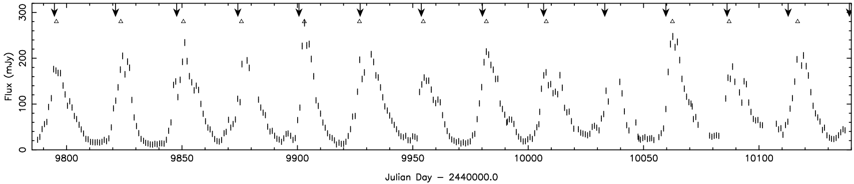
Frail & Hjellming (1991), Casares et al. (2005), Gregory (2002)



Radio emission of LS I +61 303

Large variability at radio frequencies

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



Ray et al. (1997)

The outbursts are different from cycle to cycle

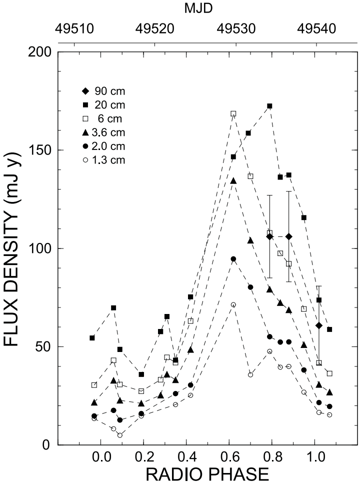
Radio pulsar searches have been conducted without success

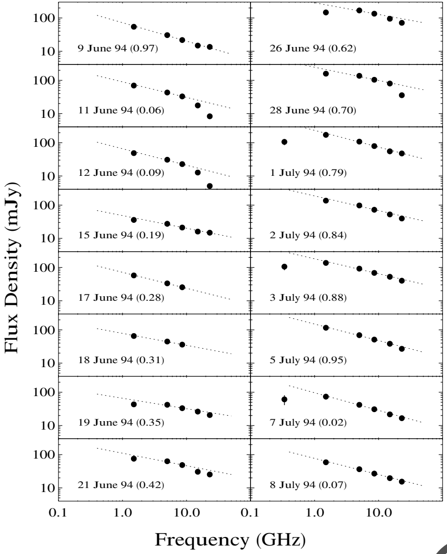
(McSwain et al. 2011, Cañellas et al. 2012)

The observed radio emission is not pulsed

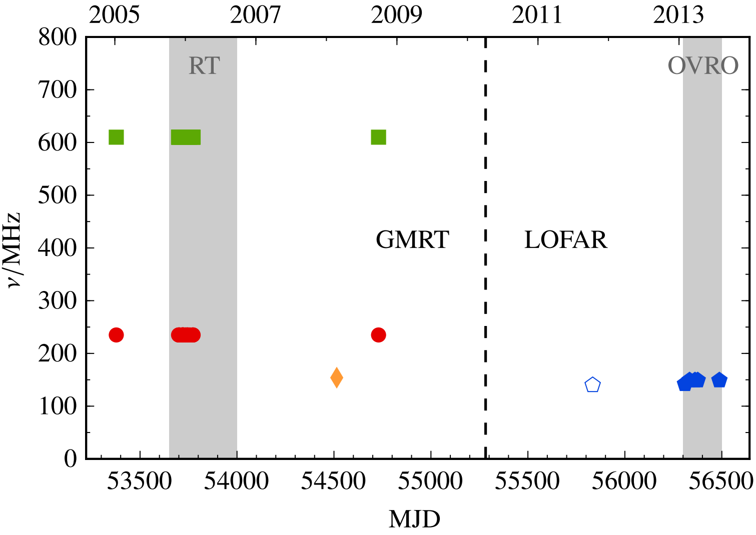
Radio emission of LS I +61 303

Focusing on a single outburst (Strickman et al. 1998)





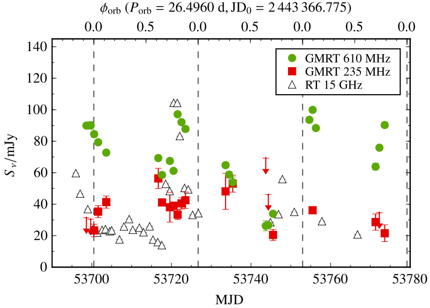
Summary of the observations analyzed in this work

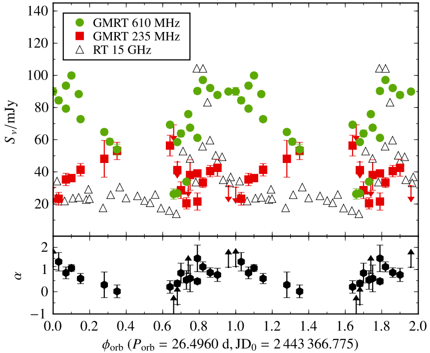


GMRT archival data analyzed in this work

LOFAR observations conducted within the TKP (RSM obs)

Radio emission of LS I +61 303





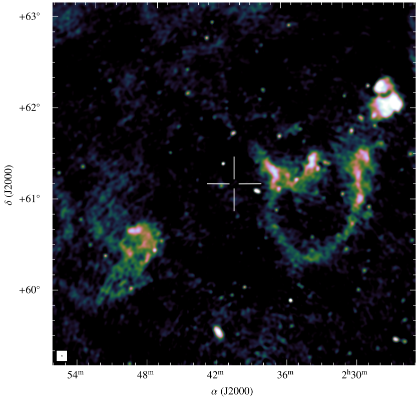
Orbital and superorbital modulation

235 MHz $\approx$ anticorrelated with 610 MHz

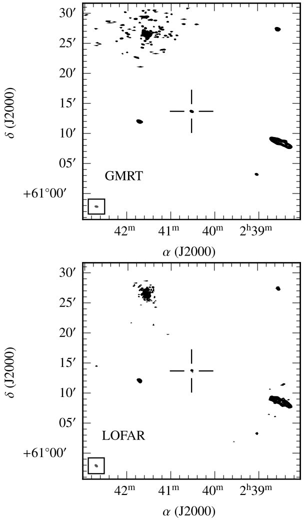
Significant differences between frequencies

Delays in orbital phase, $\Delta\phi$, between frequencies

First detection of LS I +61 303 at 150 MHz



Field of view around LS I +61 303 at 150 MHz as seen by LOFAR



First detection of LS I +61 303 at 150 MHz

Radio emission of LS I +61 303

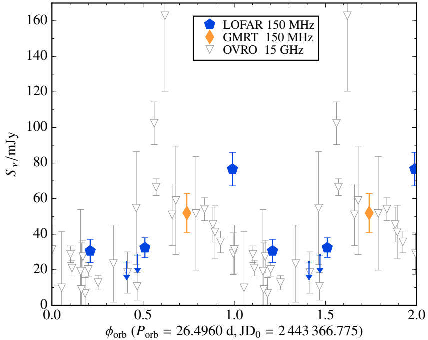
Light-curve at 150 MHz

Five 3-hr runs within the RSM
23 core + 13 remote stations
BW: 0.8 MHz

Cannot be compared with the previous ones because of the completely different superorbital phase

Poor sampling, we can only point out a possible shift between the two frequencies, but more data is clearly needed

More observations coming...!



Modeling the radio emitting region

Estimating the delays between frequencies for the peak of the emission

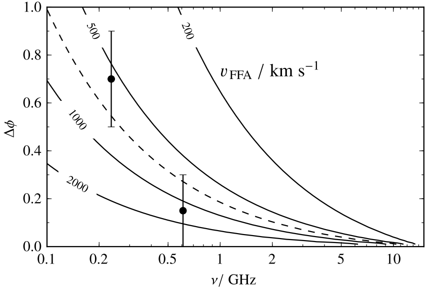
One-zone model with an expanding radio emitting region

Delays interpreted as changes in the opacity of this region due to its expansion, considering SSA and FFA

Assuming that FFA dominates, the expansion velocity would be

$$v_{\mathrm{FFA}} = 700 \pm 200\ \mathrm{km\ s^{-1}}$$

But $\dot{M}$ is not well constrained



Modeling the radio emitting region

Assuming a SSA dominated region and two different dependences of B:

$\boldsymbol{B \sim \ell^{-2}}$

$$v_{\mathrm{SSA}} = 1\,000 \pm 140 \ \mathrm{km\ s^{-1}}$$

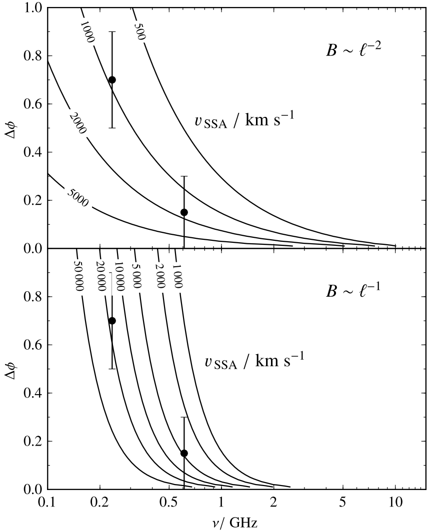
$\boldsymbol{B \sim \ell^{-1}}$

$$v_{\mathrm{SSA}} = 17\,000 \pm 3\,000 \ \mathrm{km\ s^{-1}}$$

But it is poorly constrained

FFA and SSA with $B \sim \ell^{-2}$ predict a delay of about ~ 1.0 at 150 MHz

Observed delay: 0.0–0.5 (or 1.0–1.5) but at different superorbital phase



Conclusions

Marcote, B., et al., 2015, MNRAS, accepted after minor revision

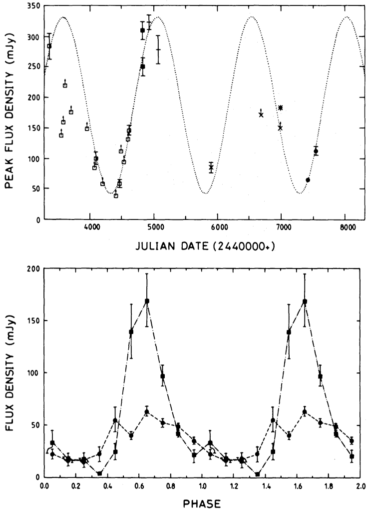
- First detection of a gamma-ray binary at a frequency as low as 150 MHz
- First light-curves at low frequencies
- The shape of the outbursts is significantly different at these low frequencies
- A simple model with an expanding emitting region is plausible to describe the observed behavior, leading to subrelativistic expansion velocities (that do not fit in the microquasar scenario)
- Simultaneous observations with GMRT and LOFAR already accepted covering a full orbital cycle. 2 runs using International stations

General conclusions

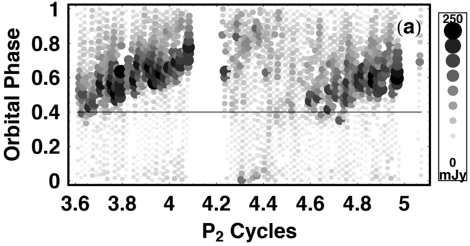
- We have performed the first detailed studies at low radio frequencies of gamma-ray binaries
- LOFAR and GMRT, in combination with high-frequency observations (WSRT and VLA), can provide important clues about the absorption processes and the emitting regions
- But we have also explored the radio emission of these kinds of sources at VLBI scales
- Simultaneous observations with LOFAR and GMRT on LS I +61 303 will be performed next months
- The study of pulsars at low frequencies is essential for a better knowledge of these systems
- And deeper searches for transient sources

Superorbital modulation

Periodic modulation of the amplitude and the phases of these outbursts with $P_{\rm so} \approx 1\,667$ d (≈ 4.4 yr)



Paredes et al. (1990)



Gregory (2002)