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ICREA

Radio pulsations from LS I 61 303 and its possible behavior as a gamma-ray pulsar

Diego F. Torres
(research partly done with S. Weng, J. Li, A. Papitto, D. Iñiguez, and many colleagues more)

Hinted since the 1970's, studied since COS-B

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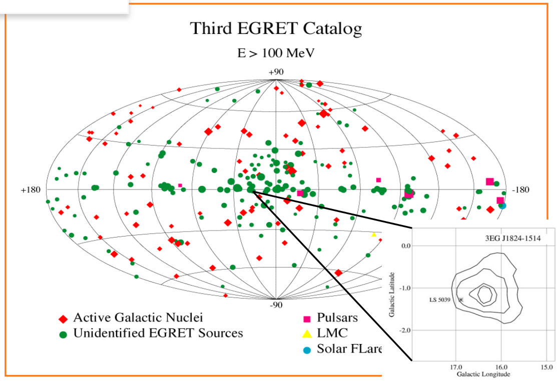
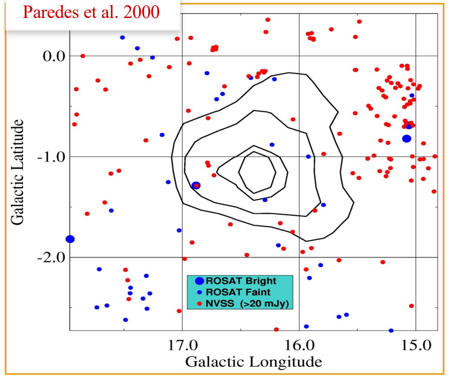
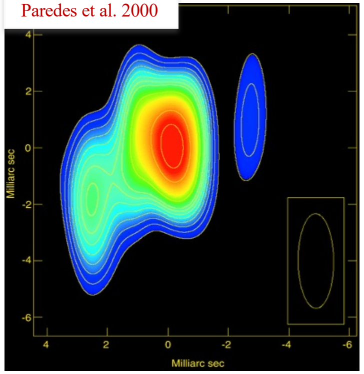
LS 5039



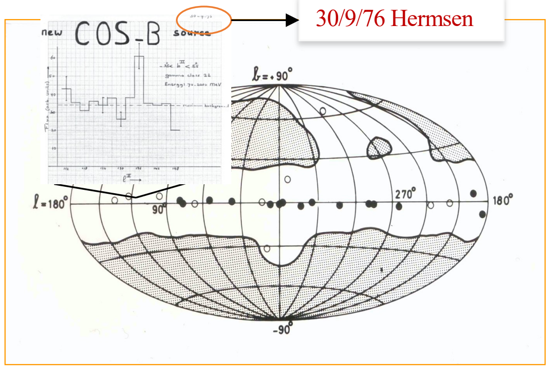
Paredes et al. 2000

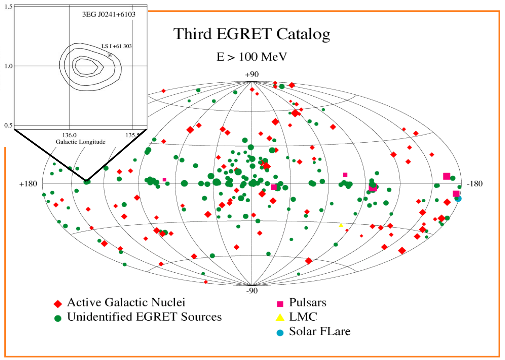


Paredes et al. 2000



30/9/76 Hermsen





But none confirmed before Fermi.

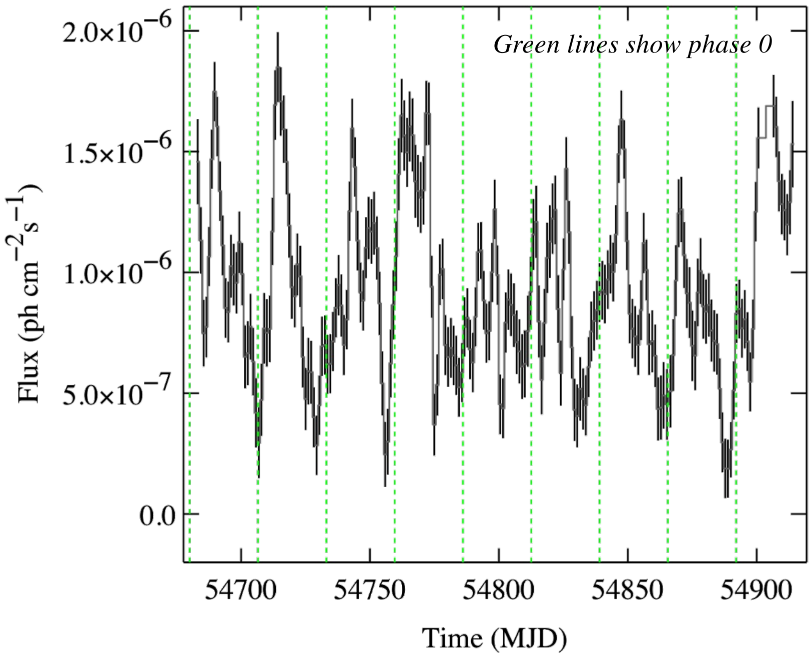
LS I +61 303

No confirmed variability (orbital) // Bad positioning // many candidates in the field led these sources to remain unidentified.

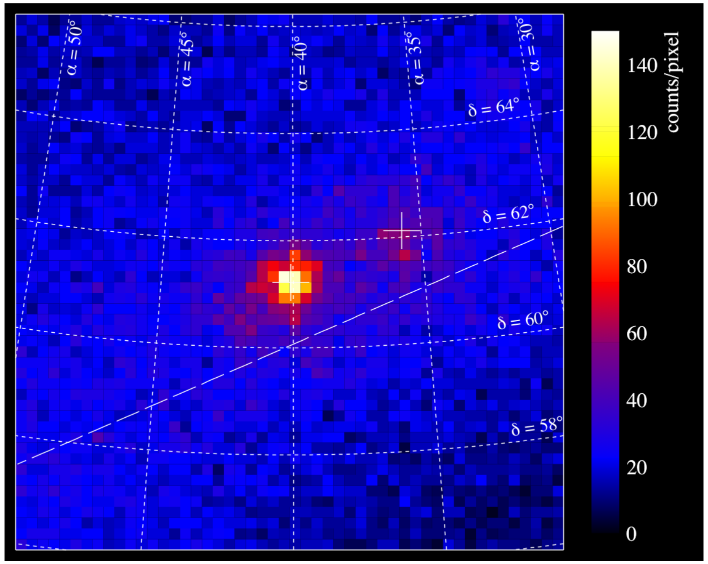
The first Fermi detection of orbital periodicity

- **LS I +61 303** location error radius of 1.8’
- consistent with the known position of the optical counterpart
- Flux variability is also clearly evident

variability



position



The first detection of super-orbital GeV/TeV variability

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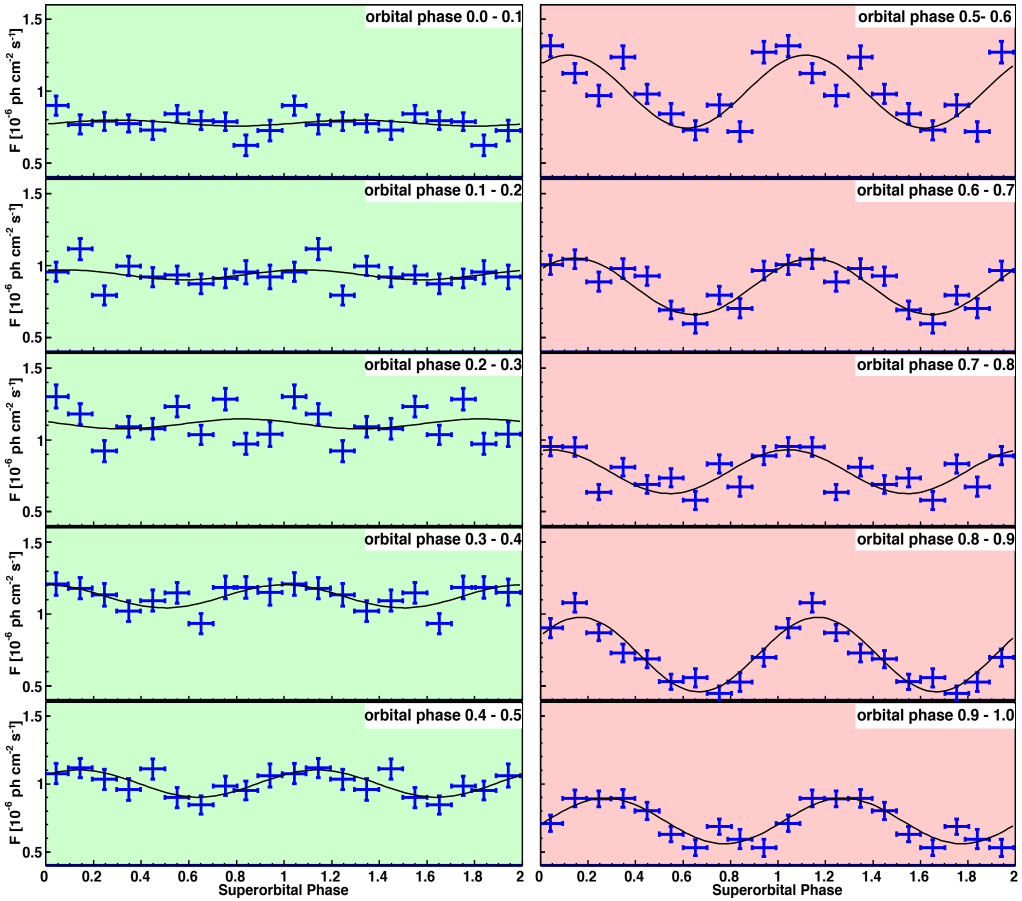


Separated in equal orbital phases, pattern seen in longer timescales

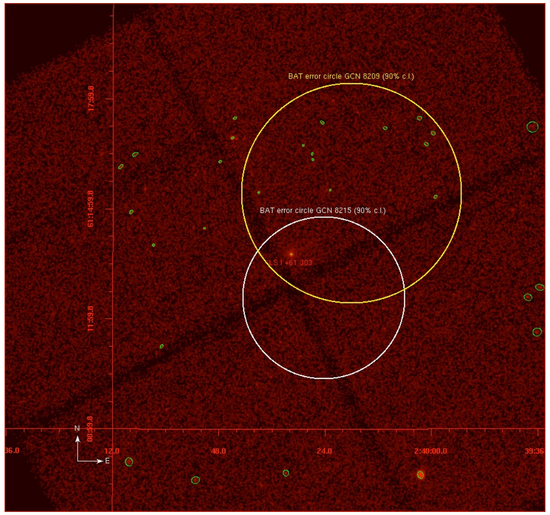
Each panel shows the GeV flux at a fixed orbital position (see labels), along a period of 4.5 years

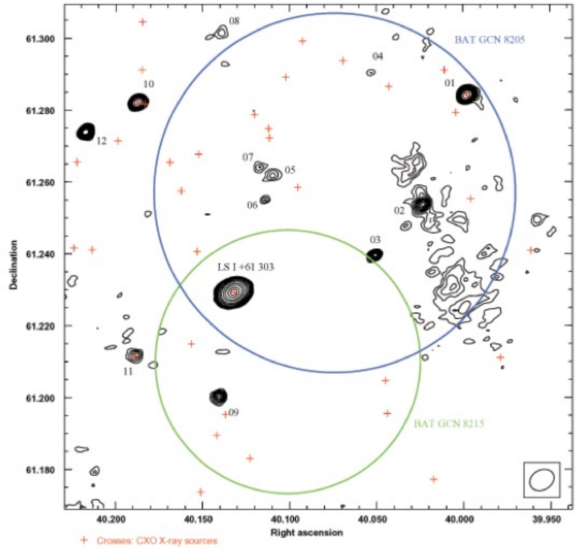
The background represent the region of **periastron** and **apastron**, respectively

Black line: Sinusoidal fit with fixed superorbital period

Ackermann et al. 2013, ApJ Letters (DFT corresponding author); confirmed with 5 years more data by Xing et al. (2017)

Short magnetar flares





On 2008 September 10th, Swift-BAT triggered on a short SGR-like burst from the direction of LS I +61 303.

The burst location, lightcurve, duration, fluence, and spectra were fully consistent with a magnetar flare

Initial claims at: GCN 8209, 8211, 8215; ATELs 1715,1731, 1740

Searching for pulsations in X-rays, UL only

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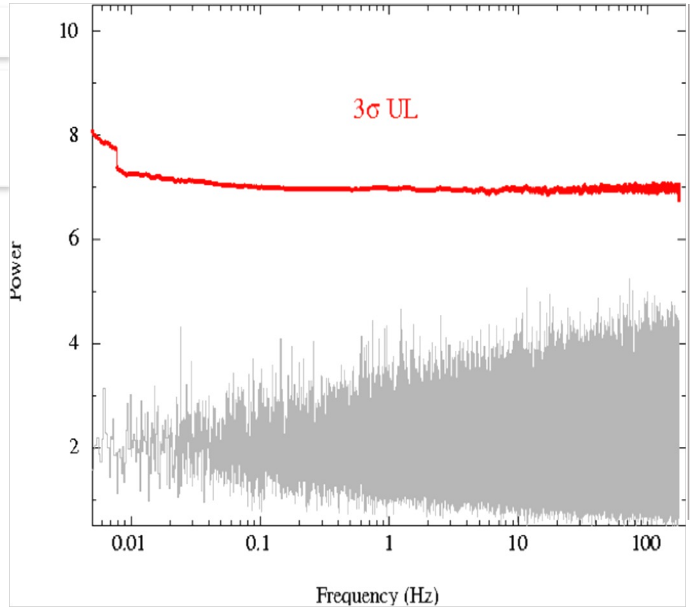
LS I +61 303

95 ks Chandra observation near apastron



Pulsed fraction 3σ UL on the semi-amplitude of a sinusoidal signal

- Search for periods with frequencies 0.005 – 175 Hz (timing resolution of the CC-mode: 0.00285 s)

- **Pulse fraction upper limits between 7 – 15 % for the whole energy range (larger % in smaller energy bands)**

- **Not restrictive:** several known pulsars have similar upper limits

Rea, DFT et al. 2010, MNRAS

Not in lack of reasons for the absence of pulses

- **In radio,**

free-free absorption -which may have a complex temporal behavior according to binary conditions- can wash out the pulses, and/or the radio cone of emission may altogether point in a different direction from Earth.

- **In X-rays,**

a pulsed fraction upper limit of ∼10% is normal, could well be larger than the actual pulsed fraction of the source as is the case for other pulsars. Only a few dozen pulsars out of the ∼ 300 detected in gamma rays and the ∼ 3000 in radio have non-thermal X-ray pulsations detected.

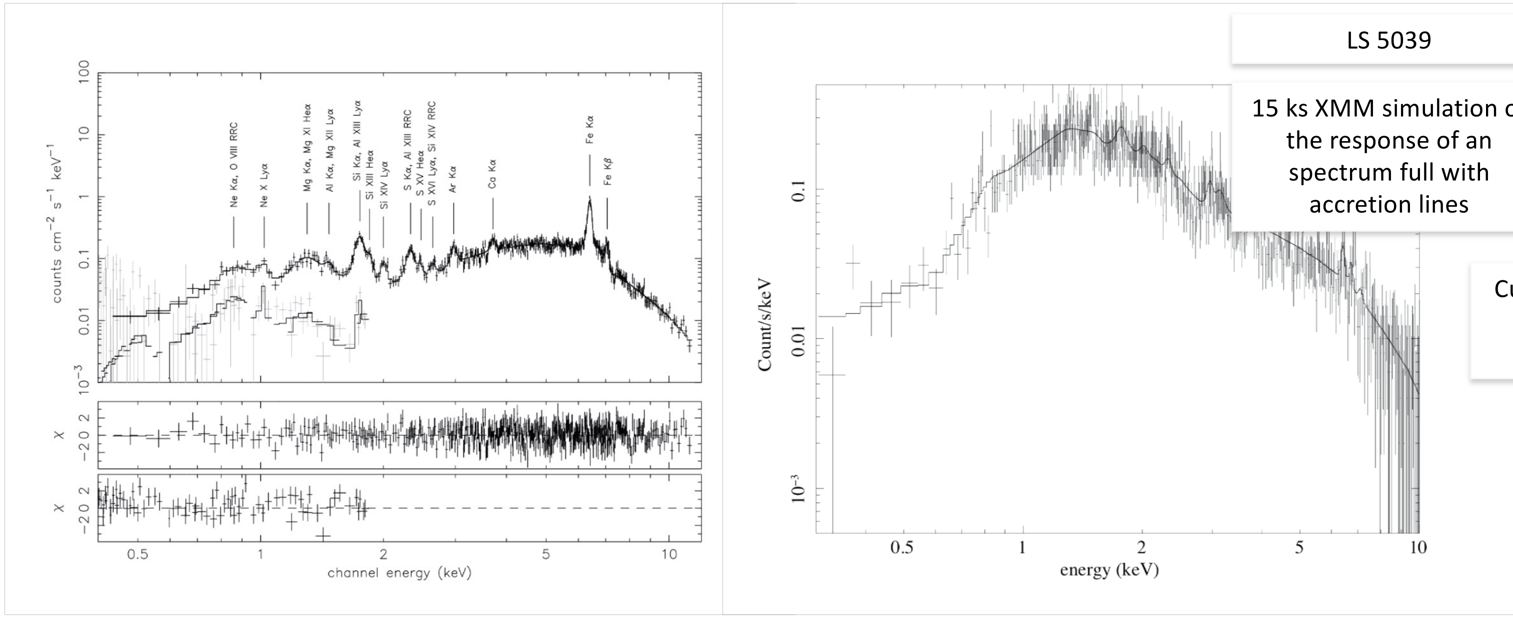
- **In gamma-rays,**

1) LS I +61 303 lies in a **complex region**, and not only the diffuse background, but the likely origin of at least part of the GeV emission beyond the magnetosphere of the putative pulsar may preclude detecting pulses.
2) the **uncertainty in the orbital parameters** reduces the sensitivity of blind searches across all frequencies when long integration times are needed

If no pulsations, nature is never certain

- Consider the accreting binary 4U 1700-37,
    - A very similar HMXB to LS 5039 (i.e., similar companion star and 4-days orbital period, but no TeV emission) located at ~ 1.5 kpc

- Left: XMM-Newton spectrum of 4U 1700-37 (first published by van der Meer et al. 2005).
- Right: how would these accretion lines look, assuming all are present, in the available data for LS 5039



LS 5039

15 ks XMM simulation of the response of an spectrum full with accretion lines

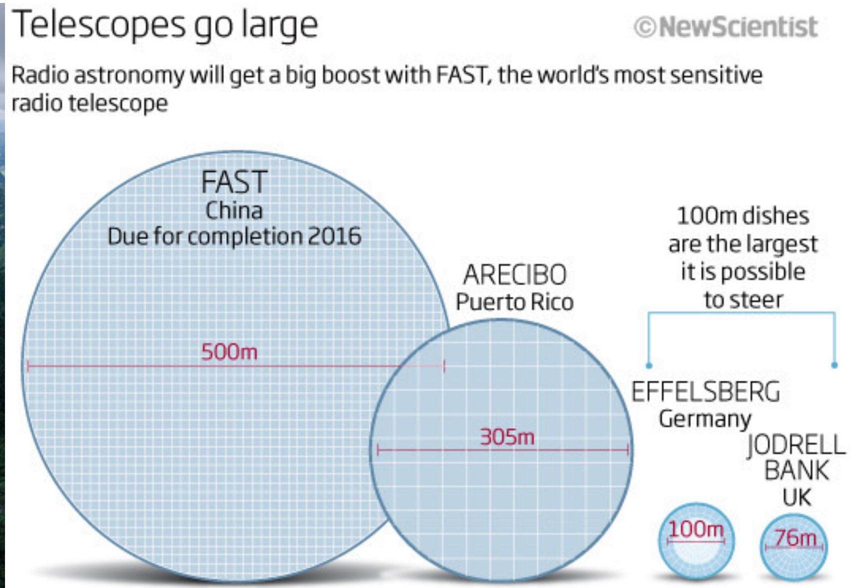
Cutoff in hard X-rays not there in gamma-ray binaries, though

Radio pulsations discovery

FAST: observing at larger radio sensitivty

- The best chance to detect pulsations from LS I +61 303 was to try observing at a large radio sensitivity in the orbital region where the free-free absorption effect due to the stellar wind (or disk) would naturally be the lowest (e.g., **Cañellas et al. 2012**)

FAST: 500 meters, single dish, ~10 better sensitivity than Arecibo.
Constructed in 2016, operated since 2019.



FAST chase of LS I + 61 303 (2020 observations)

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- We tried observing LS I 61 303 since risk-shared time was available in FAST
- We finally obtained data in 2019-2020.
- At the time, there was no unusual behavior displayed in survey data, including Swift/BAT, MAXI, and *Fermi*-LAT.

We had a total exposure time of ~ 10.2 hours: one at the orbital phase of ~ 0.07 and three around the orbital phase of ~ 0.6. The zero of orbital phase of LS I +61 303 is defined at MJD_0 = 43, 366.275, and the orbital period is estimated as P = 26.4960 days, assuming the orbital phase of periastron is ϕ_{peri} = 0.2317 from Aragona et al. 2009.

	Mid of observation time	Orbital phase	Exposure Time/h	Sampling Time/μs	Pulse detected	$S_{mean}/S_{UL}/\mu Jy$
11-01-2019	58,788.7257	0.07	2.2	98.304	No	–/1.61
01-07-2020	58,855.5278	0.59	3.0	98.304	Yes	4.40/1.37
09-01-2020	59,093.8646	0.58	3.0	196.608	No	–/1.37
09-02-2020	59,094.8681	0.62	2.0	196.608	No	–/1.68

Radio pulsations recorded: P~0.27 s

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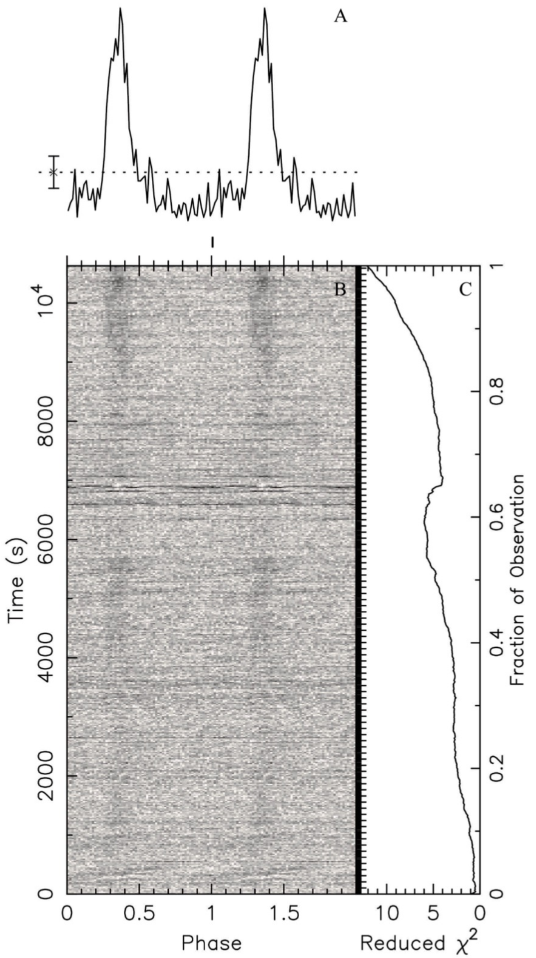

- **An unambiguous pulse signal (~22.4σ) with a single-peak profile emerges from the data taken on 2020 January 7th (MJD = 58,855.5278).**
- **The period, pulse width and DM of this pulsar are 269.15508(16) ms, 33.30 ± 0.96 ms, and 240.1 pc cm−3, respectively**
- The pulsations disappeared in the 3rd and 4th observations (one-day apart of each other), taken several months after the positive detection, at a similar orbital phase.
- A single pulse search was conducted for our observation, and more than 40 were detected
- Given that our observations are short in comparison to the orbital period of the binary, and the pulsation appears to be non-steady in nature, the orbital imprint cannot be detected in our data.

Weng et al. Nature Astronomy 2022 (Weng, DFT corresponding authors)

Details of radio pulsations recorded

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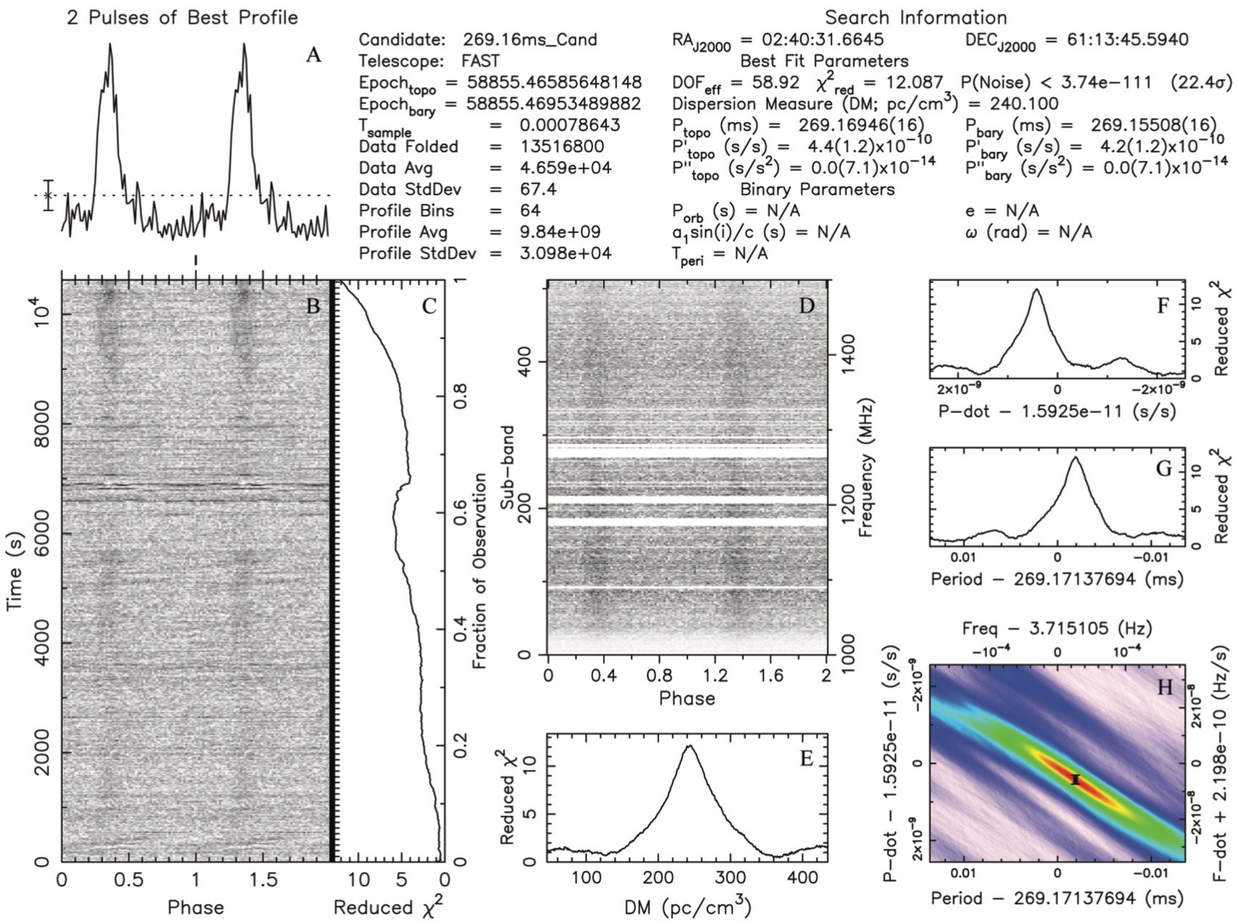

- Standard plot of the radio-pulsation search results with the routine prepfold in the PRESTO package.
- The validity of derived parameters can be found in the panels E-G
- The confidence contour of P and dotP is shown in H.
- The averaged pulse profile as a function of observing frequency is shown D. Pulse profile is shown in A.
- Pulse profiles are shown in the left-hand plots.

Many single pulses detected from LS I + 61 303

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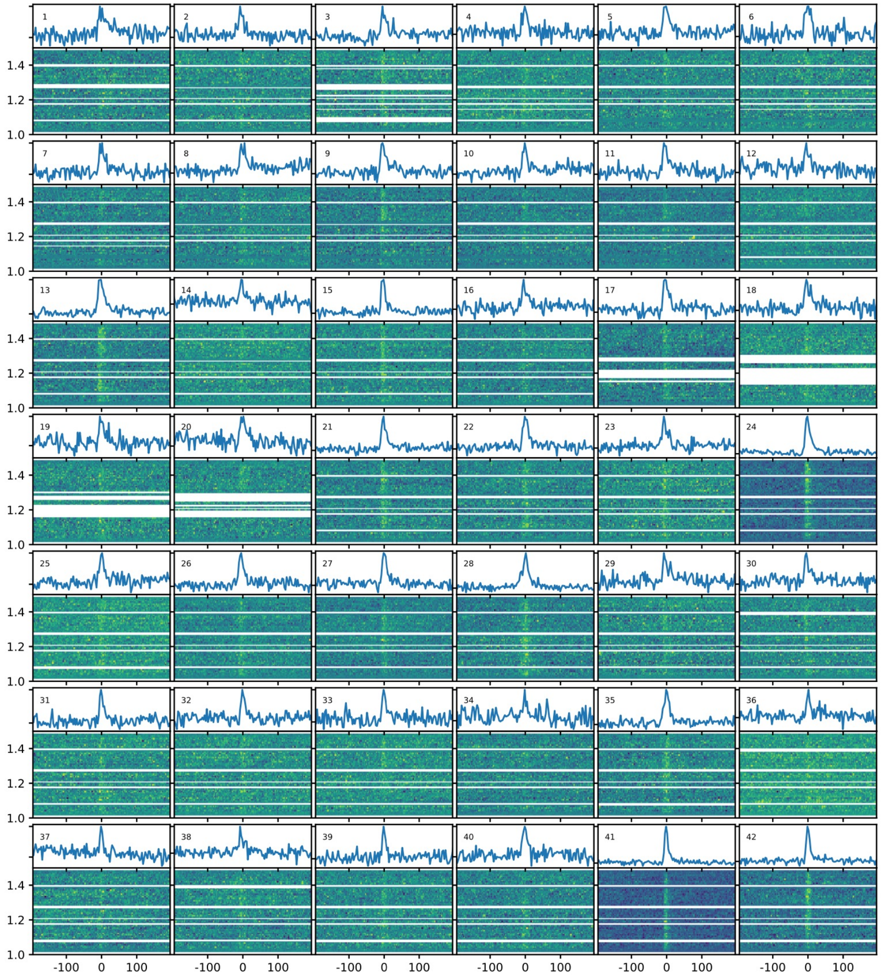

- **Single pulses detected in the *FAST* data for 2020 January 7.**
- The profile of the single pulse varies from each other, as is commonly found in other pulsars.

Weng et al. Nature Astronomy 2022 (Weng, DFT corresponding authors)

Single pulses detected all along the 2^{nd} obs.

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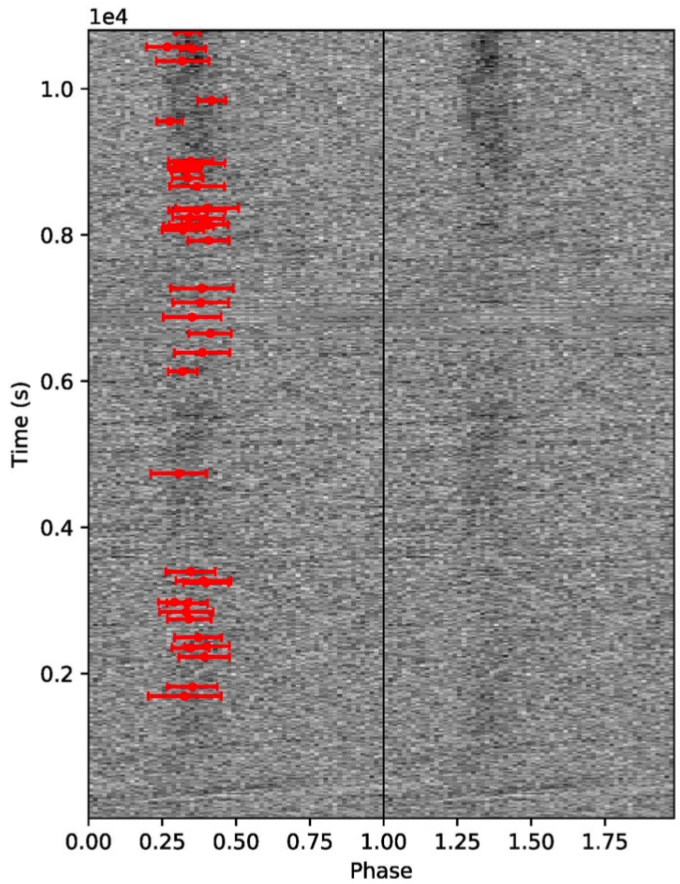

- The intensity versus the pulse phase and the observational time.
- The red bars mark the pulse phase and the occurrence time of the single pulses having a S/N ratio larger than 7. Many others seen.

Weng et al. Nature Astronomy 2022 (Weng, DFT corresponding authors)

FAST chase of LS I + 61 303 (2021 cycle)

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Project ID: PT2021_0006

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Name	Mode	Length(s)	Start Time	End Time
LS_I+61303	Tracking	1800	2021-12-28 21:00:00	2021-12-28 21:30:00
LS_I+61303	Tracking	1800	2021-12-27 21:00:00	2021-12-27 21:30:00
LS_I+61303	Tracking	1800	2021-12-26 21:30:00	2021-12-26 22:00:00
LS_I+61303	Tracking	1800	2021-12-25 21:40:00	2021-12-25 22:10:00
LS_I+61303	Tracking	1800	2021-12-24 21:40:00	2021-12-24 22:10:00
LS_I+61303	Tracking	1800	2021-12-23 21:40:00	2021-12-23 22:10:00
LS_I+61303	Tracking	3600	2021-11-29 22:30:00	2021-11-29 23:30:00
LS_I+61303	Tracking	3600	2021-11-28 22:40:00	2021-11-28 23:40:00
LS_I+61303	Tracking	3600	2021-11-27 22:50:00	2021-11-27 23:50:00
LS_I+61303	Tracking	1800	2021-11-20 00:15:00	2021-11-20 00:45:00
LS_I+61303	Tracking	1800	2021-11-17 00:40:00	2021-11-17 01:10:00
LS_I+61303	Tracking	1800	2021-11-14 01:10:00	2021-11-14 01:40:00
LS_I+61303	Tracking	1800	2021-11-11 00:30:00	2021-11-11 01:00:00
LS_I+61303	Tracking	1800	2021-11-08 00:30:00	2021-11-08 01:00:00
LS_I+61303	Tracking	1800	2021-11-07 00:30:00	2021-11-07 01:00:00
LS_I+61303	Tracking	1800	2021-11-06 00:30:00	2021-11-06 01:00:00
LS_I+61303	Tracking	1800	2021-11-05 00:30:00	2021-11-05 01:00:00
LS_I+61303	Tracking	1800	2021-11-04 00:30:00	2021-11-04 01:00:00
LS_I+61303	Tracking	1800	2021-11-03 00:30:00	2021-11-03 01:00:00
LS_I+61303	Tracking	1800	2021-11-01 01:35:00	2021-11-01 02:05:00
LS_I+61303	Tracking	1800	2021-10-30 01:22:00	2021-10-30 01:52:00
LS_I+61303	Tracking	1800	2021-10-28 01:25:00	2021-10-28 01:55:00
LS_I+61303	Tracking	3600	2021-10-26 00:24:00	2021-10-26 01:24:00

Several observations in October – December 2021 covering the whole orbital phase.

The analysis reveals several single pulses on 2021 November 2rd (UTC), corresponding to an orbital phase of ~ 0.69.

All in all similar properties to those reported.

FAST chase of LS I + 61 303 (2022 cycle)

In last cycle we only got 5 hours ranked A, 14 hours ranked B.

Why not more?

-message: the pulsations are already detected, the pulsar is already discovered, not clear what else can FAST do except pulsar monitoring (and there is a large competition for this kind of projects with less clear discovery potential in the midst of many other ON/OFF pulsars)

A trivial argument like variable absorption: 'the variable nature show that the ionized wind is likely variable, yet quite dense, so that it almost always affects the radio emission at L-band' is difficult to overcome.

We plan to use all of 5 hours in 4 observations (orbital phase ~ 0.5-0.8).

Only one was completed (orbital phase ~ 0.5) till now.

Rapid changes of conditions

The fact that the pulsations are not present in three out of four observations (a couple of them very close to one another) reveals a rapid change of conditions:

Scintillation?

Nulling?

Variable absorption?

Rapid changes of conditions: scintillation

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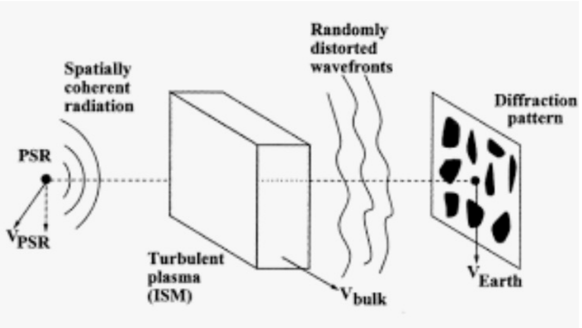

- Scintillation is unlikely:

$$\Delta t_d = 2.53 \times 10^4 (D\Delta\nu_d)^{1/2}/(\nu V_{\rm ISS})\ \mathrm{s},$$

- could explain changes in flux up to a few minutes, but not the several hours, in consecutive days, when pulsations are absent.

Diffractive scintillations occur over typical timescales of minutes to hours and radio bandwidths of kHz to hundreds of MHz, and they can cause more than order-of-magnitude flux-density fluctuations.

Refractive scintillations tend to be less than a factor of ∼2 in amplitude and occur on timescales of weeks.

Rapid changes of conditions: nulling?

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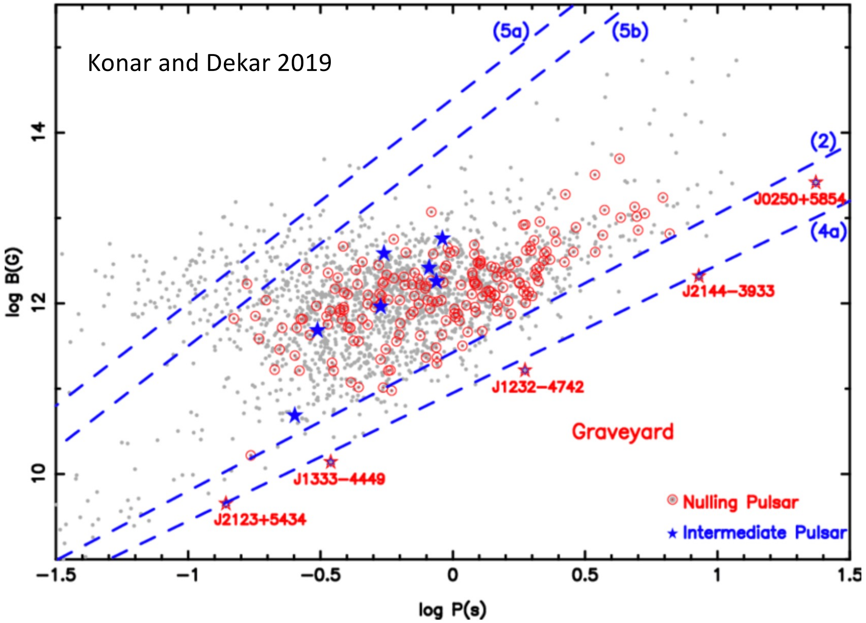
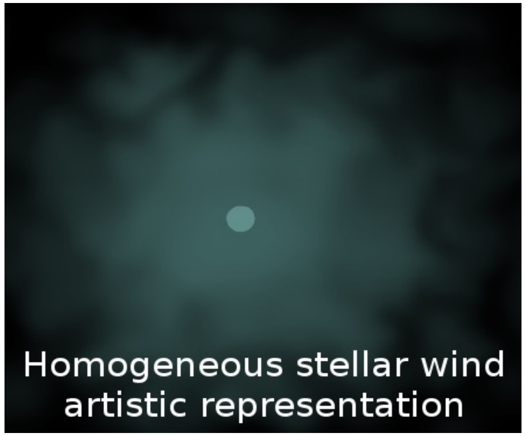
More than 200 radio pulsars have been already seen to experience nulling (that is >8% of the ATNF Catalog!).

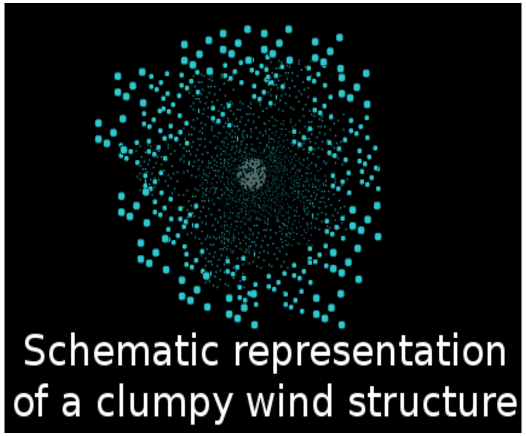


Observed radio pulsars and theoretical death-lines in the P s -B s plane. Top Panel: The death lines have been marked according to their numbering in the text. Bottom Panel: Nulling pulsars and intermediate pulsars have been highlighted with a small subset of death-lines. A number of pulsars have been specially identified (red open star) which appear to be functioning beyond the least stringent death line. The data for the known pulsars have been obtained from the ATNF pulsar cataloghttp://www.atnf.csiro.au/research/pulsar/psrcat/ (Manchester et al. 2005).

- The null fraction (the total fraction of pulses without detectable emission) and the null length (the duration of a nulling episode) exhibit a wide range of values
  - the null fraction goes from just a few % to over 90%,
  - the null length goes from a few single pulses to a complete disappearance of the emission for years at a time.
- Intermittent pulsars also exist where nulling can last from days to years,
  - for example - J1933+2421 (Kramer et al. 2006a), J1832+0029 (Lorimer et al. 2012), J1910+0517 & J1929+1357 (Lyne et al. 2017).
- Also similar to RRATs,
  - pulsars which sporadically emit single pulse outbursts instead of continuous pulse trains

Rapid changes of conditions: absorption?





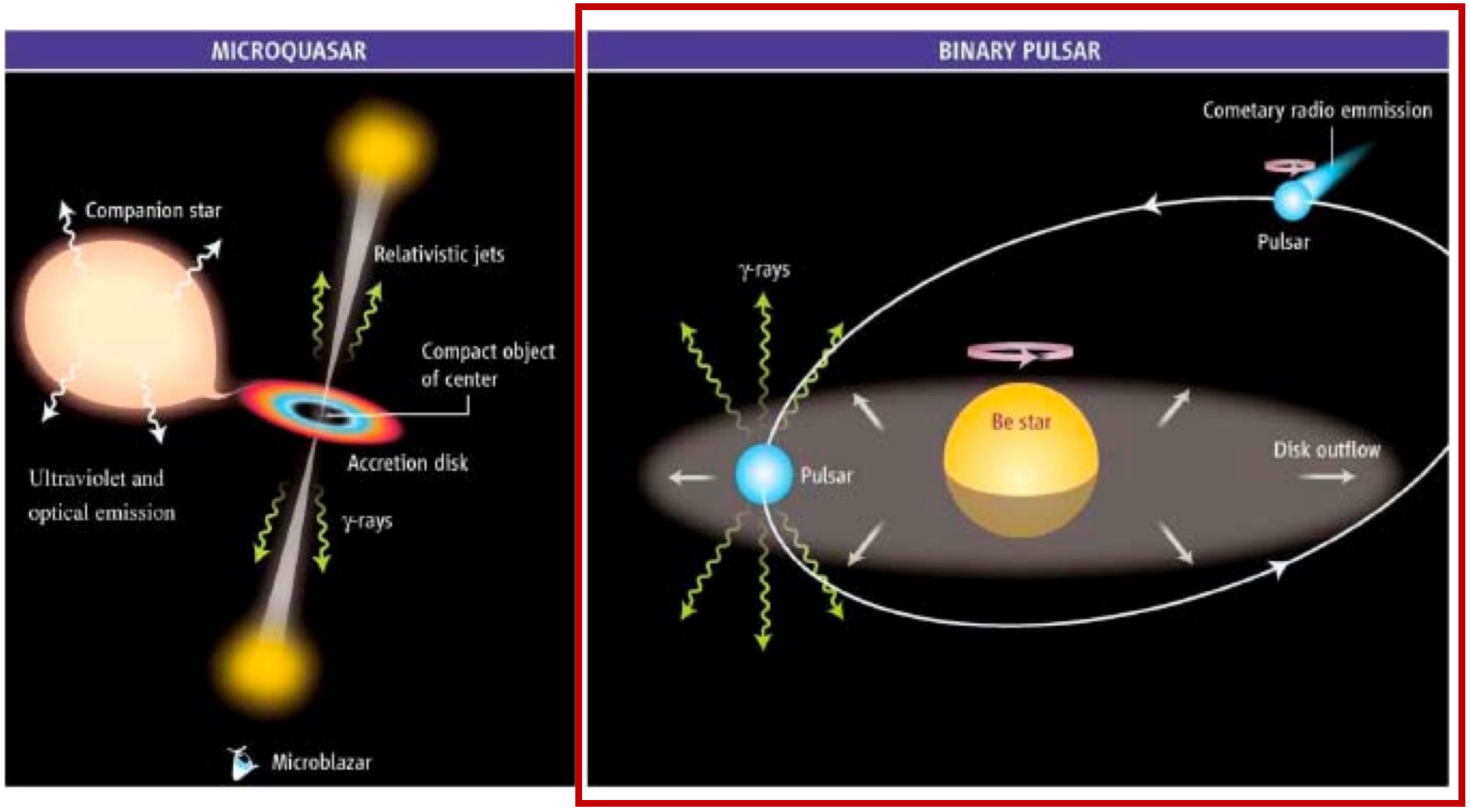
- Changes in the wind properties can easily affect the pulsed signal. And as the Be stellar wind is likely to be clumpy.

- The transient behaviour could plausibly be interpreted as a result of the rapid change in the environmental conditions.

- Similar to the gamma-ray binary PSR B1259-63: Despite this system has a much larger orbit, radio flux variations at a time scale of minutes to hours were also reported, together with changes in the local properties of the Be star wind/disk encountered by the pulsar.

- It is reasonable to expect these same effects apply to LS I +61 303, and that they are even enhanced due to the smaller spatial scale of the system.

Period consistent with young, energetic system



Plot from Mirabel 2006

In the range for flip-flop btw propeller and ejector

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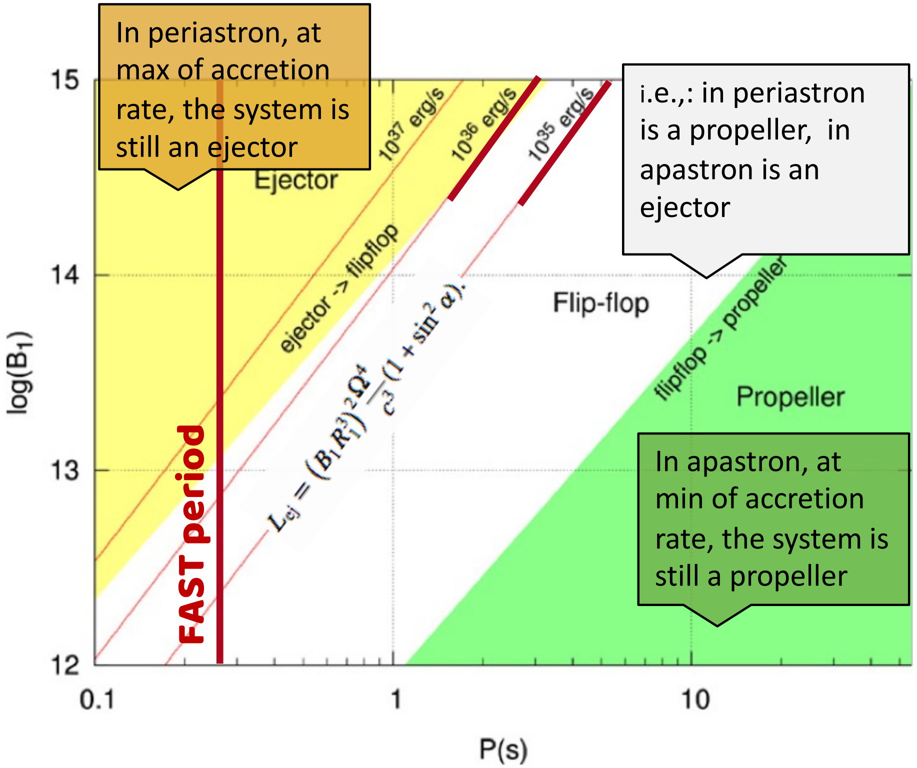


Figure 6. Ejector, *flip-flop*, and propeller states plotted in the NS magnetic field vs. spin period phase space, evaluated for a NS in LS I +61°303 and for the fiducial values adopted for the maximum and minimum mass capture rate ($\dot{m}^{\max} = 1, \dot{m}^{\min} = 1$). From top to bottom, the red solid lines mark the relation between the period and the magnetic field of the NS when the ejector luminosity is 10^{37}, 10^{36}, and 10^{35} erg s^{-1}, respectively, and the magnetic offset angle is $\alpha = 45°$.

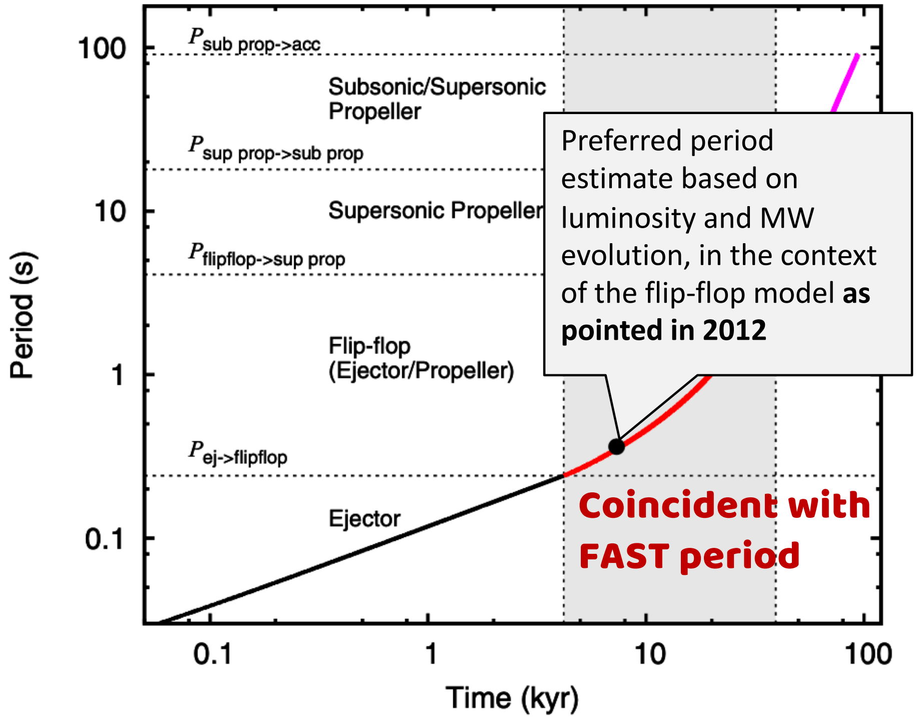


Figure 4. Evolution of the spin period of a NS in a system such as LS I +61°303, obtained considering the fiducial values of the system parameter (see Table 2). Dashed horizontal lines mark the transition among different states, while the gray shaded area marks the time interval during which the NS is expected to lie in the *flip-flop* state. The black filled circle marks the spin period at which the system emits an ejector luminosity of 5×10^{35} erg s^{-1}.

Plots from Papitto, Torres, Rea, ApJ 2012

LS I +61 303 as a gamma-ray pulsar: constraints

- **The pulsed emission must (most likely) be orbitally invariant**

- The lowest gamma-ray flux (e.g., in the apastron or superior conjunction (SUPC) region, amounts to a bolometric (MW) luminosity of $\sim 5\times10^{35}$ D_2 erg s^{-1}, where D_2 is the distance to the source in units of 2 kpc

- If such luminosity is connected with the pulsar, the spin-down power of the pulsar, $E_{sd} = 3.9 \times 10^{46}$ P $(s)^{-3}$ (dP/dt) (s s^{-1}) erg s^{-1}, has to be larger than $\sim 5\times10^{35}$ D_2 erg s^{-1}

- From this condition, and using the measured value of P we can impose **a lower limit for the period derivative**: (dP/dt) > 2.5×10^{-13} (s s^{-1})

LS I +61 303 as a gamma-ray pulsar: constraints

- We can also safely assume as **upper limit for dP/dt**, 2.5×10^{-11} s s^{-1} (2 order of mag. larger than the lower limit)

- This is a plausible assumption for several reasons:

  - there is no other known pulsar with such characteristics (the highest dP/dt pulsar has a 3.5 times lower value).

  - At the upper limit, log Bs(G) = 13.9 at the equator, and a factor of 2 larger at the poles. The spin-down power would be > 5×10^{37} erg s^{-1}, (2 order of mag. larger than any other magnetar with that surface field).

  - It would be the only high-magnetic field magnetar emitting in gamma-rays, i.e. short of strong flares associated to different phenomenology [Fermi-LAT Collaboration et al. 2021], deep Fermi-LAT searches on all others turn out to be negative (Li et al. 2017).

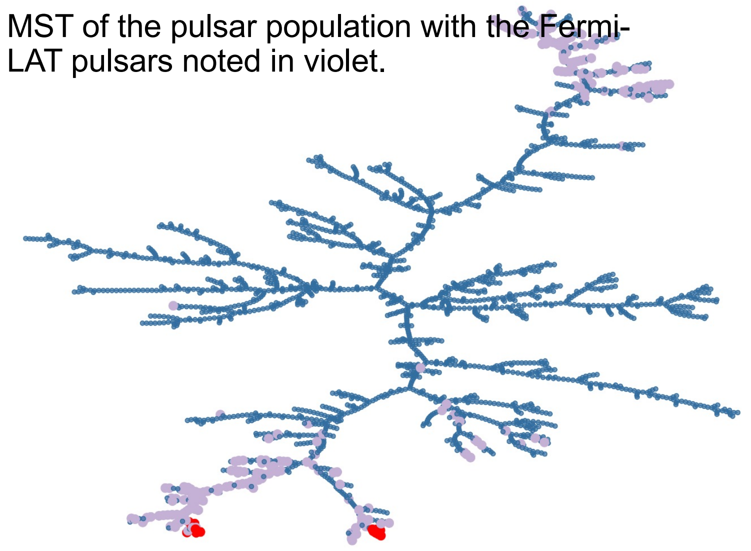
  - And also, no other gamma-ray pulsar is detected with such high dP/dt

Plot from Mirabel 2006

LS I +61 303 most similar neighbours

Table 1. Physical ranges of magnitudes for LS I 61 303 based on the usual rotating dipole model. The remaining columns for other pulsars shows the values of the physical magnitudes for the most-repeating closest neighbors that appear in the different possible incarnations of the LS I +61 303's period derivative explored. See text for a discussion.

			LFM?	LFM		LFM
Magnitude & Symbol	LS I +61 303 range	J1640-4631	J1208-6238	J1119-6127	J1513-5908	J1846-0258
Spin period: P (s)	0.2691	0.2064	0.4406	0.408	0.1516	0.3266
Period derivative: $\dot{P}$ (s s^{-1})	$(2.5 \times 10^{-13}, 2.5 \times 10^{-11})$	9.76×10^{-13}	3.27×10^{-12}	4.02×10^{-12}	1.53×10^{-12}	7.11×10^{-12}
Surface field (equator): B_s (G)	$(8.3 \times 10^{12}, 8.3 \times 10^{13})$	1.43×10^{13}	3.84×10^{13}	4.08×10^{13}	1.54×10^{13}	4.87×10^{13}
Light-cylinder field: B_{lc} (G)	$(4.0 \times 10^{3}, 4.0 \times 10^{4})$	1.54×10^{4}	4.21×10^{3}	5.66×10^{3}	4.15×10^{4}	1.31×10^{4}
Energy loss rate: $\dot{E}_{sd}$ (erg s^{-1})	$(5 \times 10^{35}, 5 \times 10^{37})$	4.38×10^{36}	1.51×10^{36}	2.34×10^{36}	1.73×10^{37}	8.05×10^{36}
Characteristic age: τ (yrs)	$(1.7 \times 10^{2}, 1.7 \times 10^{4})$	3.35×10^{3}	2.13×10^{3}	1.60×10^{3}	1.57×10^{3}	7.28×10^{2}
Goldreich-Julian density: η_{GJ} (cm^{-3})	$(6.7 \times 10^{4}, 6.7 \times 10^{5})$	1.53×10^{5}	1.91×10^{5}	2.19×10^{5}	2.23×10^{5}	3.26×10^{5}
Surface electric voltage: $\Delta\Phi$ (V)	(2.25, 22.5)	6.63	3.89	4.84	13.2	9.00



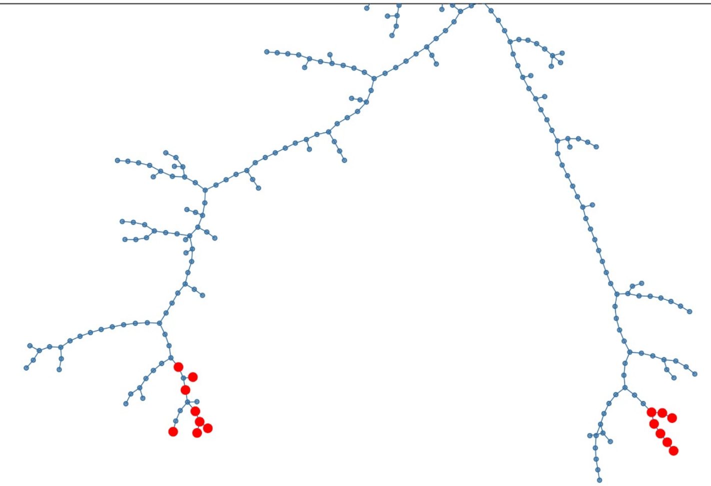
MST of the pulsar population with the Fermi-LAT pulsars noted in violet.

With the measured P and the range of dP/dt we check which are the most similar pulsars to a particular incarnation of LS I, (P, dP/dt).

Most repeating neighbours are in the Table and include 2+ low-field magnetars (LFMs).

The lower part of the MST in this depiction groups energetic and young pulsars (see Garcia et al. (2022); Garcia & Torres (2023) for details).

The most repeating neighbors of LS I +61 303 appearing for different realizations of the period derivative are noted in red. LS I +61 303 would always locate, for any period derivative in the range explored, close to these pulsars. Bottom: zoom of the MST in the region of interest.



http://www.pulsartree.ice.csic.es

Plot from Mirabel 2006

What GeV gamma-ray spectrum to expect?

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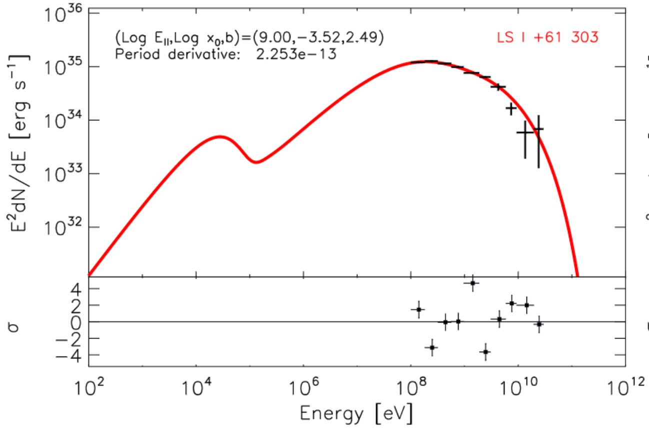
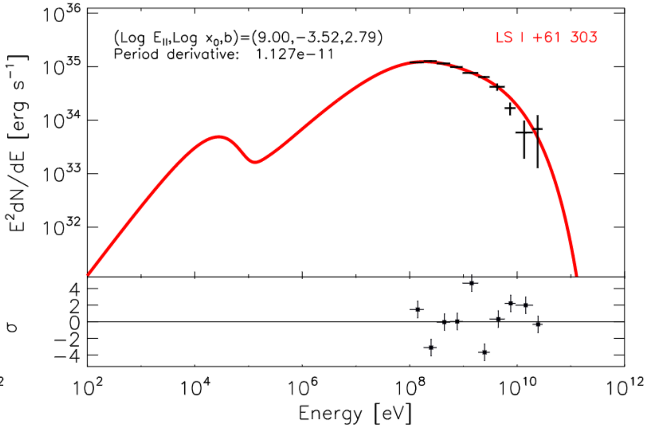
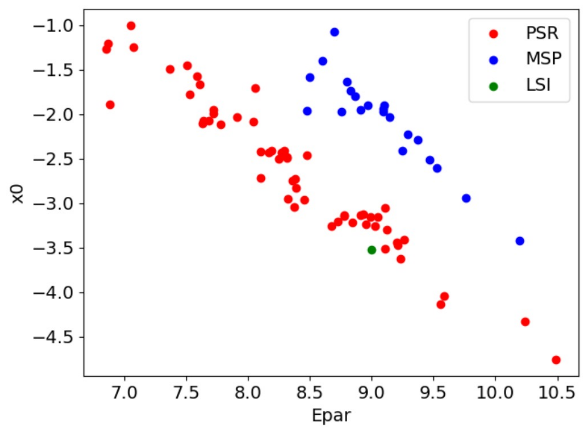
- Examples of the (lowest flux) LSI SUPC data fitting in the range of the dP/dt explored.
  - At the two extremes of dP/dt, we have similar fits (SUPC data considered, lower gamma-ray flux).
  - Values of the fit parameters quite in agreement with the rest of the gamma-ray pulsar population.
- Currently exploring the impact of the X-ray pulsations upper limit, to obtain additional dP/dt constraints

Preliminary







Preliminary, no X-ray UL considered

DFT et al., in preparation

Conclusions

Changing the mystery…

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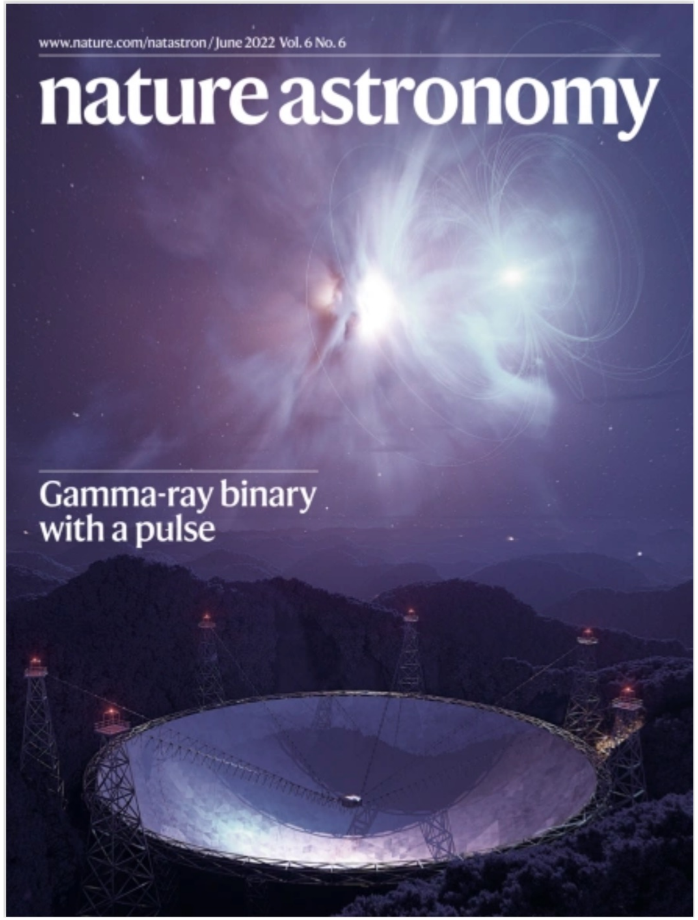
- LS I 61 303 is a pulsar-composed system with P=0.27 s.
- LS I 61 303 is the first system containing a pulsar behaving as a magnetar, probably one of the low-field magnetars class.
- The period found is consistent with being a flip-flopping system: it is right at the spot that is better suited to qualitatively explain the MW behavior with it.
- The gamma-ray properties of the LSI pulsar are in agreement with the rest of the population.
- The pulsar turns ON and OFF, and appears to be OFF (or absorbed) a significant amount of time.
- Subsequent observations are ongoing. But monitoring will prove difficult.
- Aim is no longer to determine the nature of LS I 61 303 but to understand better the cause of the turning off of the pulsar, and characterize its behavior. This is however, a common behavior in hundreds of pulsars, and is not fully understood for them either.



Thank you

https://sites.google.com/view/dft-research

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