The Long-Term Modulation of LS I +61°303 Across the Electromagnetic Spectrum

Frédéric Jaron

TU Wien, Austria
Max-Planck-Institut für Radioastronomie, Bonn, Germany

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Max-Planck-Institut für Radioastronomie
MAX-PLANCK-GESELLSCHAFT
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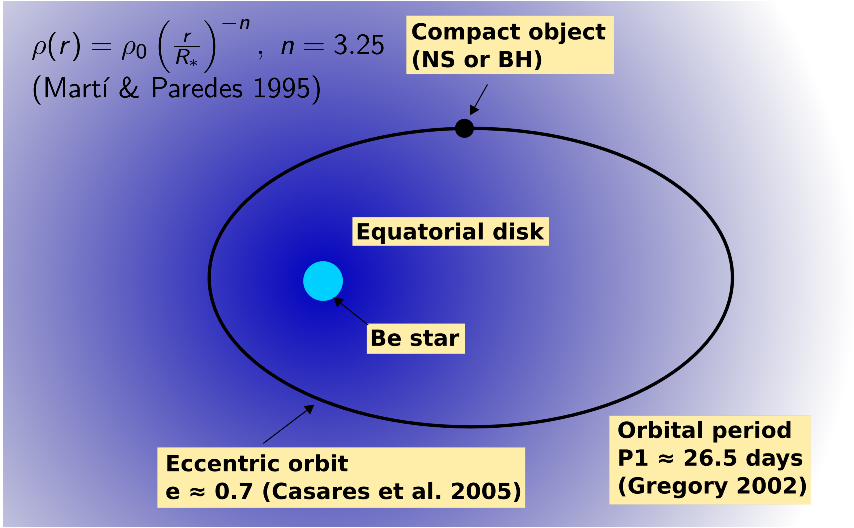
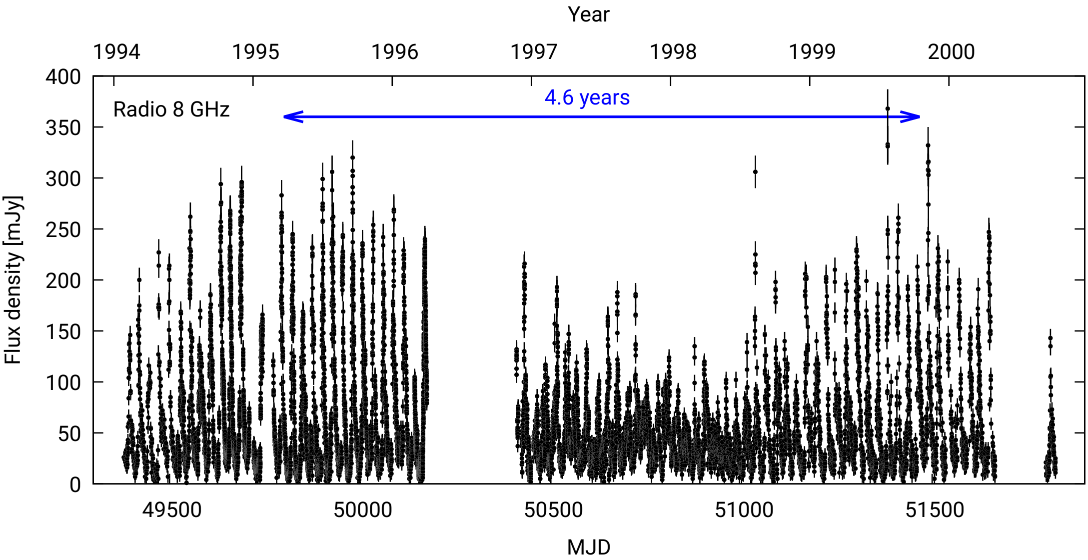
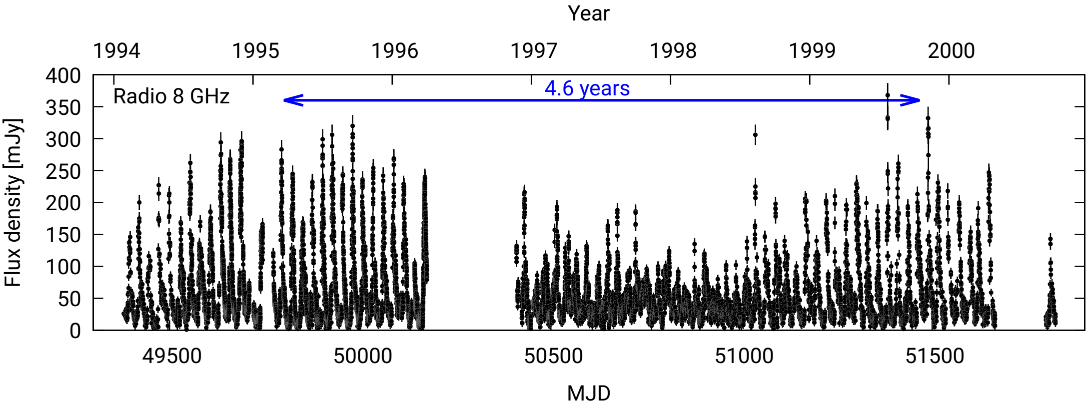


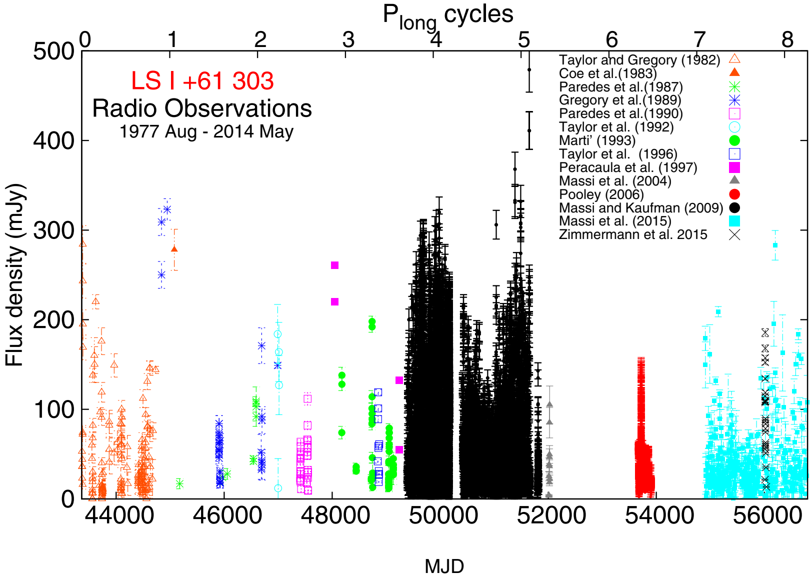
Orbital phase $\Phi = \frac{t-t_0}{P_1} - \mathrm{int}\left(\frac{t-t_0}{P_1}\right)$

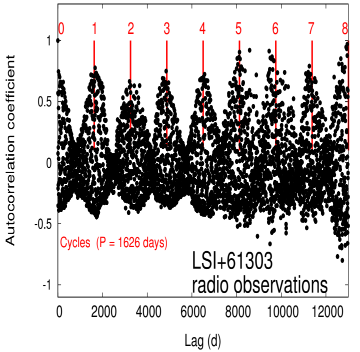


Long-term monitoring of LS I +61°303 by the Green Bank Interferometer at 8 GHz. Ray *et al.*, 1997, ApJ, 491, 1

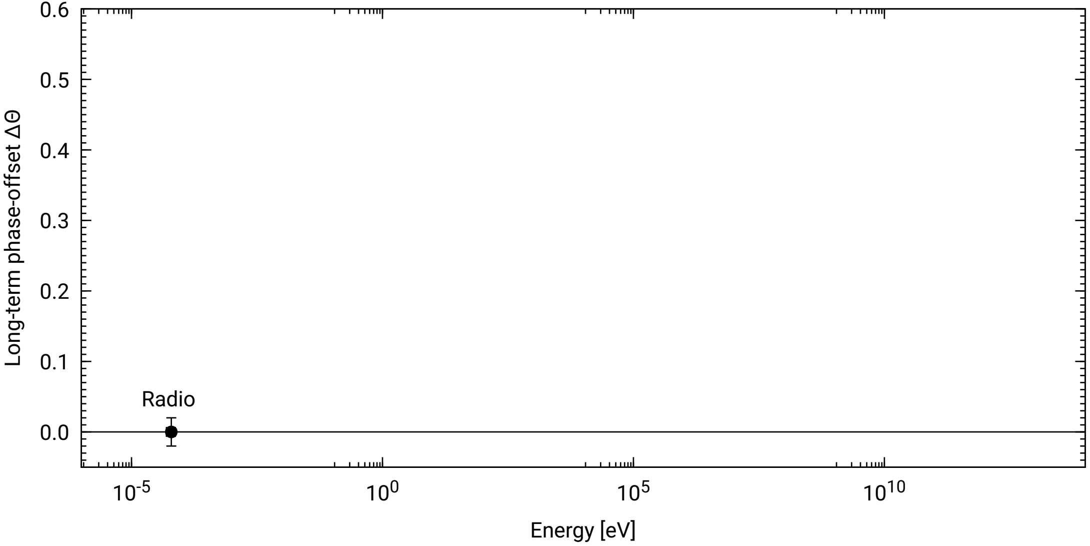
Subject of this talk: Behavior of the long-term modulation across the EM spectrum.
Long-term phase: $\Theta = \frac{t - T_0}{P_{\mathrm{long}}} - \mathrm{int}\left(\frac{t - T_0}{P_{\mathrm{long}}}\right)$, $P_{\mathrm{long}} = 4.6$ years.







Massi & Torricelli-Ciamponi 2016, A&A, 585, A123 → and ongoing Jaron *et al.* 2018, MNRAS, 478, 1



Jaron, Universe 2021, 7(7), 245

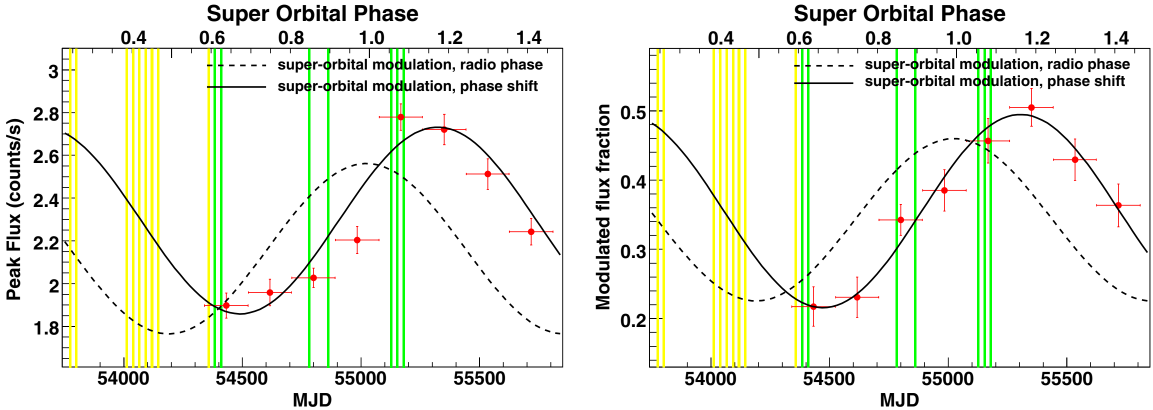
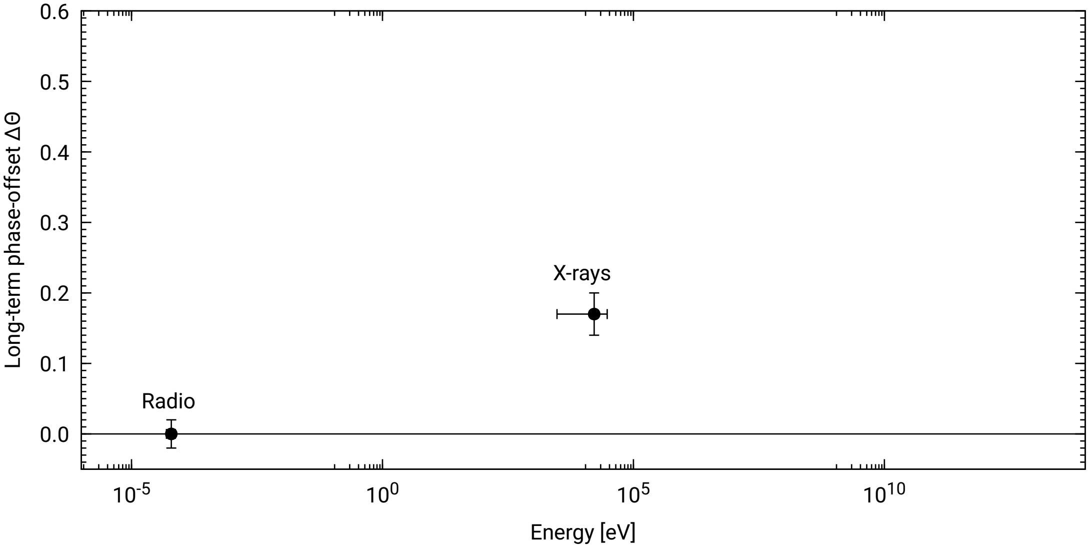


Figure 1 in Li *et al.* (2012)

⇒ Phase offset between X-rays and radio: $\Delta\Theta = 0.17 \pm 0.03$

Li *et al.* 2012, ApJL, 744, 1, L13



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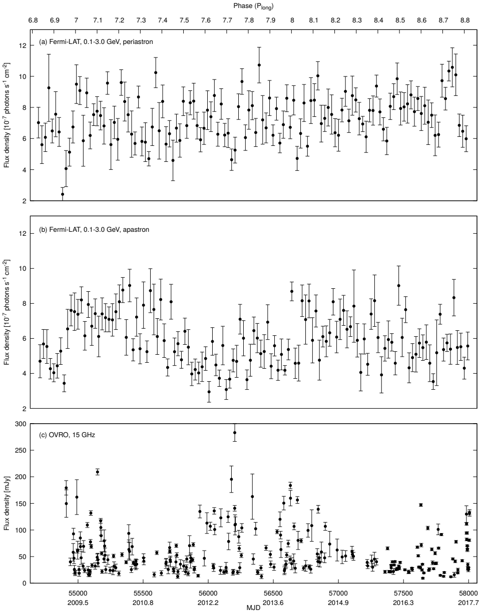
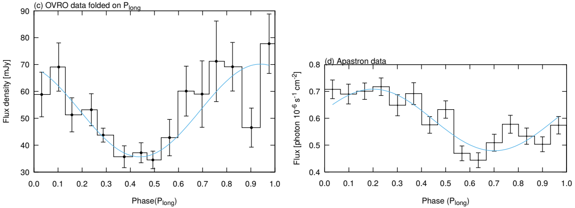


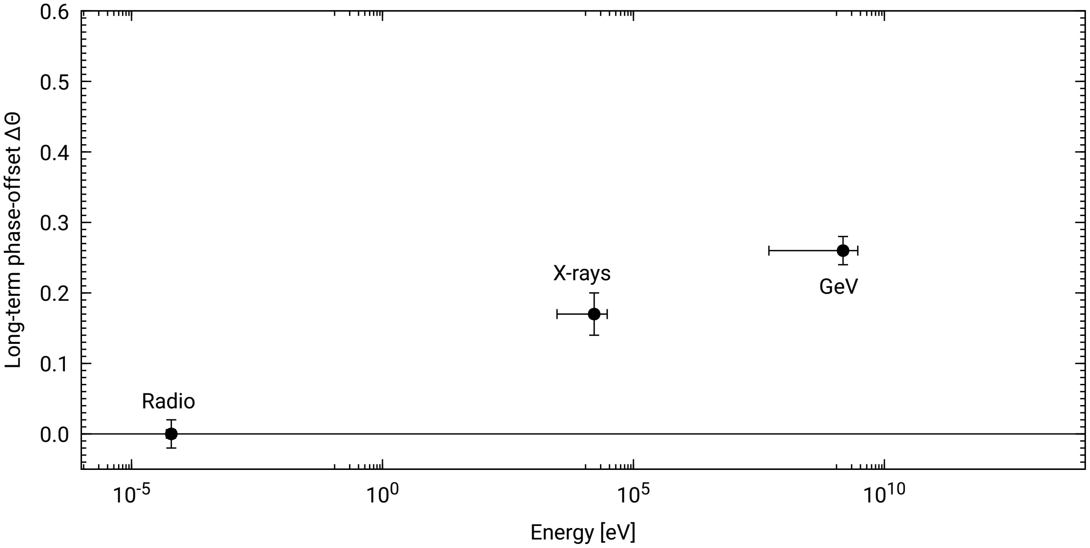
Long-term modulation profiles



Radio | Gamma-rays

$\Rightarrow$ Phase-offset between GeV and radio: $\Delta\Theta = 0.26 \pm 0.03$

Jaron *et al.* 2018, MNRAS, 478, 1



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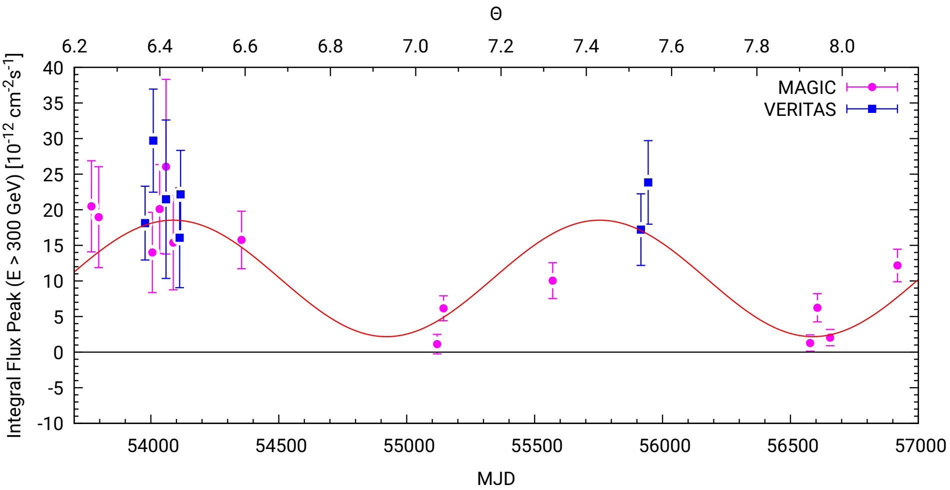
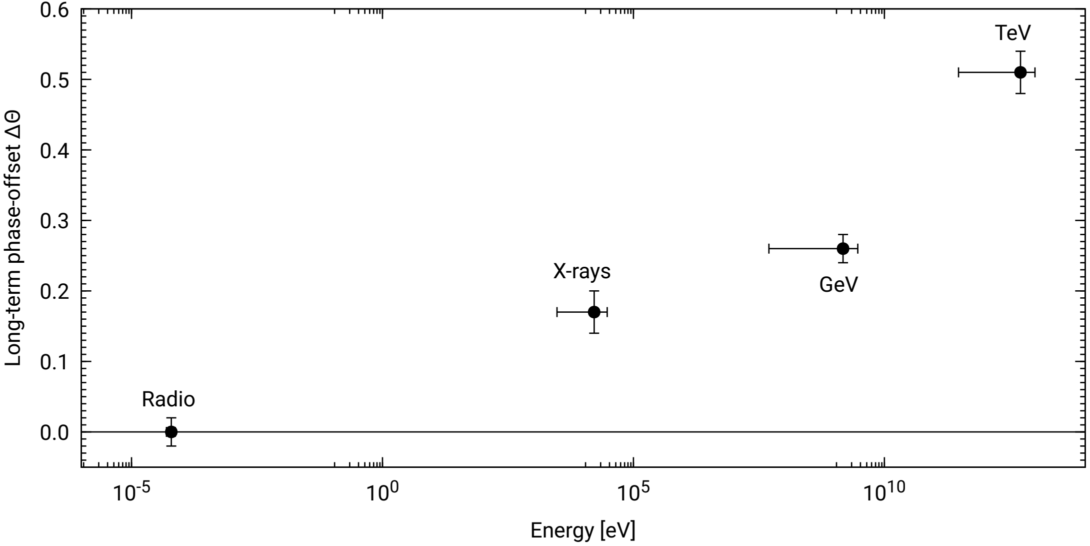


⇒ Long-term phase-offset between TeV and radio: $\Delta\Theta = 0.51 \pm 0.03$

Ahnen *et al.* 2016, A&A, 591, A76 ; Jaron, Universe 2021, 7(7), 245



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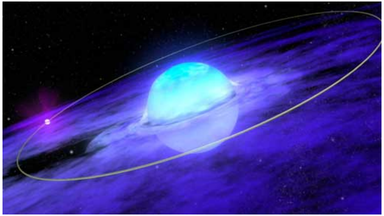
What is the physical reason for the long-term modulation in LS I +61°303?

1. Changes in the Be star disk?



Credit: Walt Feimer, NASA/GFSC

First suggested by Gregory *et al.* (1989)

Still discussed (see Chernyakova *et al.* 2019)

But: Be stars are not so periodic.
See review by Rivinius *et al.* 2013.

2. Precessing jet

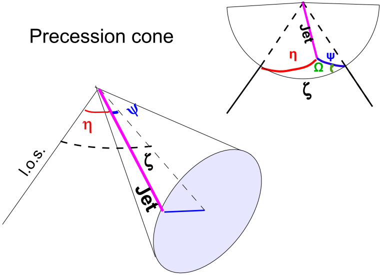


Figure 1 in Massi & Torricelli-Ciamponi (2014)

First rejected by Gregory *et al.* (1989)

Physical model reproduces observations:
Massi & Torricelli-Ciamponi 2014, A&A, 585, A123
Jaron *et al.* 2016, A&A, 595, A92

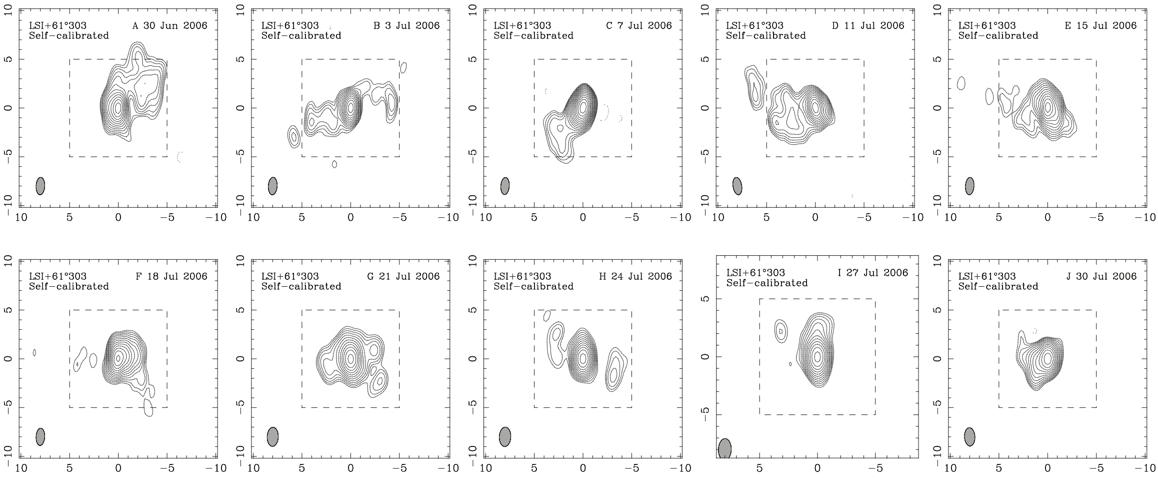


Figure: Detail from Fig. 1 in Massi, Ros, & Zimmermann 2012, A&A, 540, A142

⇒ Precession period $P_{\text{precession}} \approx 27 - 28$ days (C.f. $P_{\text{orbit}} \approx 26.5\,\text{days} \neq P_{\text{precession}}$)

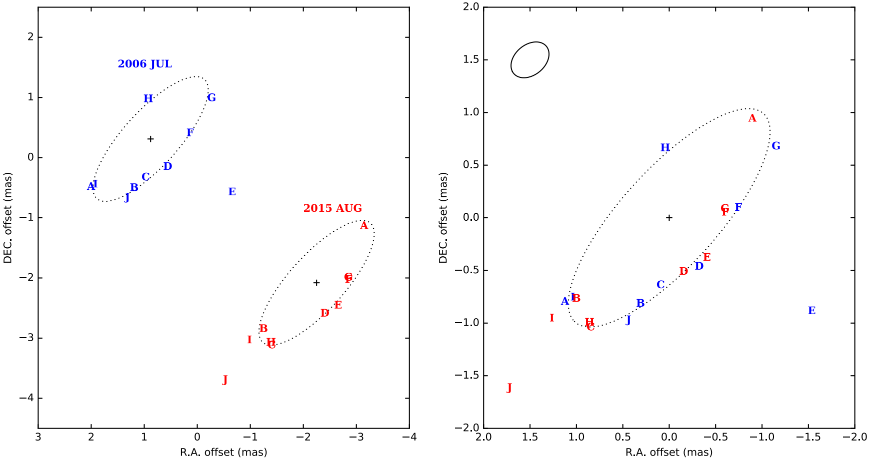
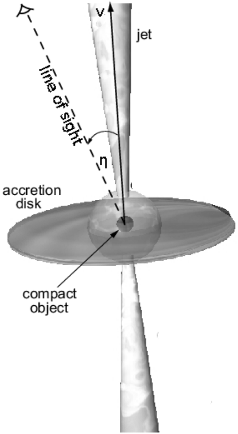


Figure 4. *Left-hand panel*: astrometric results of 2006 and 2015 VLBA observations, with parallax motions removed. Blue characters denote jet peaks in 2006, and red characters denote jet peaks in 2015. The reference coordinate (zero-point) is $02^h40^m31\overset{s}{.}6645$, $61^d13^m45\overset{s}{.}594$. *Right-hand panel*: same as left-hand panel, but with centres of the two ellipses overlaid. The solid ellipse in the top left corner indicates the scale of the orbit, with a semimajor axis of 0.22 mas (Massi et al. 2012).

$\Rightarrow P_{\text{precession}} = 26.926 \pm 0.005\,\text{days}$ Wu *et al.* 2018, MNRAS, 474, 3

Doppler boosting



Observed flux amplified (attenuated) for approaching (receeding) jet with velocity v,

$$S_a = S_0 \left(\frac{1}{\gamma \left(1 - \beta \cos \eta\right)} \right)^{\kappa - \alpha} = S_0 \delta_a^{\kappa - \alpha},$$

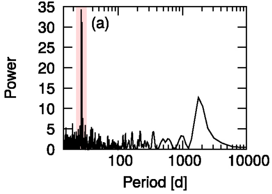
$$S_r = S_0 \left(\frac{1}{\gamma \left(1 + \beta \cos \eta\right)} \right)^{\kappa - \alpha} = S_0 \delta_r^{\kappa - \alpha},$$

where $\beta = \frac{v}{c}$, $\gamma = \frac{1}{\sqrt{1-\beta^2}}$, and η is the angle between v and the line of sight.

Based on Fig. 1 in Reynoso & Romero 2009, A&A, 493, 1

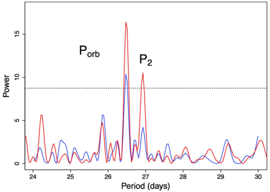
Lomb-Scargle Periodogram

Radio:



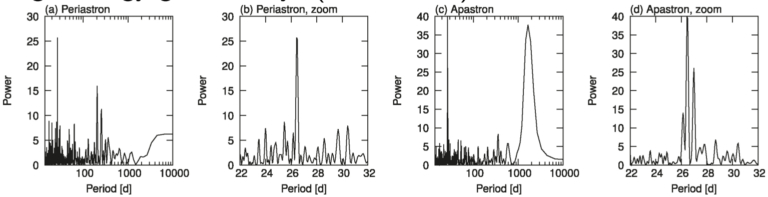
Jaron *et al.* 2018, MNRAS, 478, 1

X-rays:



D'Aì *et al.* 2016, MNRAS, 456, 2

High-energy gamma-rays (*Fermi*-LAT):



Jaron *et al.* 2018, MNRAS, 478, 1

Further publications on P_1 and P_2

- Massi & Jaron 2013, A&A, 554, A105
- Jaron & Massi 2014, A&A, 572, A105
- Massi, Jaron & Hovatta 2015, A&A, 575, L9
- Massi & Torricelli-Ciamponi 2016, A&A, 585, A123
- Jaron, Torricelli-Ciamponi, Massi 2016, A&A, 595, A92

The long-term modulation is the beating between orbit and precession

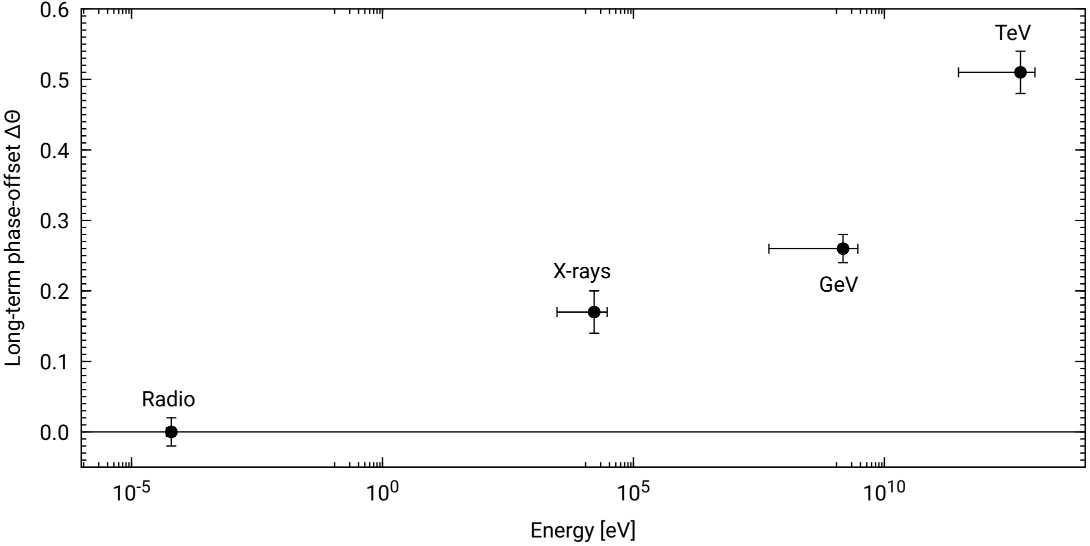
Two close periods:

Orbit	$P_1 = 26.4960 \pm 0.0028\,\mathrm{d}$	Gregory 2002, ApJ, 575, 1
Precession	$P_2 = 26.926 \pm 0.005\,\mathrm{d}$	Wu *et al.* 2018, MNRAS, 474, 3

Interference: Beating (Massi & Jaron 2013, A&A, 554, A105)

$$\cos\omega_1 t + \cos\omega_2 t = 2\cos\left(\frac{\omega_1+\omega_2}{2}t\right)\cos\left(\frac{\omega_1-\omega_2}{2}t\right),\ \omega = \frac{2\pi}{P}$$

Envelope of interference pattern has period $P_{\mathrm{beat}} = 1659 \pm 22\,\mathrm{d}$
C.f. $P_{\mathrm{long}} = 1667 \pm 8\,\mathrm{d}$ by Gregory 2002, ApJ, 575, 1



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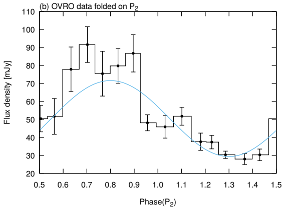
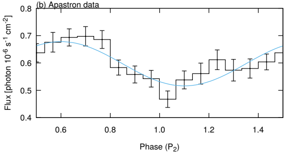
Reason for phase-offset in interference pattern

$$f_{\mathrm{beat}}(t) = f_{\mathrm{orb}}(t) + f_{\mathrm{prec}}(t) = \cos 2\pi\left(\frac{t-T_0}{P_1}\right) + \cos 2\pi\left(\frac{t-T_0}{P_2} - \phi_{\mathrm{mp}}\right)$$
$$\propto \cos 2\pi\left(\frac{t-T_0}{P_{\mathrm{avg}}} - \frac{\phi_{\mathrm{mp}}}{2}\right) \cos 2\pi\left(\frac{t-T_0}{2P_{\mathrm{beat}}} + \frac{\phi_{\mathrm{mp}}}{2}\right)$$

Precession profile phase-shifted by $\phi_{\mathrm{mp}} \Rightarrow$ Envelope of interference pattern shifted by $-\phi_{\mathrm{mp}}$.

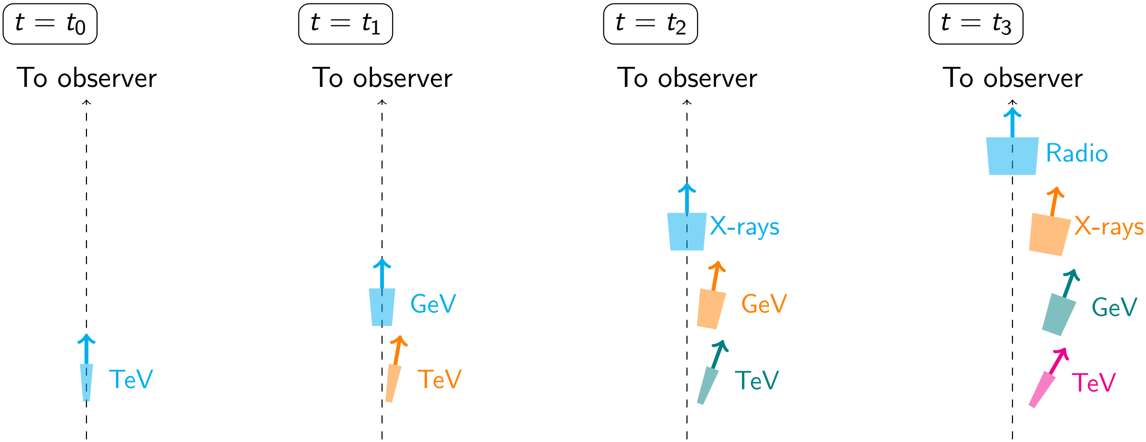
Explicitely observed for radio and GeV:





$$P_2: \quad \Delta\phi = -0.20 \pm 0.03$$
$$P_{\mathrm{long}}: \quad \Delta\phi = +0.26 \pm 0.03$$

Jaron *et al.* 2018, MNRAS, 478, 1



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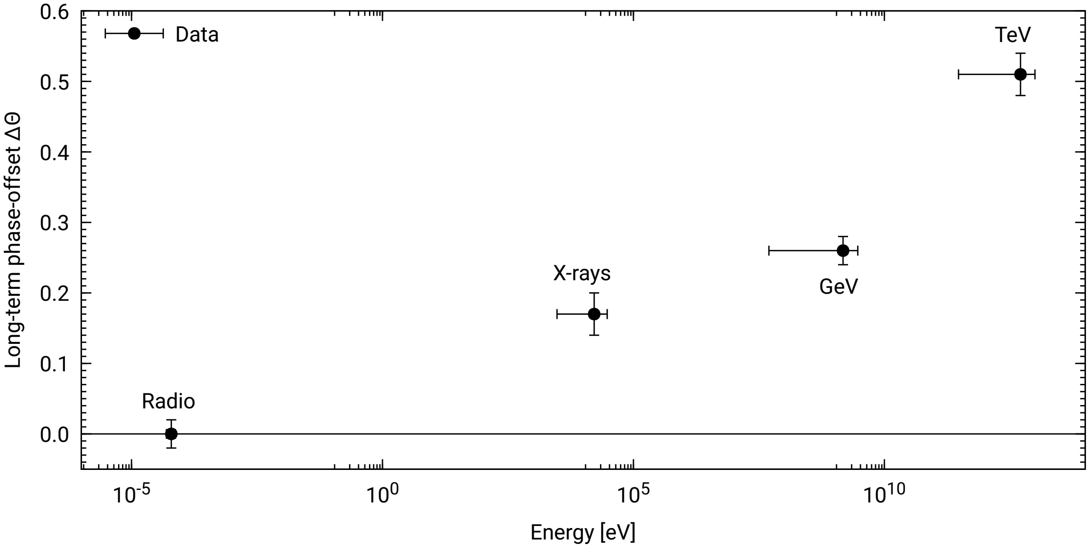

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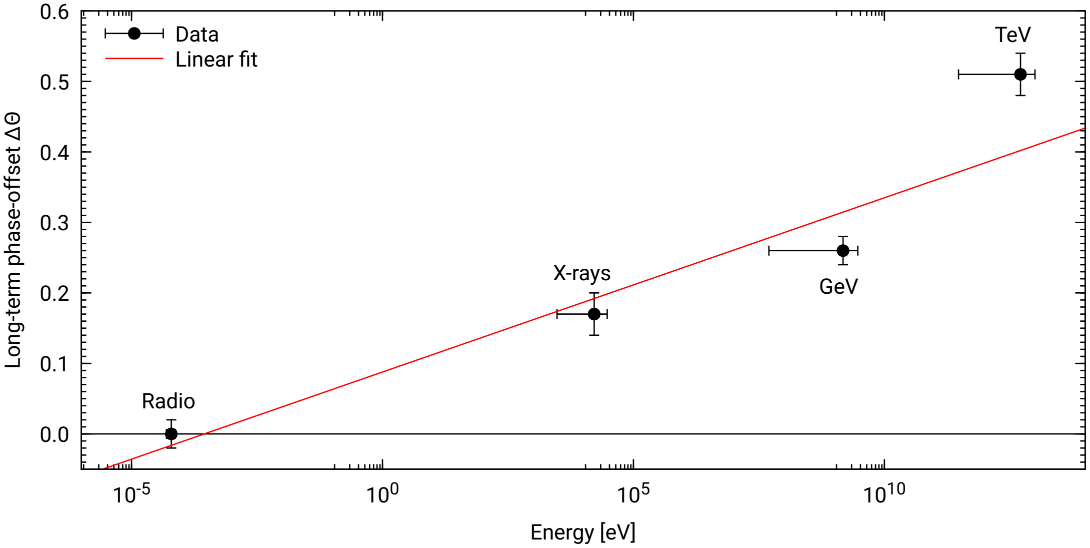

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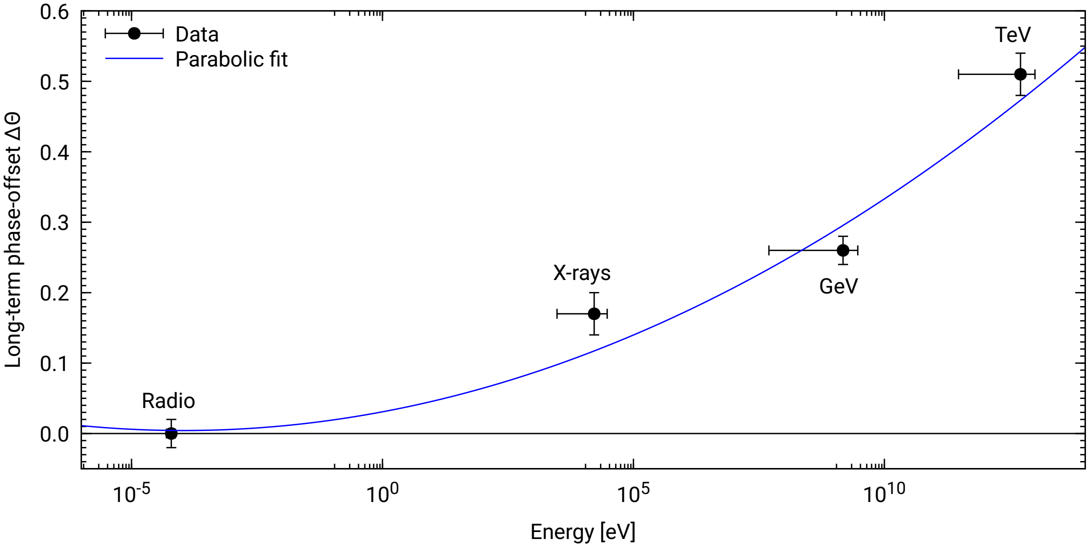

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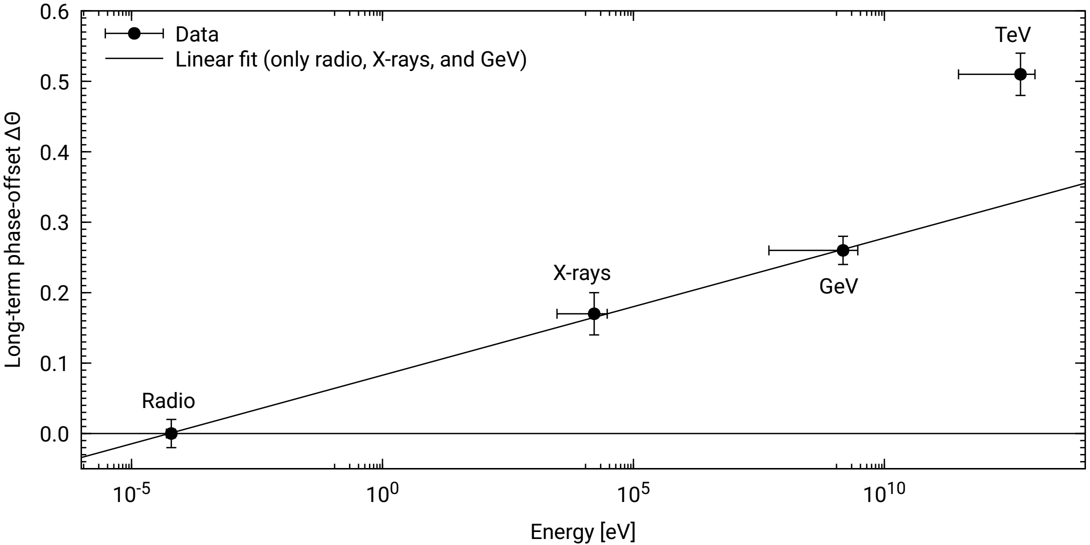

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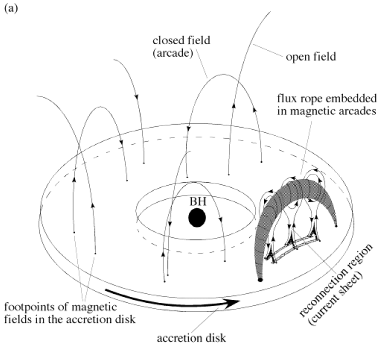


Fig. 1 a in Yuan *et al.* 2009, MNRAS, 395, 2183

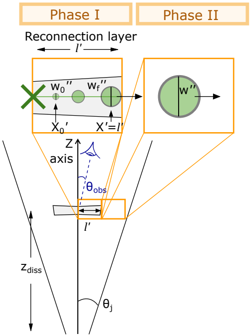
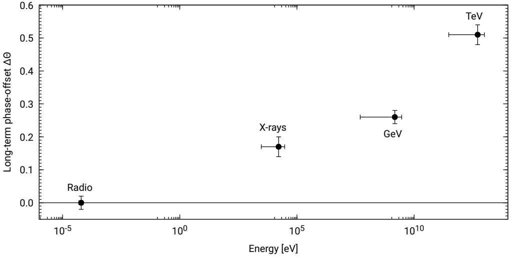


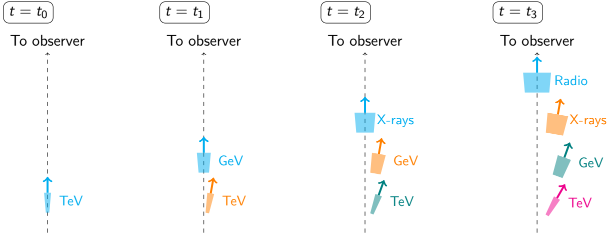
Fig. 1 in Petropoulou *et al.* 2016, MNRAS, 462, 3325

Magnetic reconnection can occur in the...

- disk Yuan *et al.* 2009, MNRAS, 395, 2183
- jet Petropoulou *et al.* 2016, MNRAS, 462, 3325; Sironi *et al.* 2016, MNRAS, 462, 48

In magnetic reconnection events the current sheet fragments into a chain of plasmoids that can be of different size and can be ejected with different timescales (minutes, hours, days).
Micro-variability observed: Sharma *et al.* (2021) ; Nösel *et al.* (2018) ; Jaron *et al.* (2017) ; Peracaula *et al.* (1997).





1. The 4.6 years long-term modulation is a very stable feature of LS I +61°303.
2. The phase of the long-term modulation pattern is increasingly offset from the radio with increasing energy.
3. Scenario: Higher energy emission originates upstream from lower energy emission in a precessing jet.
4. Modification: The TeV emission is produced in magnetic reconnection events.
5. Continued long-term monitoring and at additional wavelengths will help to better understand the physical processes in LS I +61°303.