Results from Long-Term Radio Monitoring of LS I +61°303 at 15 GHz

Frederic Jaron

Technical Unversity of Vienna, Austria
Max-Planck-Institute for Radio Astronomie, Bonn, Germany

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Max-Planck-Institut für Radioastronomie

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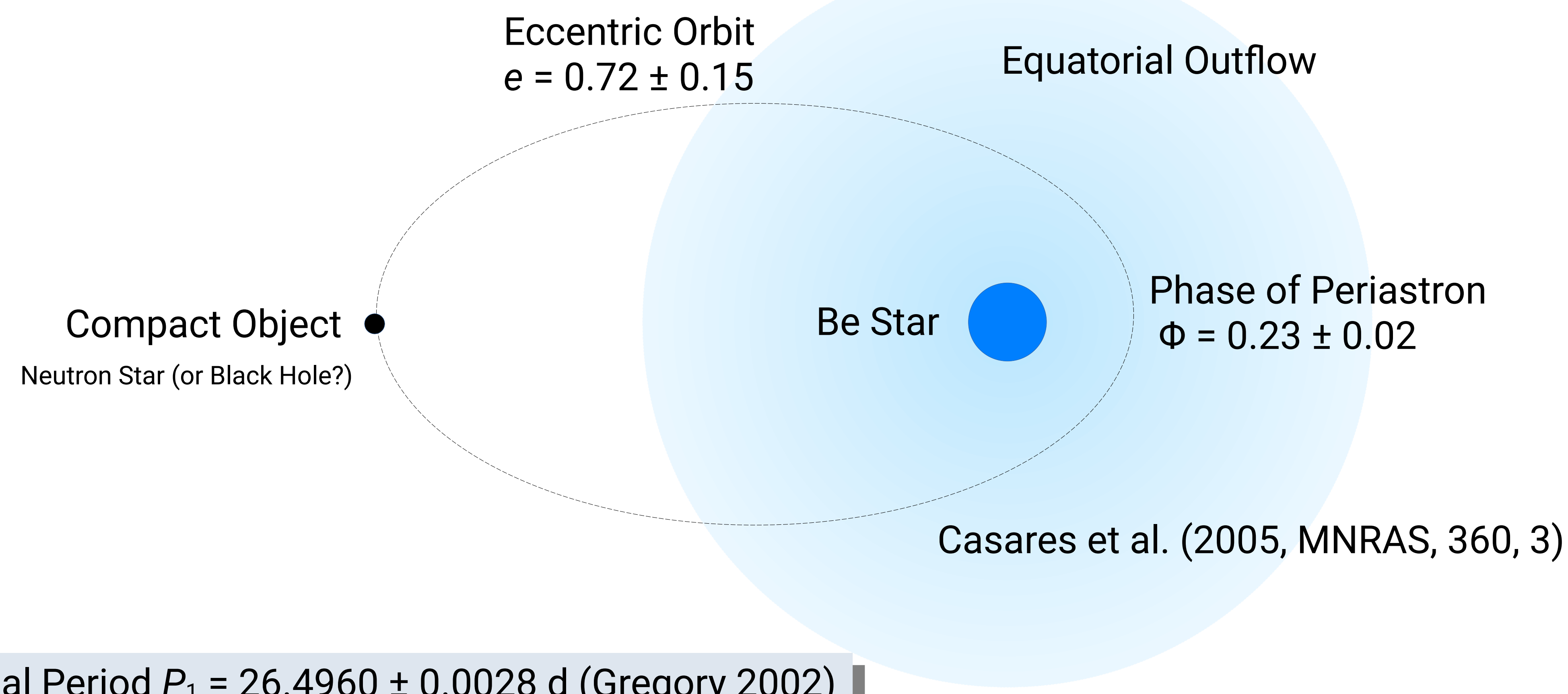
1. Introduction

The binary star LS I +61°303

Other eccentricity estimates:
$e = 0.537 \pm 0.034$ (Aragona et al. 2009)
$e \approx 0.1$ (Kravtsov et al. 2020)

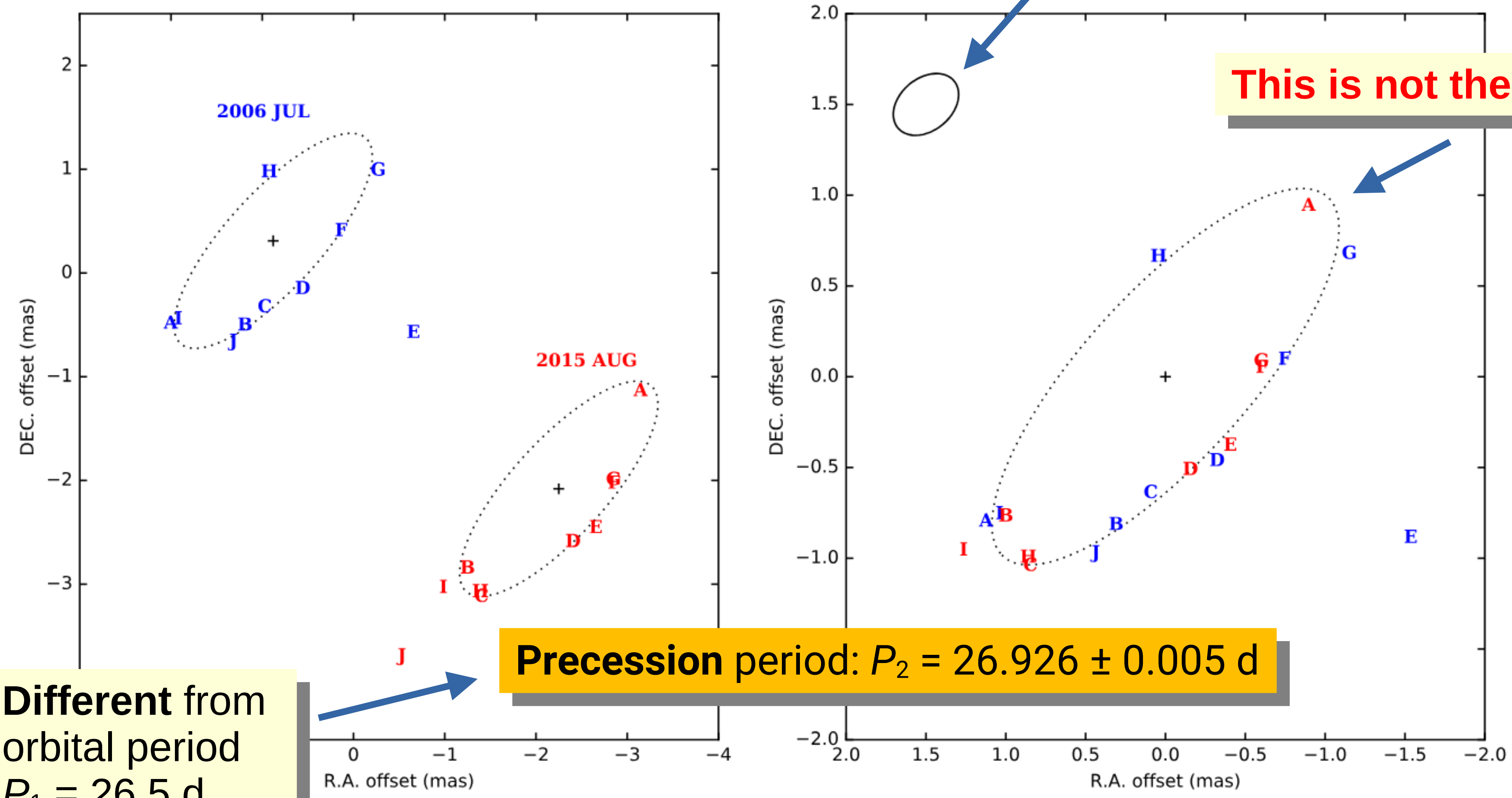


Orbital Period $P_1 = 26.4960 \pm 0.0028$ d (Gregory 2002)

VLBA Astrometry Observations of LS I +61°303

Scale of the orbit

This is not the orbit!



Precession period: P_2 = 26.926 ± 0.005 d

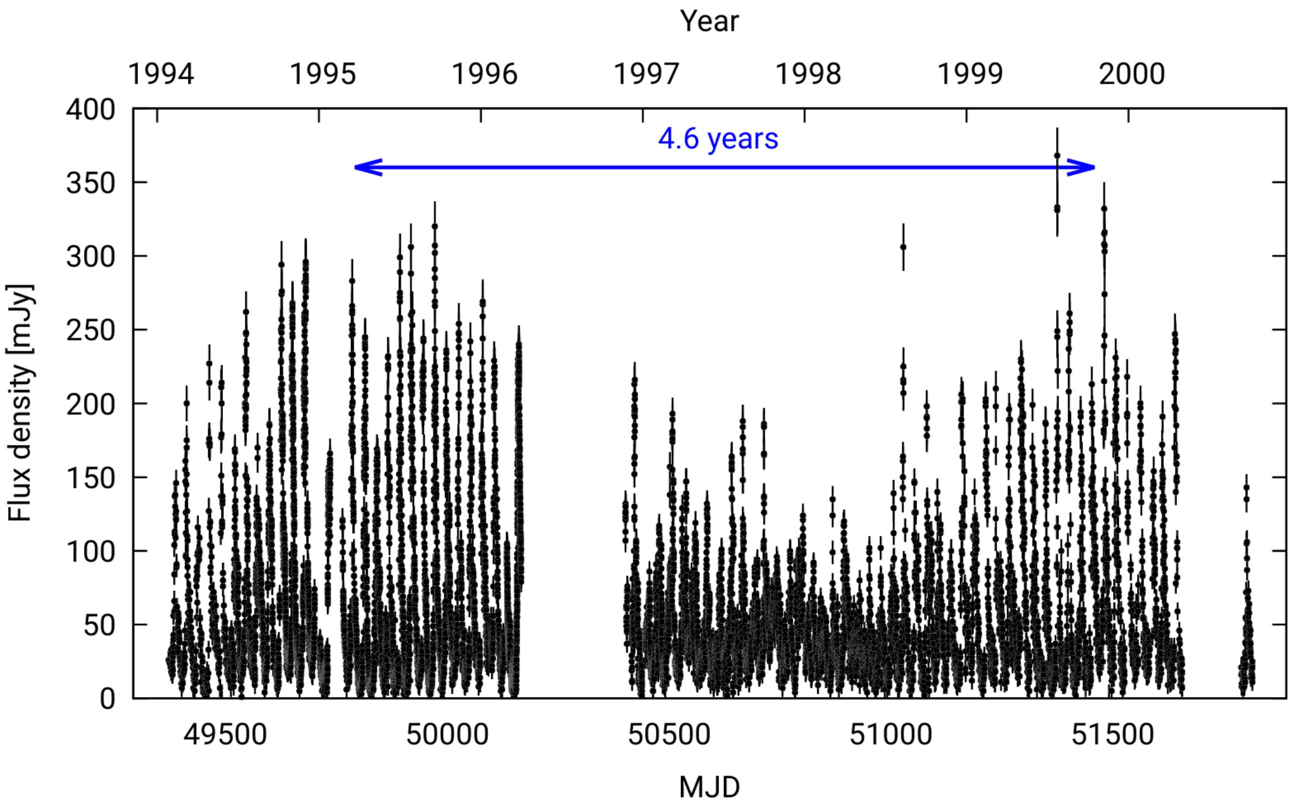
Different from orbital period P_1 = 26.5 d

Wu, Torricelli-Ciamponi, Massi, Reid et al. (MNRAS 2018, 474, 3)

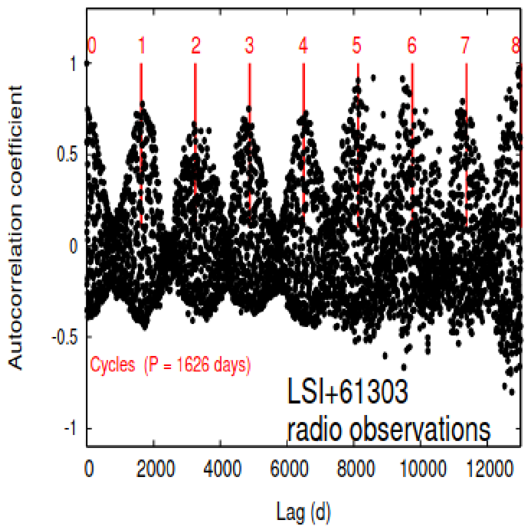
Long-Term Modulation

P_{long} = 1667 ± 8 d

Gregory 2002, ApJ, 575, 1



Green Bank Interferometer monitoring (8 GHz)



Very stable feature of the radio emission from LS I +61°303

Massi & Torricelli-Ciamponi (2016, A&A, 585, A123)

2. Radio monitoring of LS I +61°303 at 15 GHz

A&A, 683, A228 (2024)
https://doi.org/10.1051/0004-6361/202347871

Astronomy & Astrophysics

Owens Valley Radio Observatory monitoring of LS I +61°303 completes three cycles of the super-orbital modulation

F. Jaron[1,2], S. Kiehlmann[3,4], and A. C. S. Readhead[5]

[1] Technische Universität Wien, Wiedner Hauptstraße 8-10, 1040 Vienna, Austria
e-mail: Frederic.Jaron@tuwien.ac.at
[2] Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany
[3] Institute of Astrophysics, Foundation for Research and Technology-Hellas, 71110 Heraklion, Greece
[4] Department of Physics, Univ. of Crete, 70013 Heraklion, Greece
[5] Owens Valley Radio Observatory, California Institute of Technology, Pasadena, CA 91125, USA

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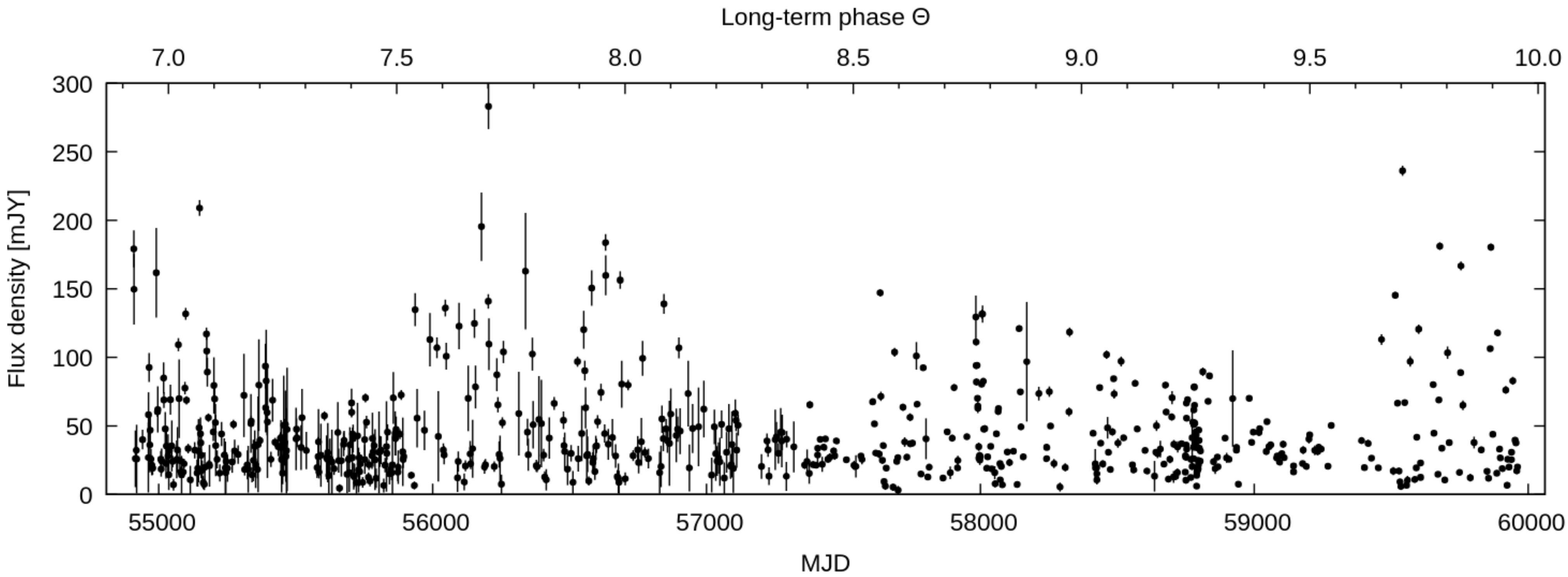


Figure 1 in Jaron et al. (2024, A&A, 683, A228)

- The OVRO 40-m telescope has been observing LS I +61°303 at 15 GHz since March 18, 2009.
- Light curve analyzed in this work spans 13.8 years (until January 17, 2023).
- These are more than three cycles of the source's intrinsic long-term period.
- Included in OVRO monitoring of *Fermi*-detected AGN (Richards *et al.* 2011, ApJS, 194, 29).

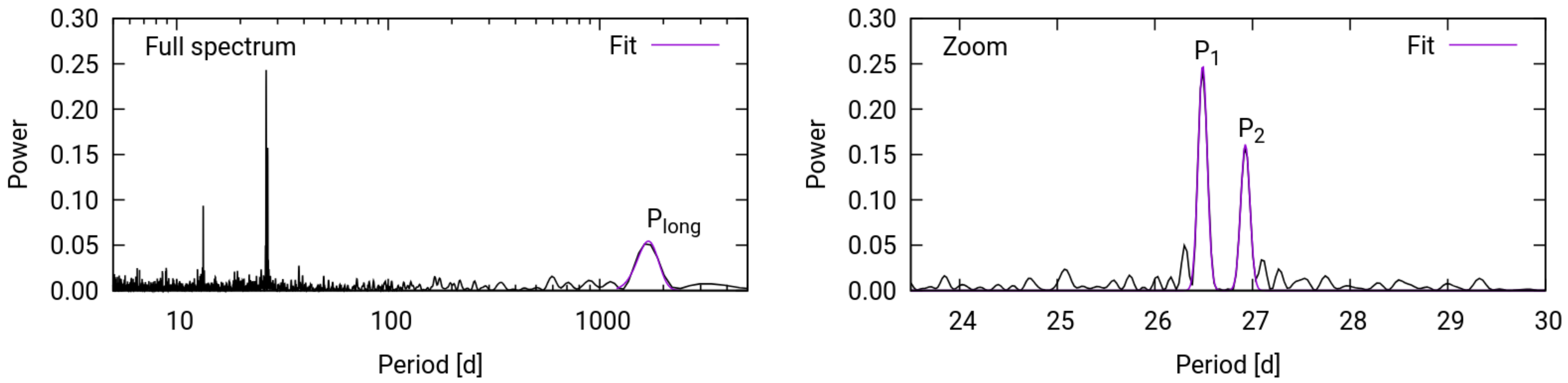


Figure 3 in Jaron et al. (A&A, 683, A228)

Generalized Lomb-Scargle timing analysis detects three periods:

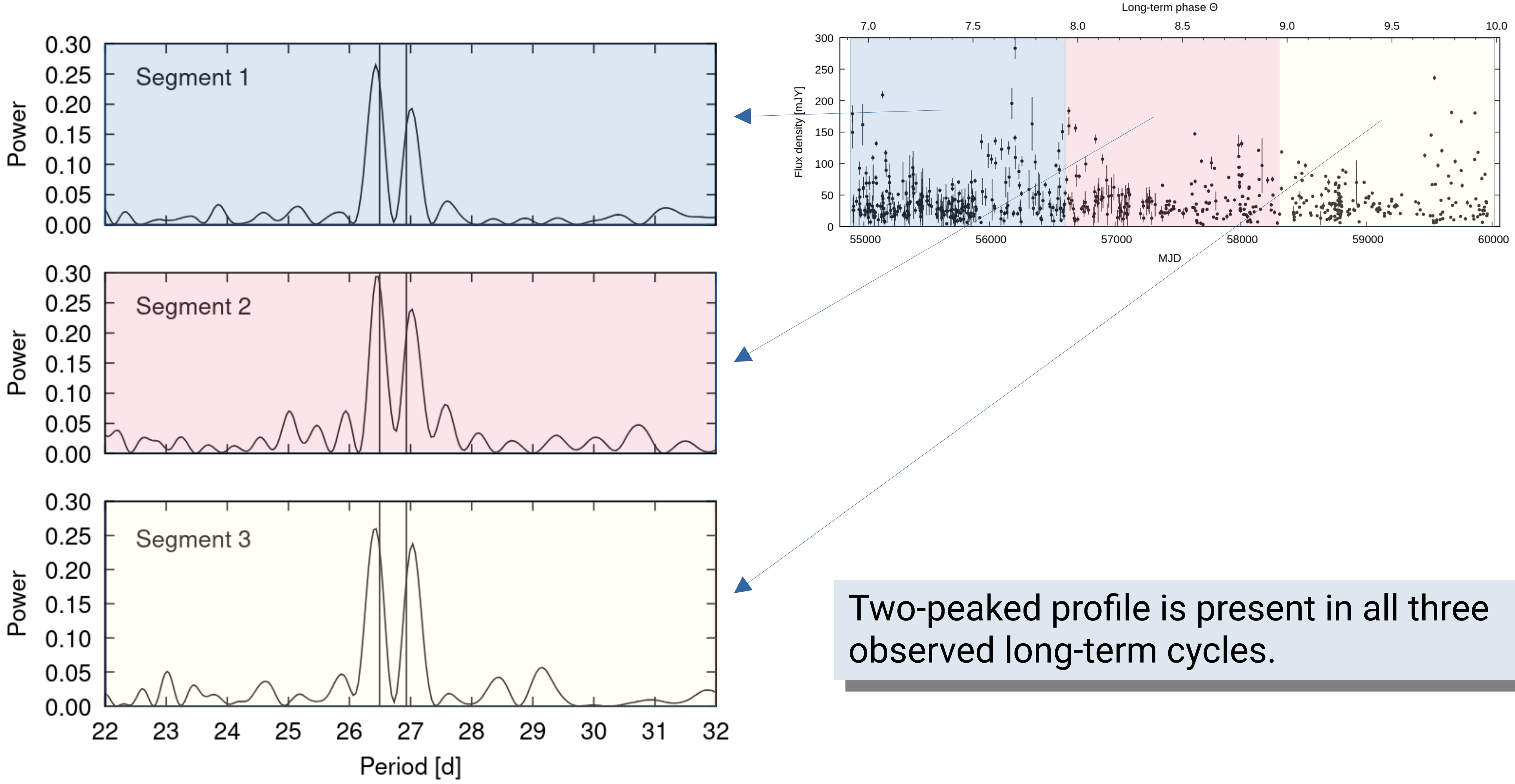
P_1 = 26.49 ± 0.05 d
P_2 = 26.93 ± 0.05 d

P_{long} = 1698 ± 196 d

In agreement with previous findings

Massi & Jaron (2013, A&A, 554, A105)
Massi, Jaron & Hovatta (2015, A&A, 575, L9)
Massi & Torricelli-Ciamponi (2016, A&A, 585, A123)
Jaron, Massi & Kiehlmann (2018, MNRAS, 478, 1)

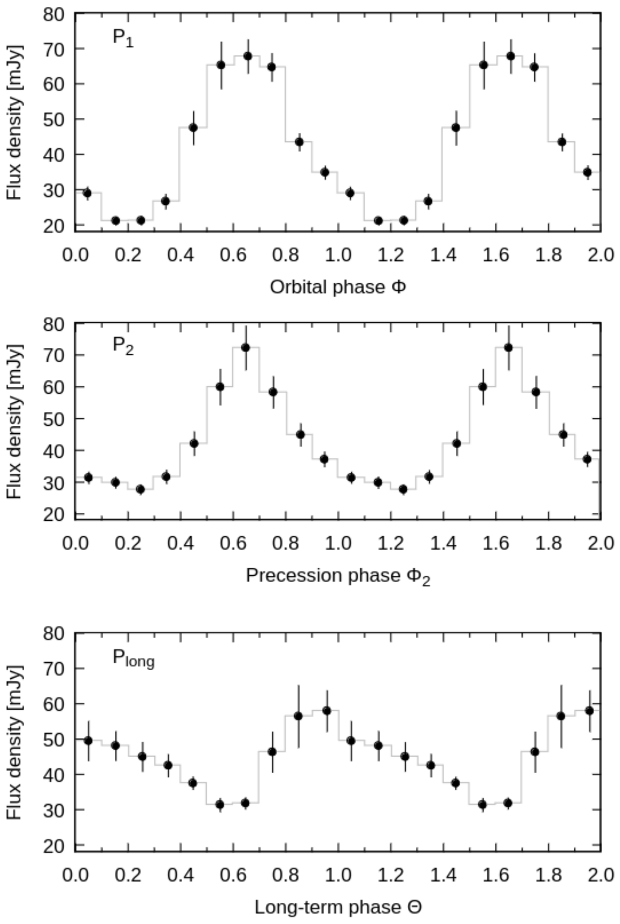
Also at higher energies...



Two-peaked profile is present in all three observed long-term cycles.

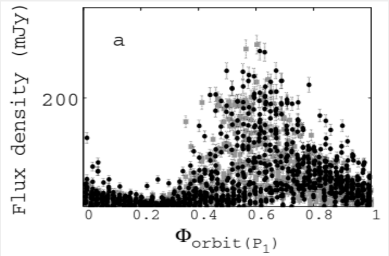
Figure 5 in Jaron et al. (2024)

Radio Modulation Patterns



Jaron et al. (2024)

Compare GBI 8 GHz (1994-2000)



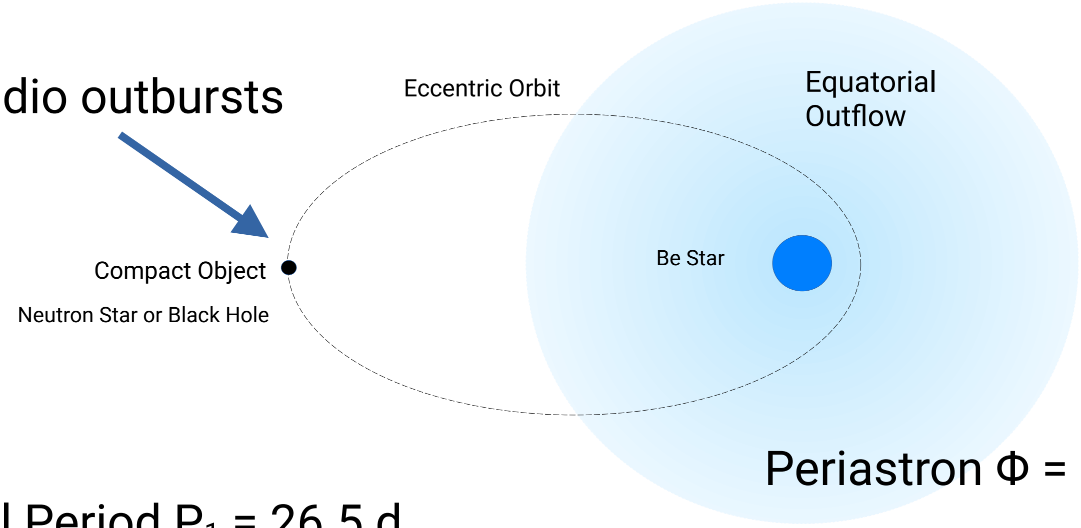
Massi & Jaron (2013)

P_1 = 26.49 ± 0.05 d
P_2 = 26.93 ± 0.05 d

P_{long} = 1698 ± 196 d

Orbital modulation profile peaks around apastron.

Radio outbursts



Periastron Φ = 0.23

Orbital Period P_1 = 26.5 d

45.5 years of radio data

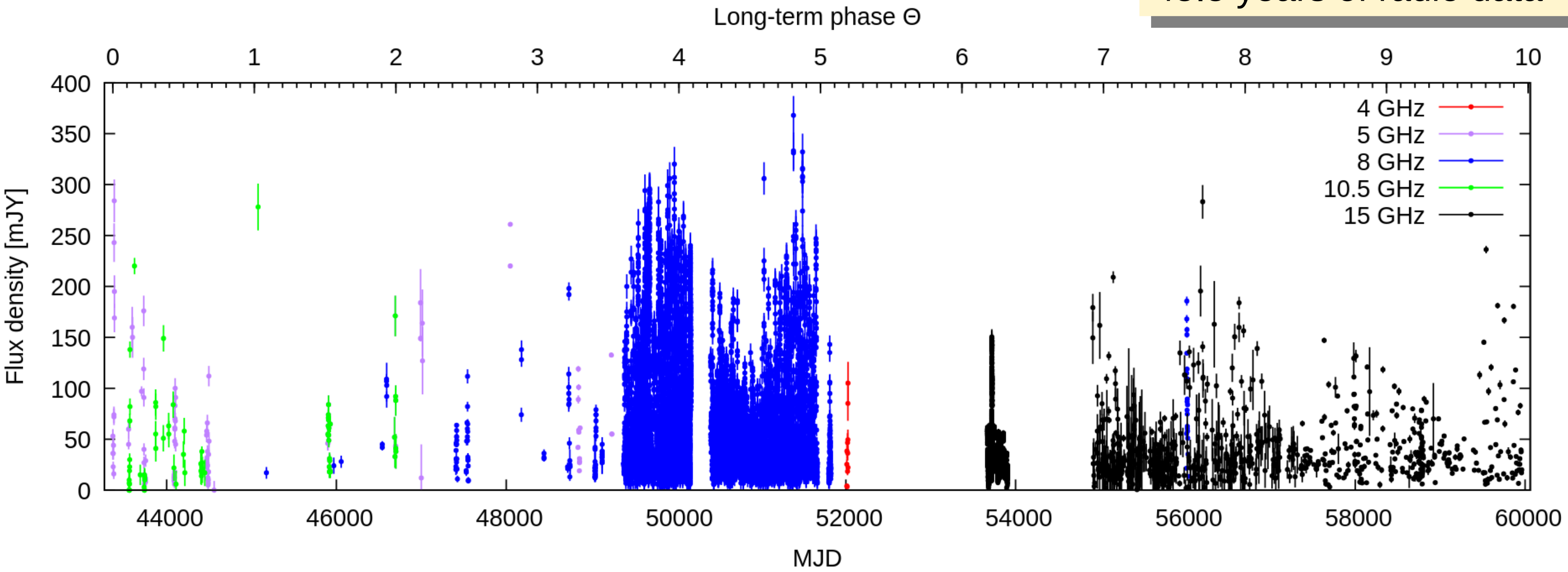
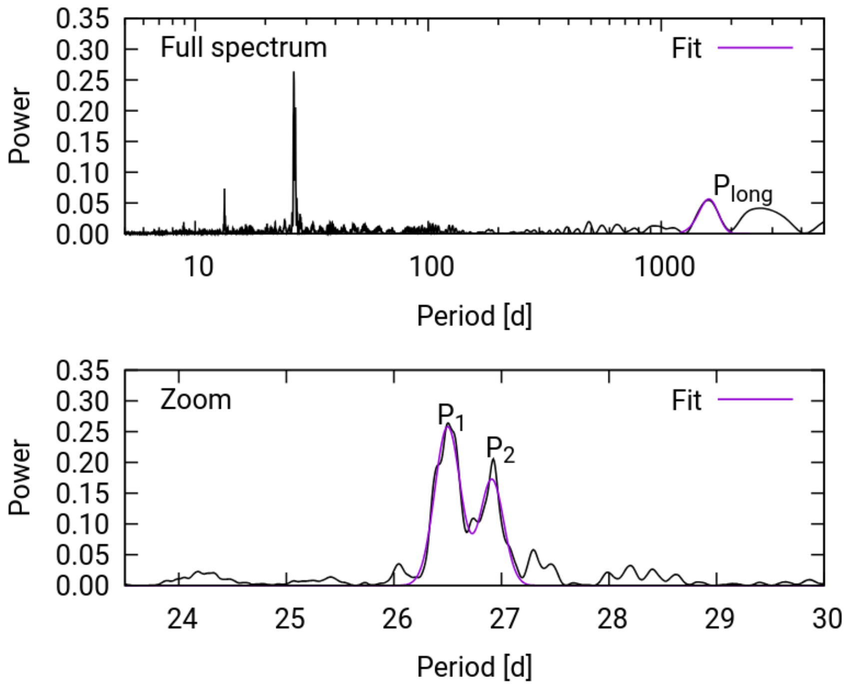


Figure 2 in Jaron et al. (2024)

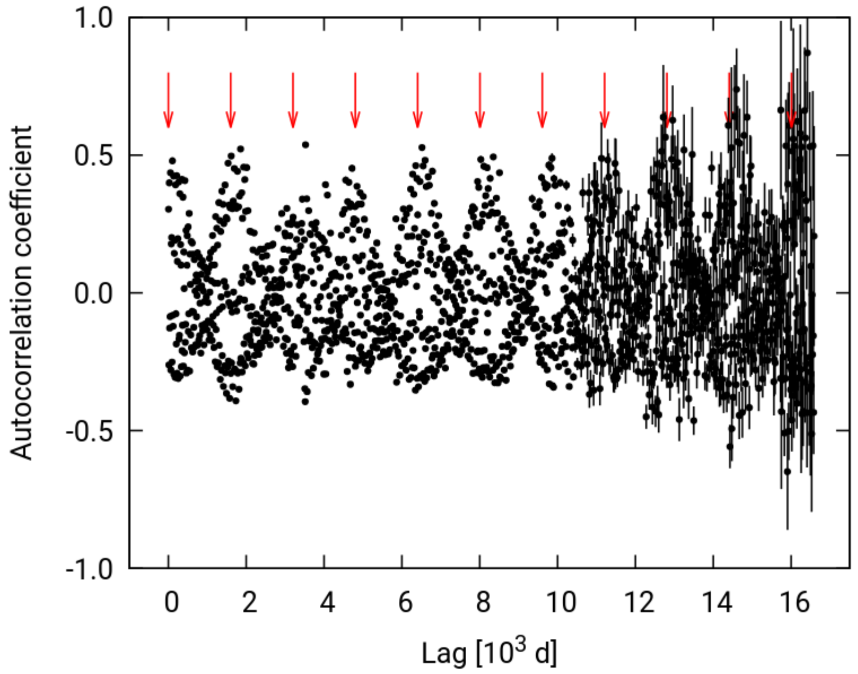
Concatenation of all available radio observations ≥ 4 GHz of LS I +61°303 since 1977.

Lomb-Scargle Periodogram



The same periodic features are found in 45.5 years of data at 4-15 GHz.

Auto-Correlation Function

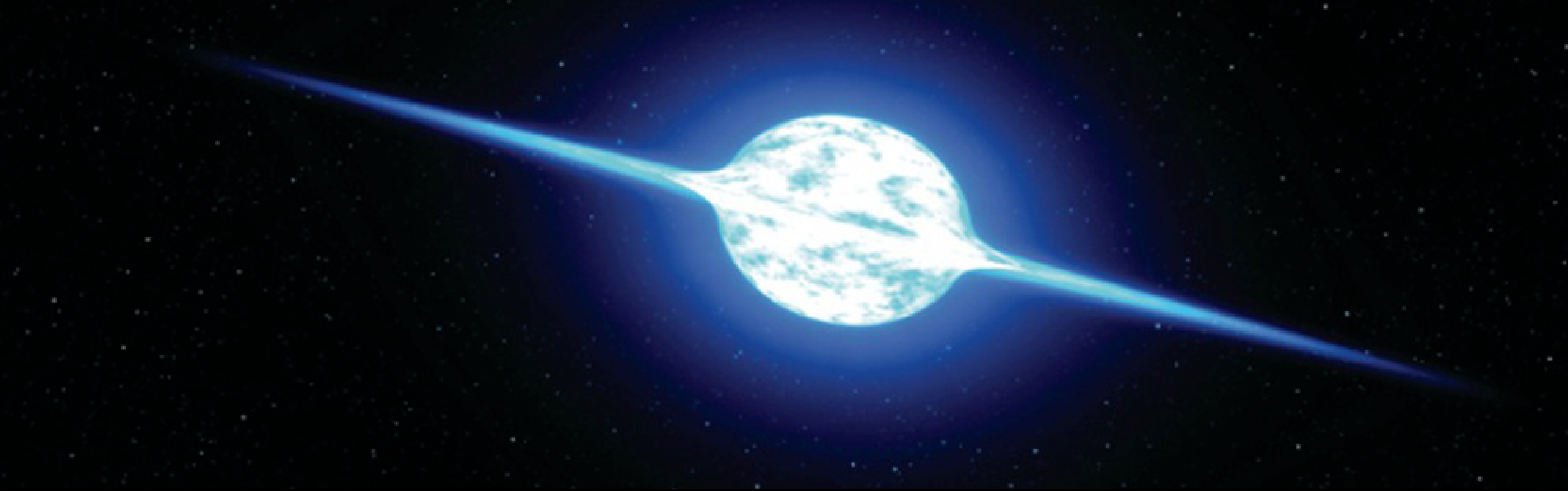


The long-term modulation has remained stable for 10 full cycles now.

See also Massi & Torricelli-Ciamponi (2016)

3. Discussion

Is the origin of the long-term modulation in the Be star disk?

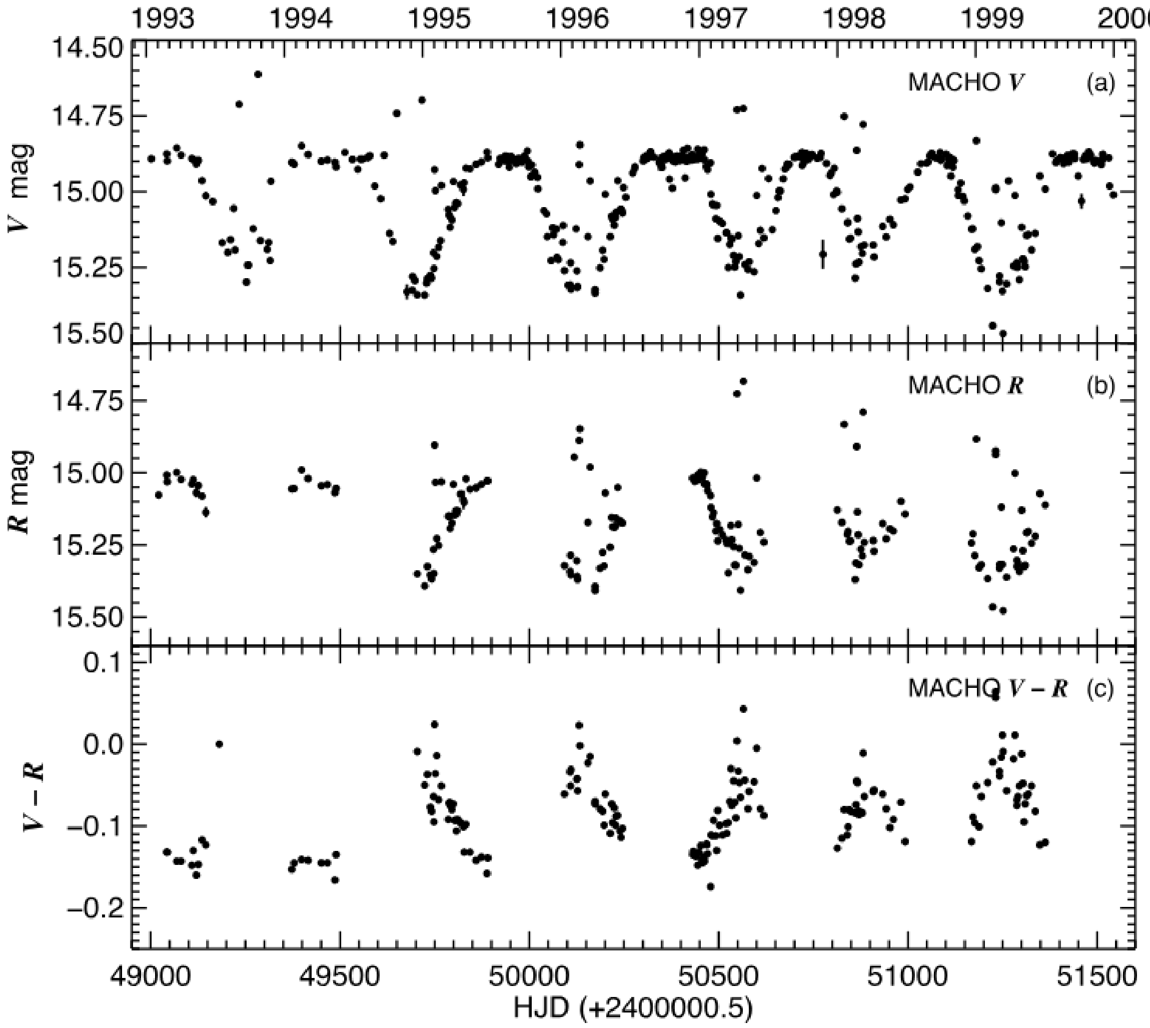


Size of Be star disk changes → Variability of photometric light curve

Size of Be star disk changes → Variability of EW(Hα)

Photometric light curve

Be/X-ray binary A0538-66

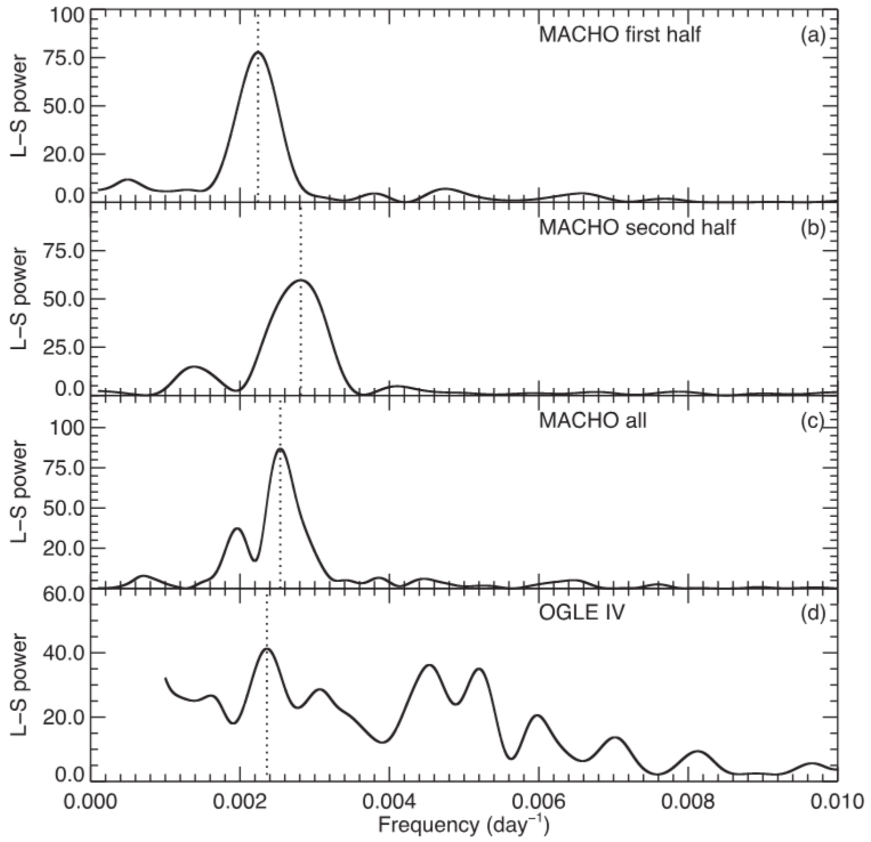


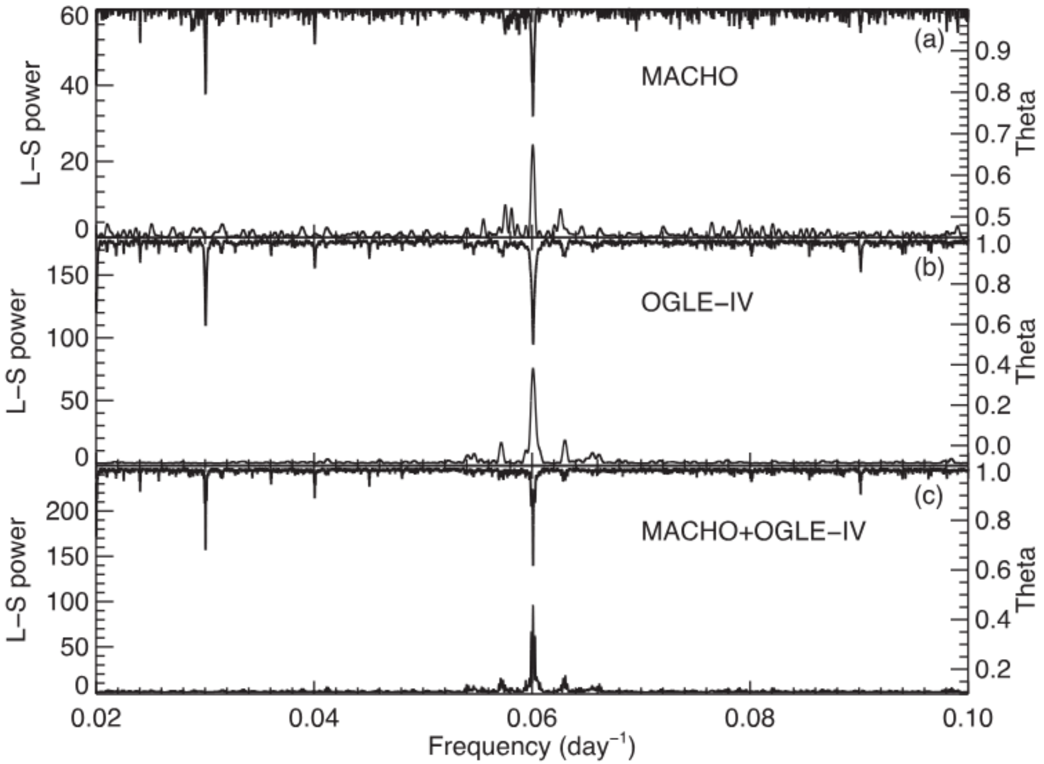
Is there any such optical light curve for LS I +61°303 ?

$P_{sorb} \approx 420$ d

Rajoelimanana et al. 2017, MNRAS, 464, 4

Be/X-ray binary A0538-66





Two-peaked profile at the orbital period?

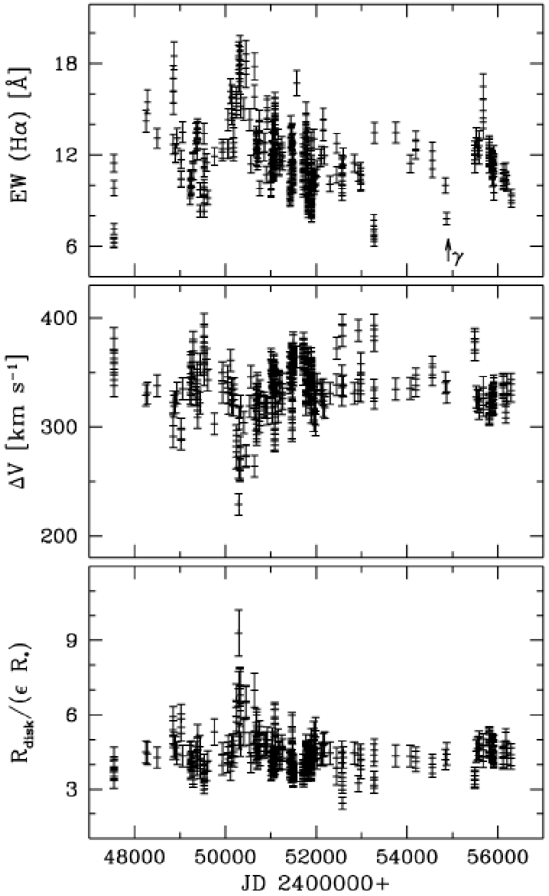
$P_{orb} = 16.6406 \pm 0.0003$ d

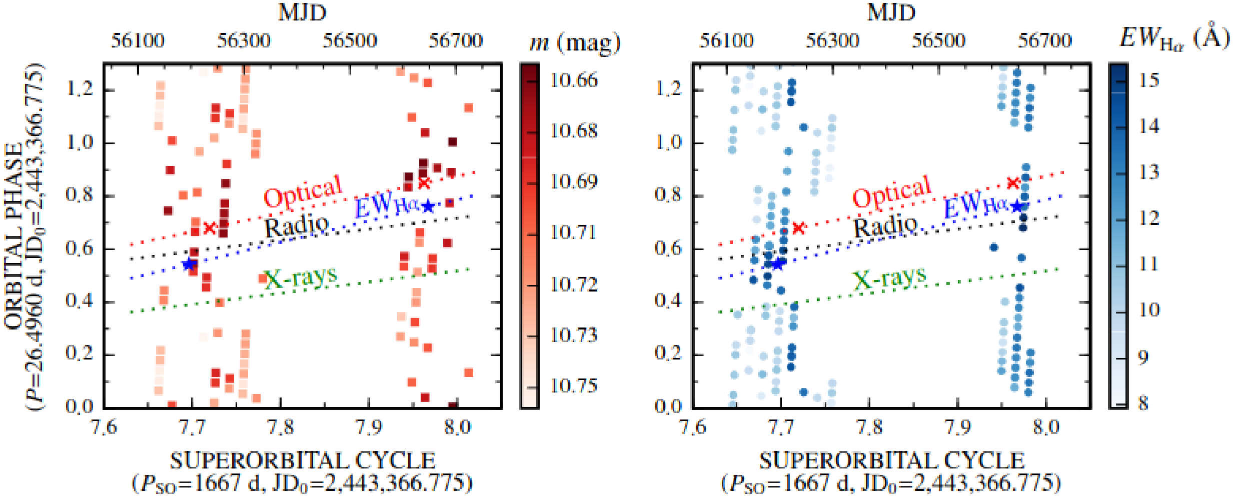
Long-term modulation only quasi-periodic

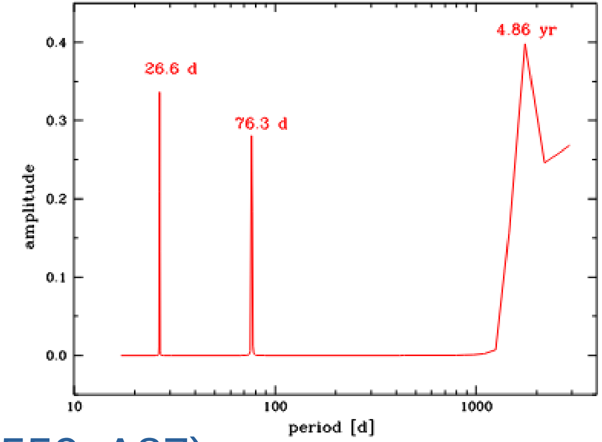
Rajoelimanana et al. 2017, MNRAS, 464, 4

Long-term modulation of EW(Hα) in LS I +61°303

Paredes-Fortuny et al. (2015, A&A, 575, L6)





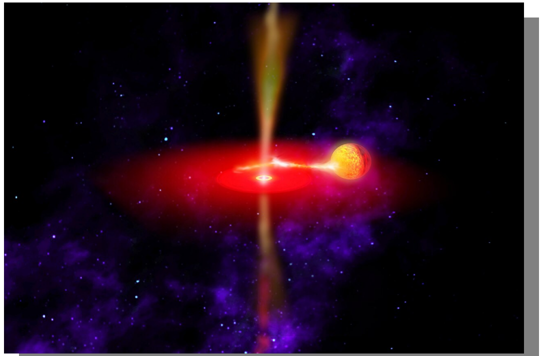


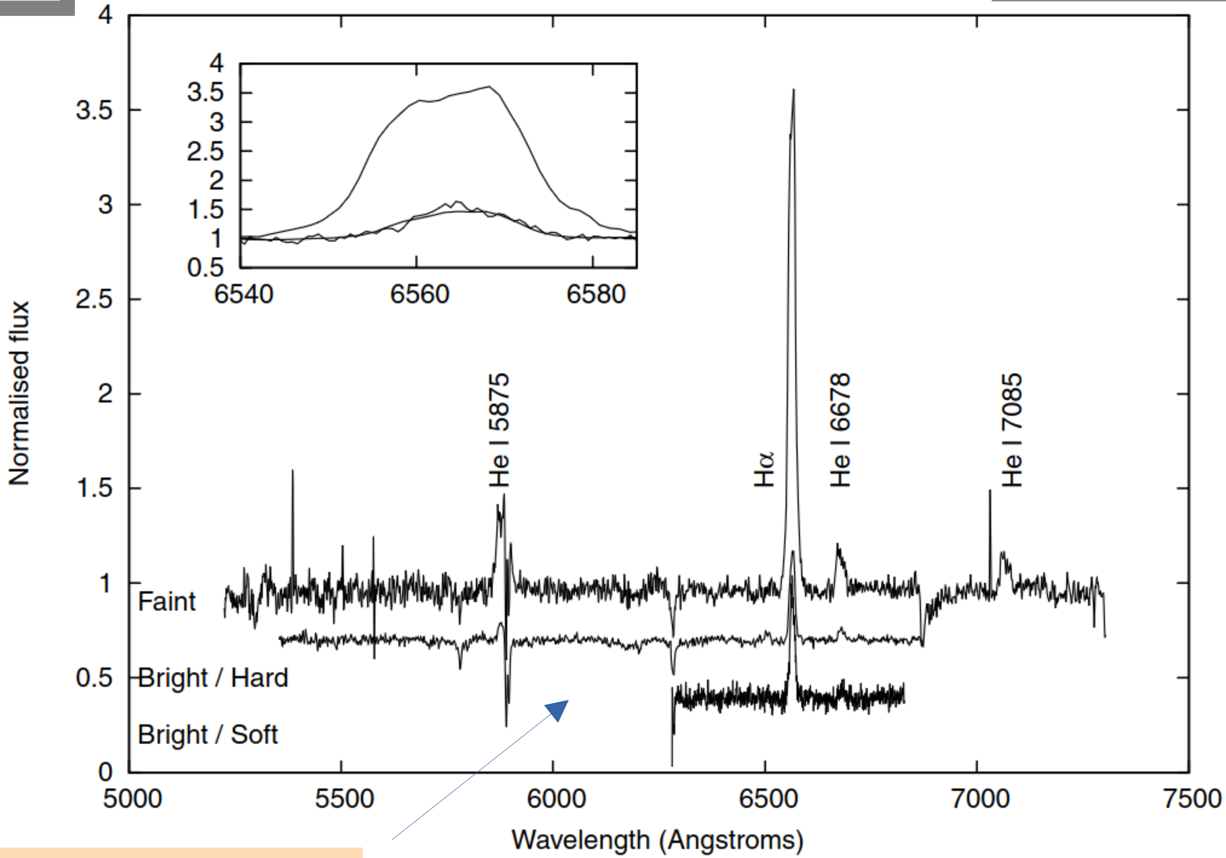
Zamanov et al. (2013, A&A, 559, A87)

Emission lines from accretion disks

GX 339-4

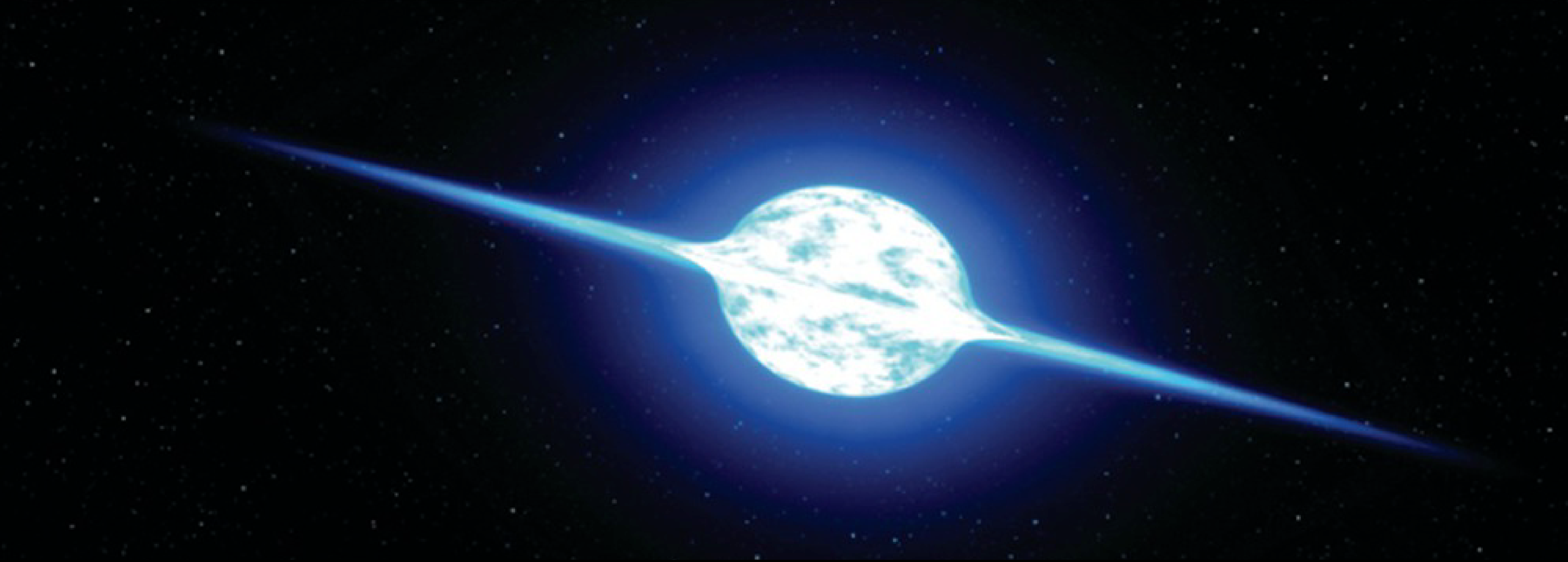
“We know of no example of emission-line profiles in B stars as broad as in LS I +61°303. Such profiles are, however, common in cataclysmic variables, in which a disk forms around a compact star.”
Hutchings & Crampton 1981, PASP, 93





“These spectra are almost certainly uncontaminated by a companion star.”

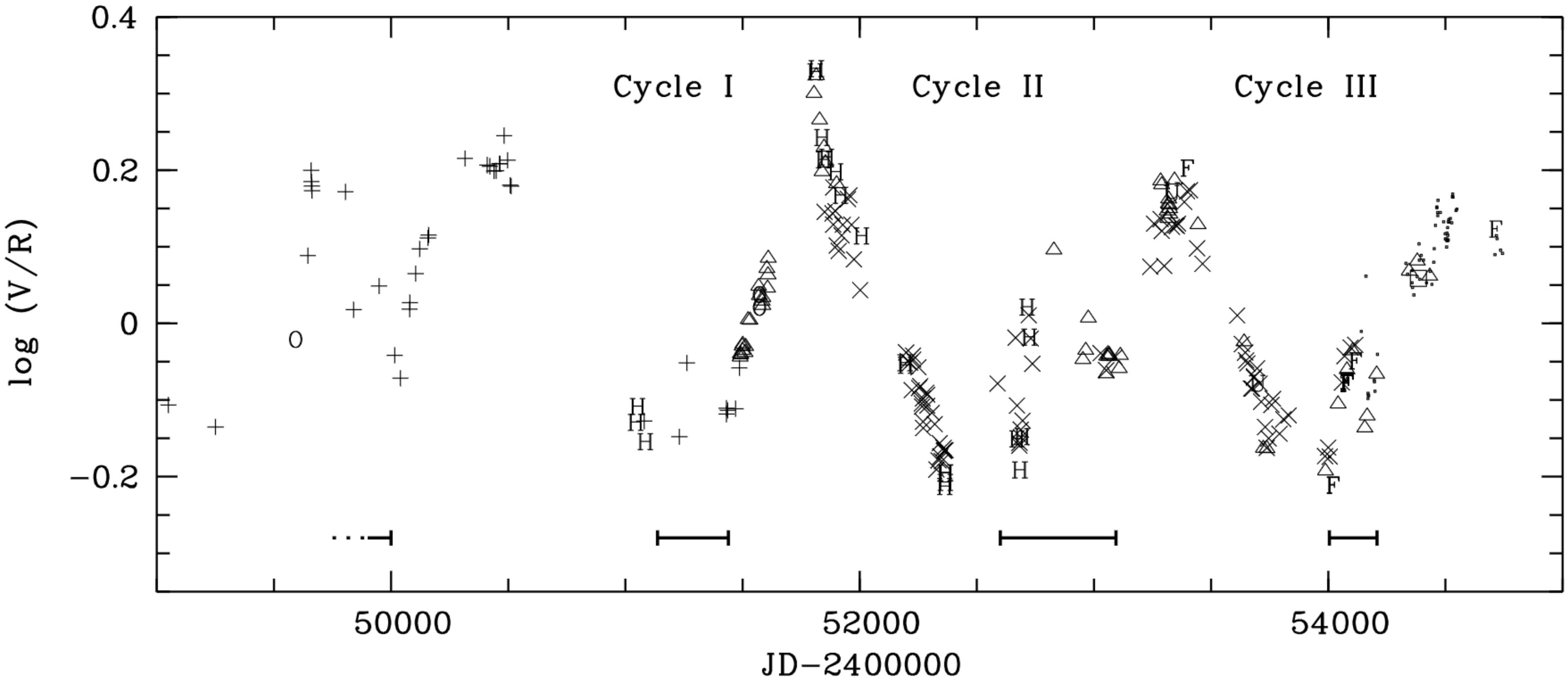
Fender et al. 2009, MNRAS, 393, 4



One-armed density wave in Be star disk → Variability of V/R of Hα line

ζ Tau

Hα V/R variations

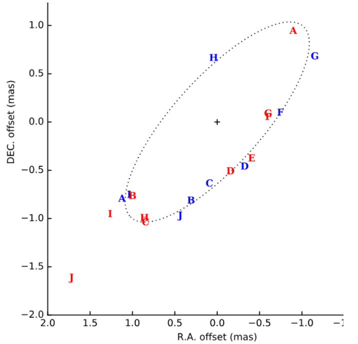


Štefl et al. 2009, A&A, 504, 3

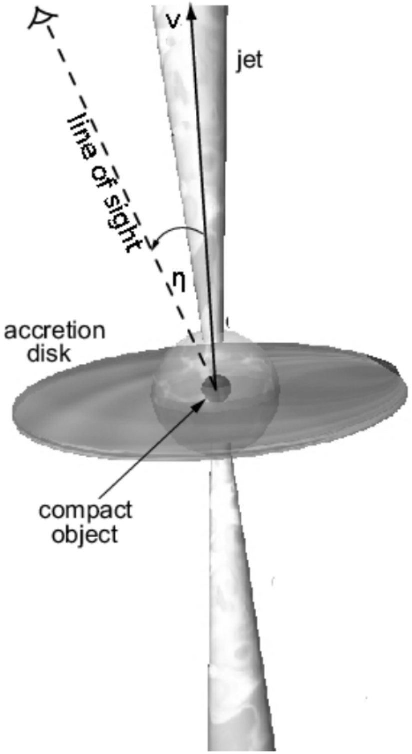
The length of these cycles changes.
Guo et al. (1995, A&AS, 112, 201)

Never observed for LS I +61°303 despite searches.
Zamanov et al. 1999, A&A, 492, 2
Zamanov et al. 2013, A&A, 559, A87

Jet precession period: P_2 = 26.926 ± 0.005 d (Wu et al. 2018)



Variable 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)

Beating between Orbit and Precession

Two close periods

P_1 = 26.4960 ± 0.0028 d (Gregory 2002) Modulates accretion rate along eccentric orbit

P_2 = 26.926 ± 0.005 d (Wu et al. 2018) Modulates Doppler boosting of intrinsic emission

P_{avg} = 26.7 d

(c.f. Ray et al. 1997, ApJ, 491, 1)

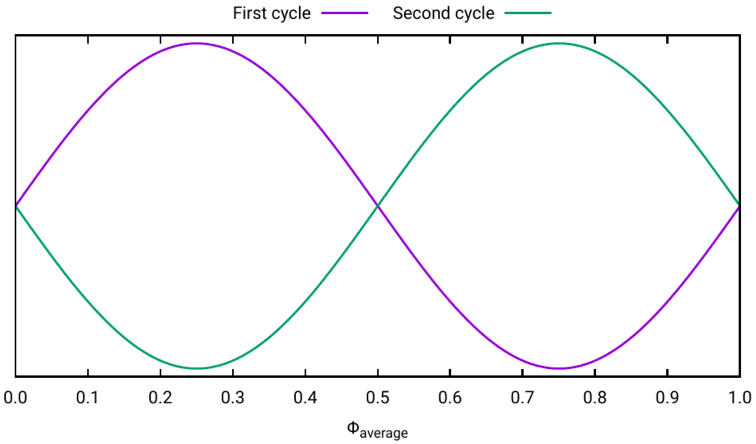
Frequency of radio outbursts

Slowly modulating cosine term

Has sign flip every P_{long}

Interference: Beating

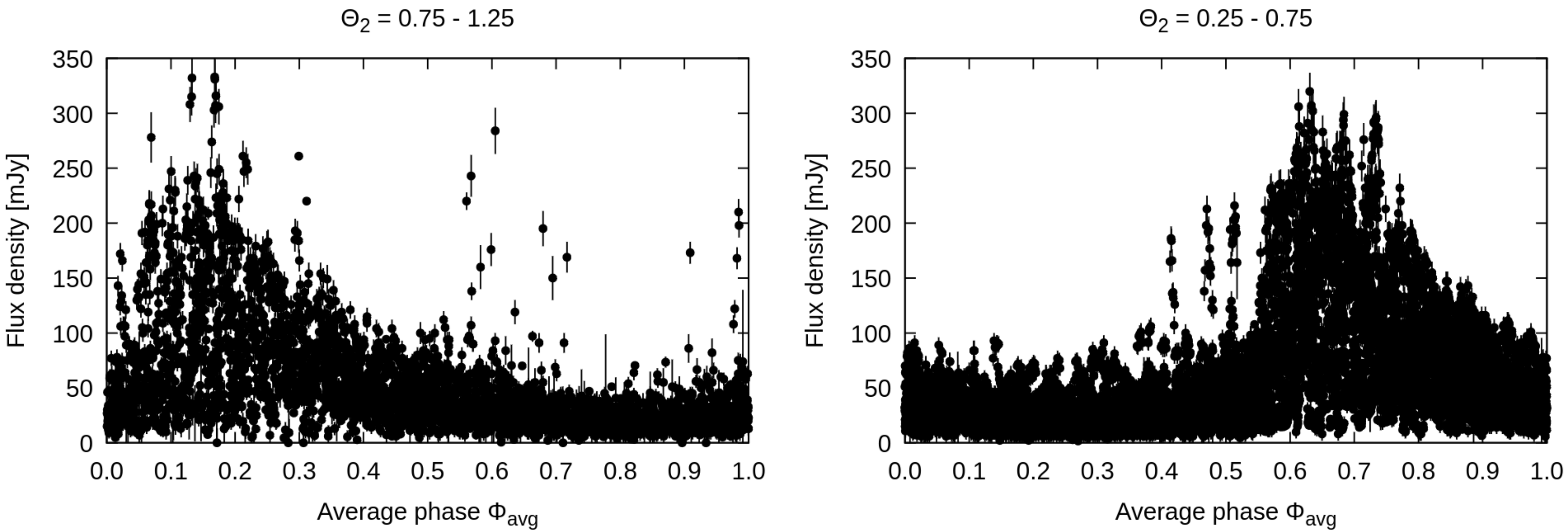
$$\sin\omega_1 t + \sin\omega_2 t = \sin\underbrace{\frac{\omega_1+\omega_2}{2}}_{\omega_{avg}} t \cdot \cos\underbrace{\frac{\omega_1-\omega_2}{2}}_{\omega_{long}/2} t,$$



Envelope of interference pattern has period P_{beat} = 1659 ± 22 d

C.f. P_{long} = 1667 ± 8 d by Gregory (2002, ApJ, 575, 1)

LS I +61°303

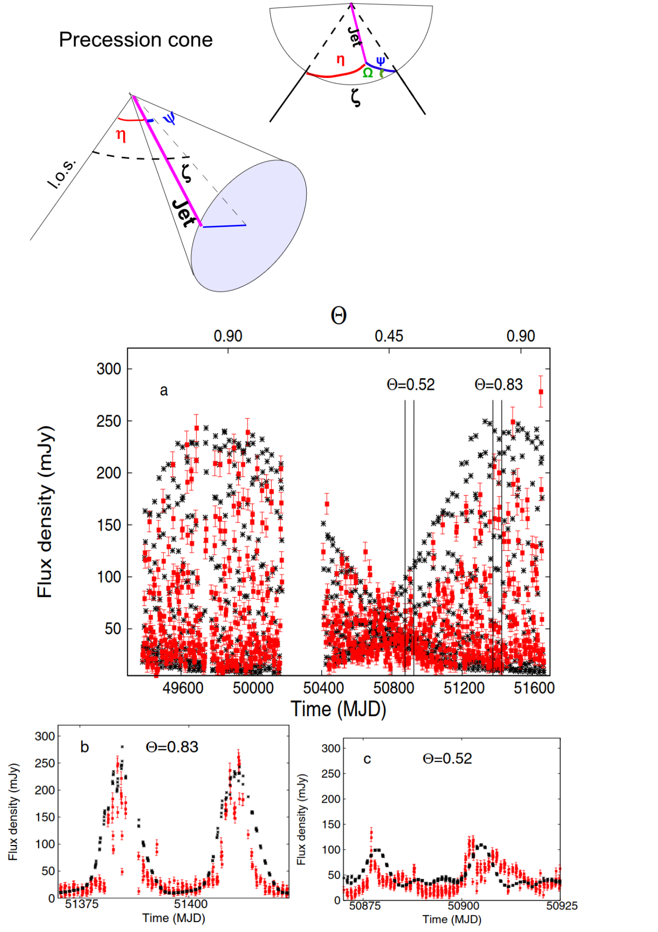


Entire radio data (1977-2023) folded on the outburst period P_{avg} = 26.709 d

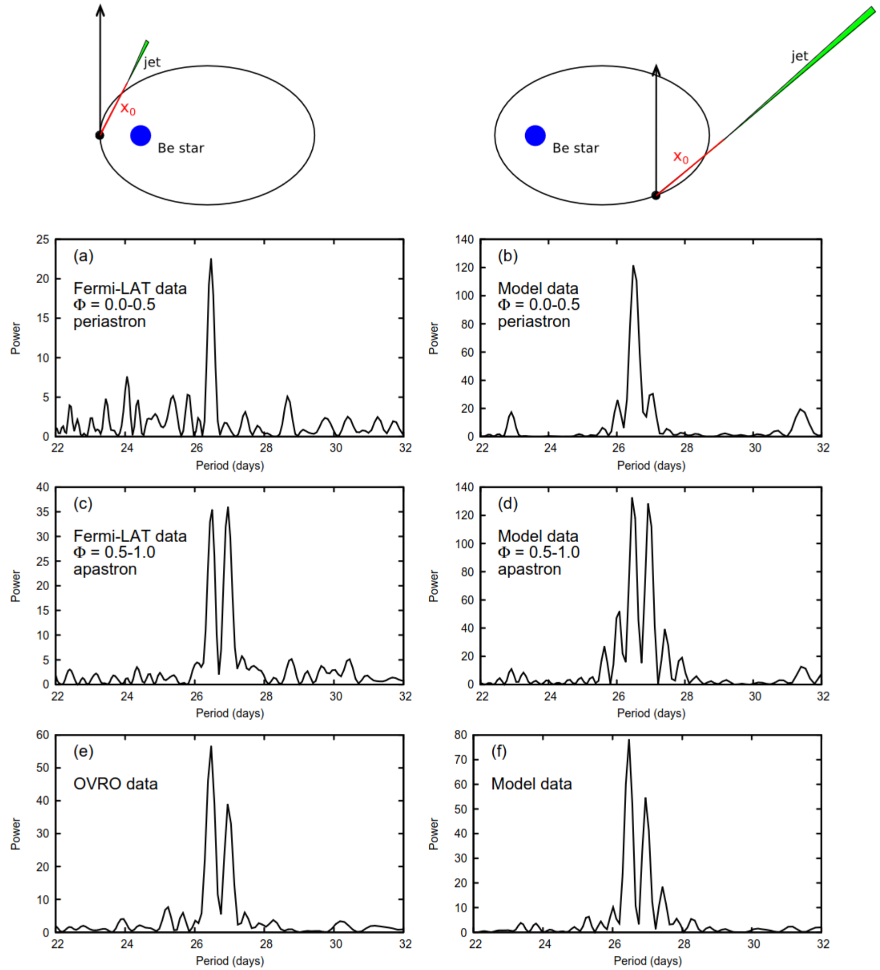
Divided into phase intervals of twice the long-term period

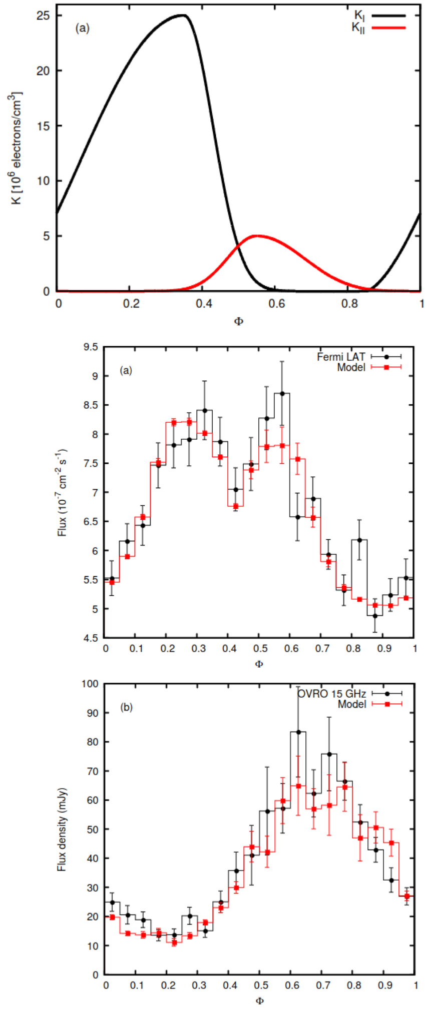
Jaron et al. 2024, A&A, 683, A228

A Physical Model for the Radio and GeV emission from LS I +61°303



Massi & Torricelli-Ciamponi (2014, A&A, 564, A23)





Jaron et al. (2016, A&A, 595, A92)

4. Conclusions

Conclusions

1. Recent monitoring of LS I +61°303 by the Owens Valley Radio Observatory confirms the decades-long stability of periodic signals in the data.

2. Orbital period: P_1 = 26.49 ± 0.05 d (OVRO), P_1 = 26.50 ± 0.12 d (full radio archive 4-15 GHz)

3. Precession period: P_2 = 26.93 ± 0.05 d (OVRO), P_2 = 26.91 ± 0.11 d (full radio archive)

4. Long-term period: P_{long} = 1698 ± 196 d (OVRO), P_{long} = 1601 ± 152 d (full radio archive)

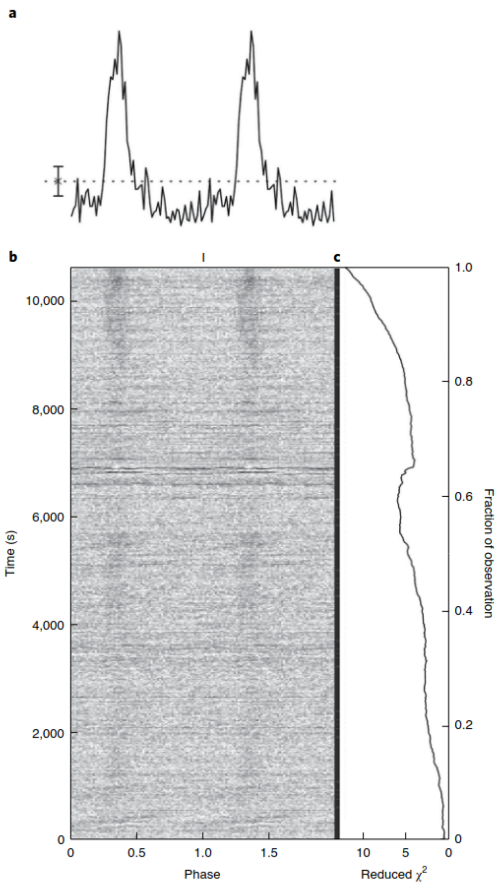
5. Auto-correlation shows that long-term modulation has remained stable for 10 full cycles.

6. The long-term modulation in LS I +61°303 is too stable for a Be star. Observational evidence is missing.

7. Precessing jet and periodic mass-loading result in long-term beating pattern. Direct VLBA astrometry confirms precession. Physical modeling reproduces radio and GeV observations.

Extra Slides

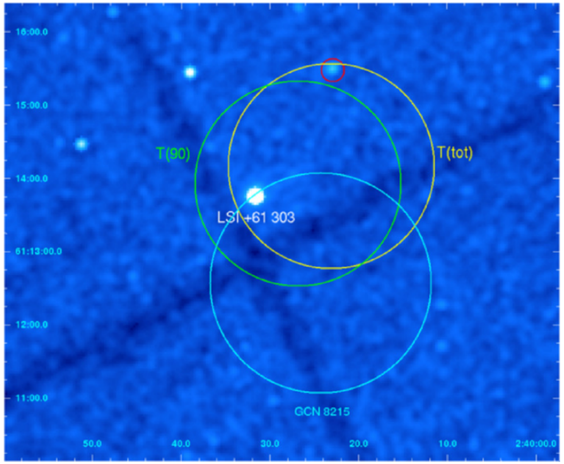
Pulses from LS I +61°303 (?)

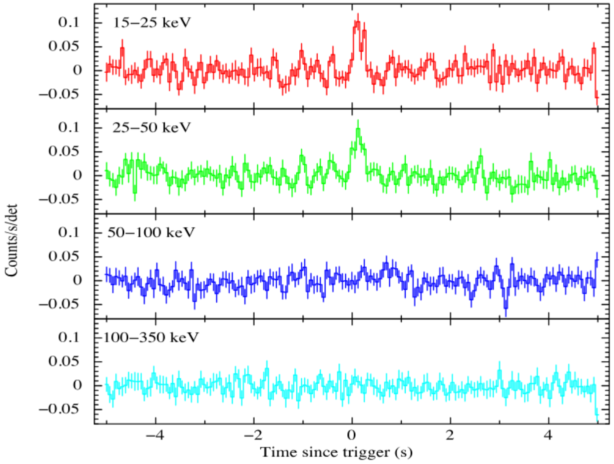


Weng et al. (2022, Nature Astronomy, 6)

P = 269.15508 ± 0.00016 ms

"A magnetar-like event from LS I +61°303"



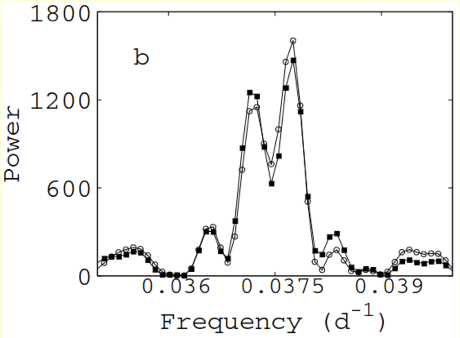


Torres et al. (2012, ApJ, 744, 2, 106)

Previous searches for radio pulsations had remained elusive.
Cañellas et al. (2012, A&A, 543, A122)

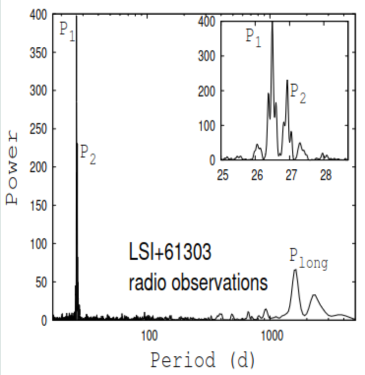
Previous Findings in the Radio Emission from LS I +61°303

Greenbank Interferometer 8 GHz
1994-2000
6.7 years of observations



Massi & Jaron (2013, A&A, 554, A105)

Multiple Observatories 5-15 GHz
1977-2014
36.9 years of observations



Massi & Torricelli-Ciamponi (2016, A&A, 585, A123)

Important: In order to resolve the close periods P_1 and P_2 one needs a sufficiently long time-series of observations.

OVRO Monitoring Sampling Rate