# PSR J1023+0038: from radio MSP to accreting system

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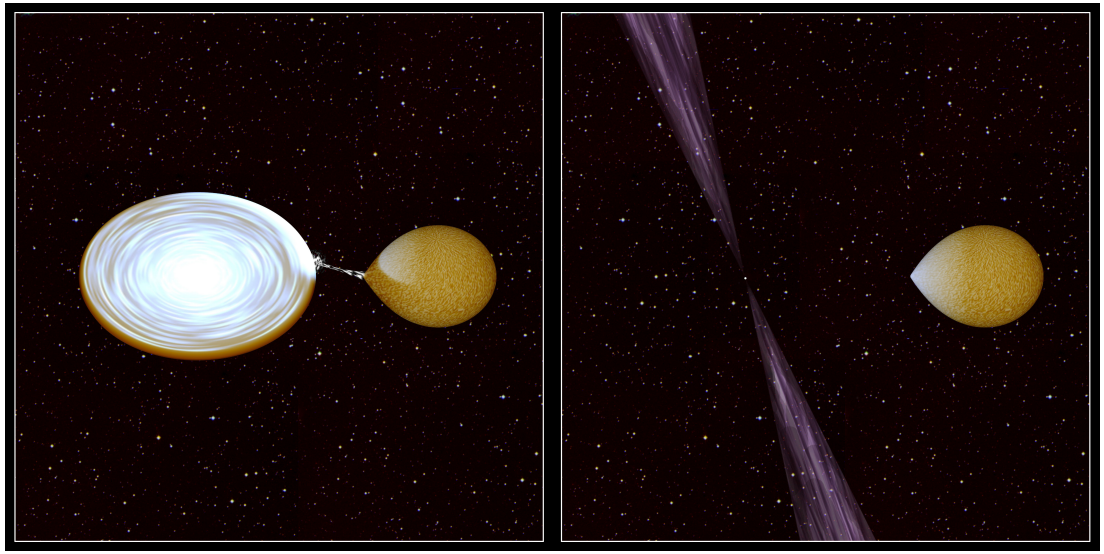
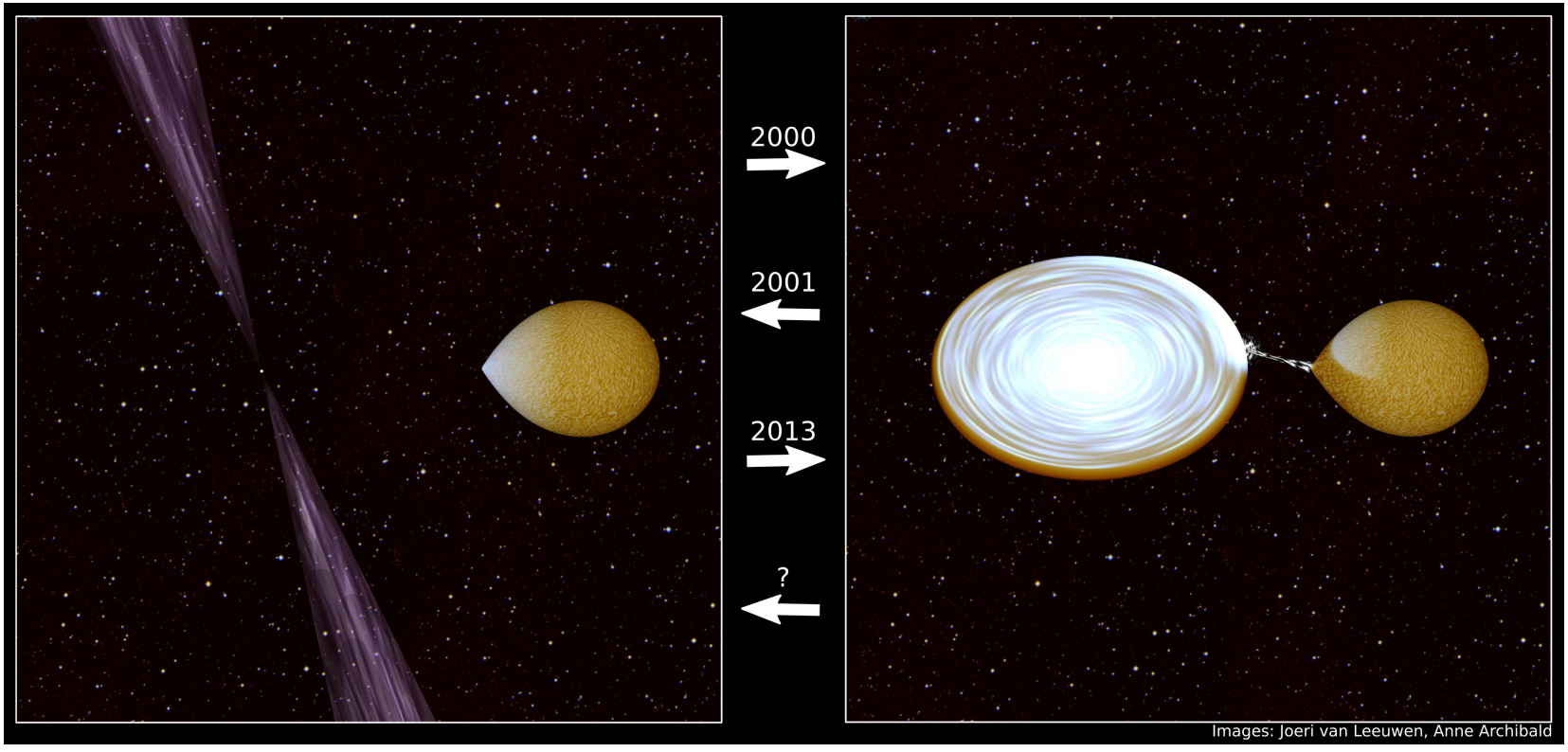
ASTRON

2015 June 25



# Timeline



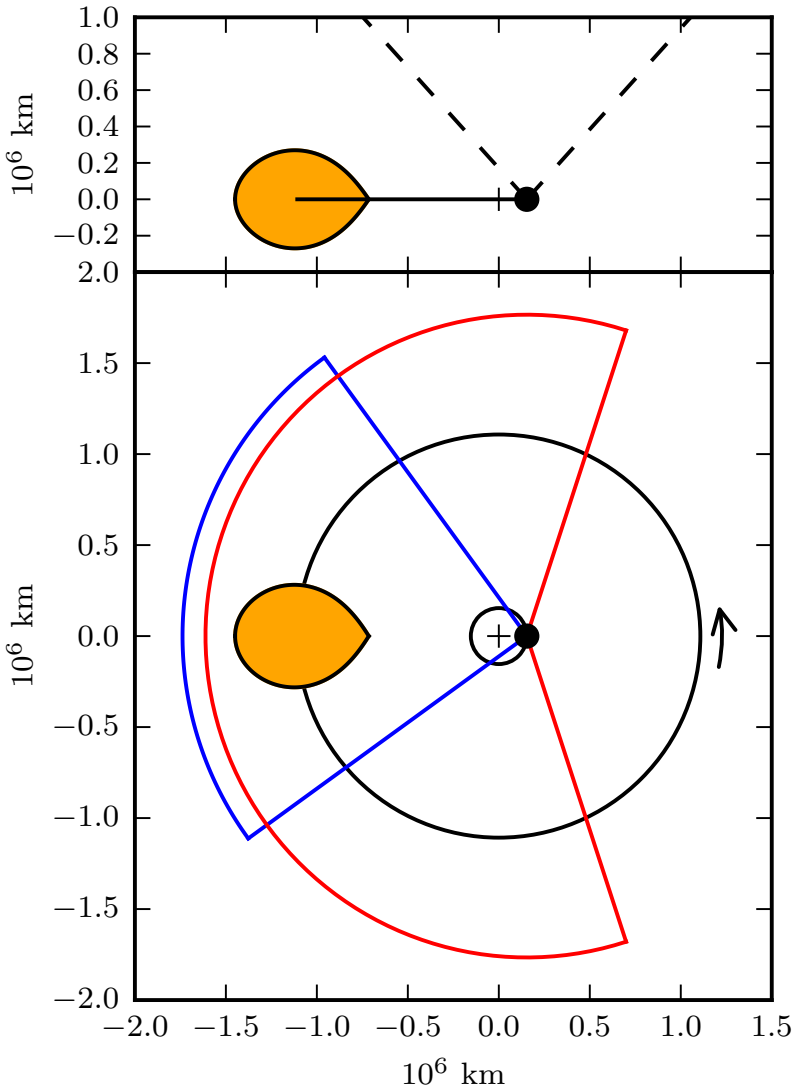
# Transitional MSPs

There are now known three systems that have transitioned between radio MSP and accreting states:

- J1023: field MSP, found in pulsar survey, detailed study in both states
- M28I: cluster MSP, X-ray pulsations allowed identification; see Carlo Ferrigno's talk
- XSS J12270-4859: field MSP, identified based on $\gamma$-rays; see Jayanta Roy's talk

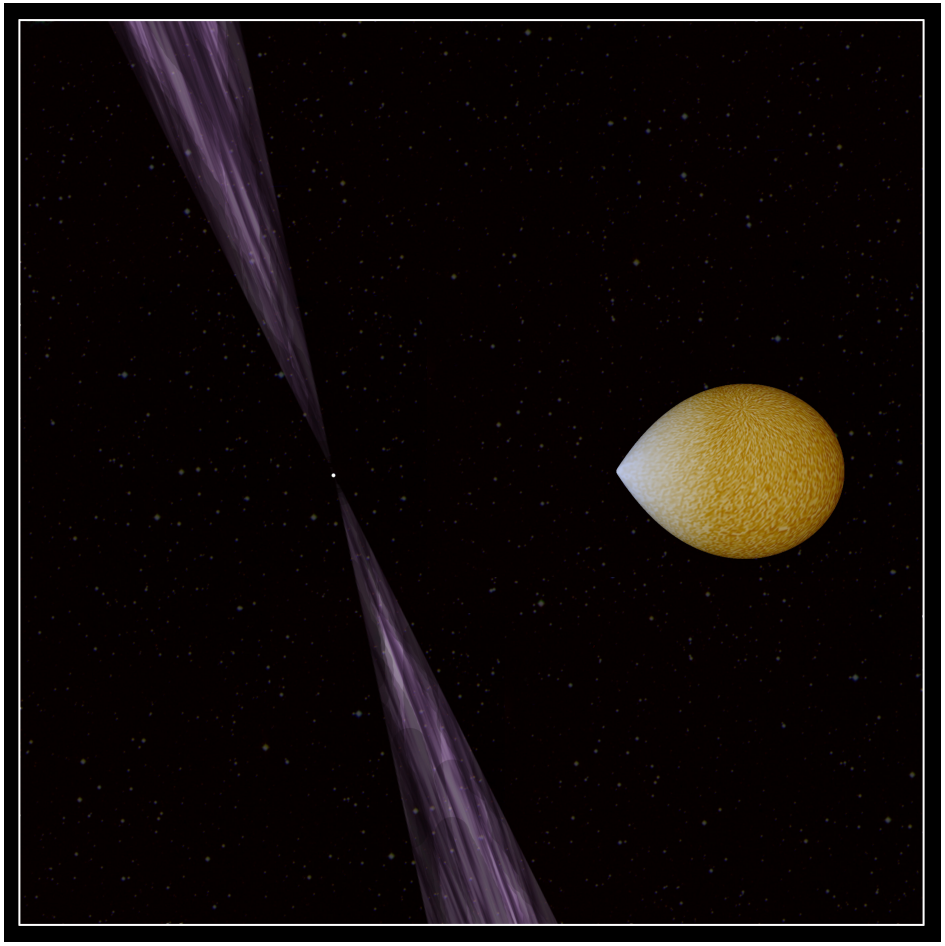
These systems share key observational features.

# J1023 system properties

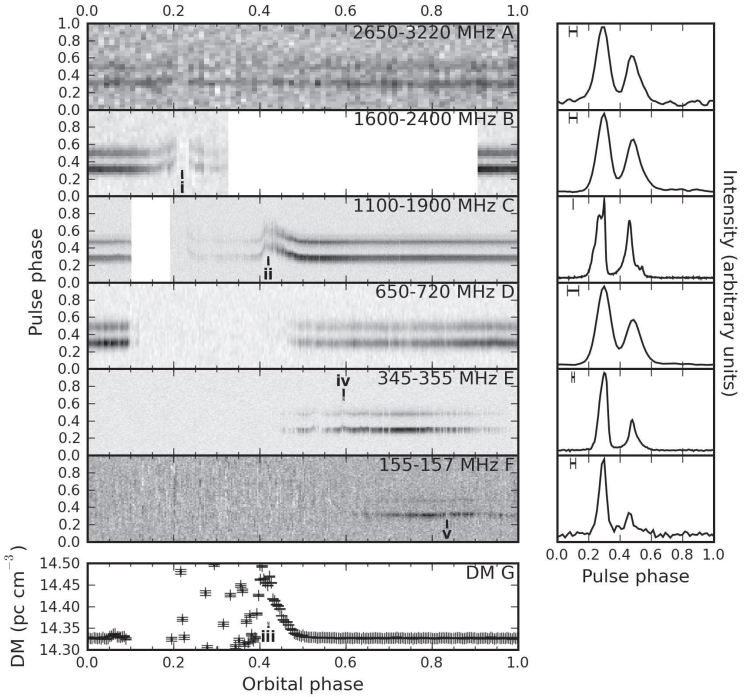



- 0.198-day orbit
- 0.2 $M_\odot$ companion
- 1.7-ms pulsar spin period
- $B = 10^8$ G
- 1.37 kpc distance
- $\sim 45^\circ$ inclination

# MSP



# Radio pulsar emission




Radio emission is messy:

- Eclipses
- Extra DM

Also seen in: M28I, XSS J12270

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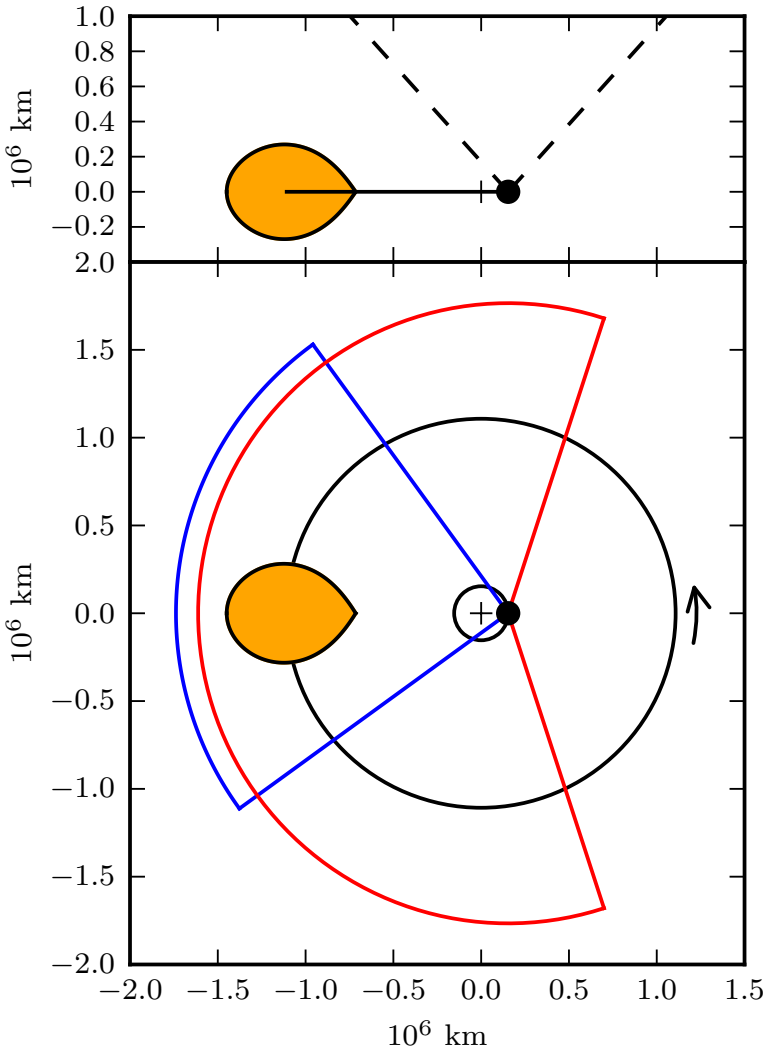


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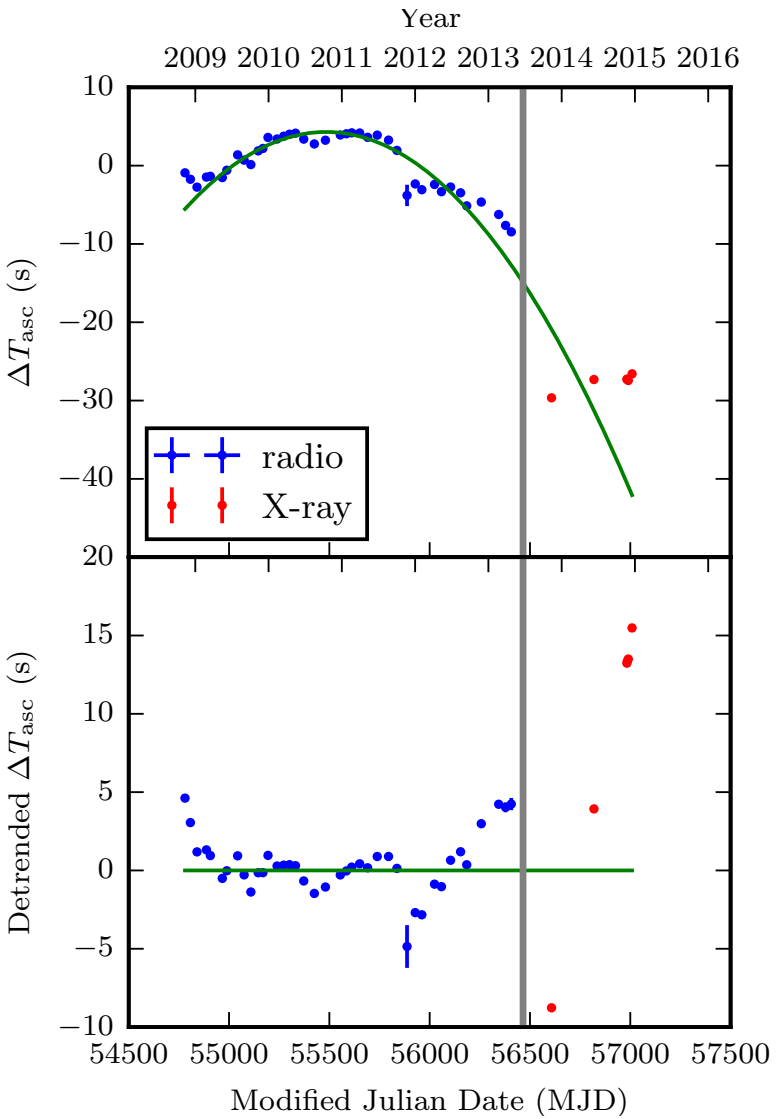
# Orbital period variations

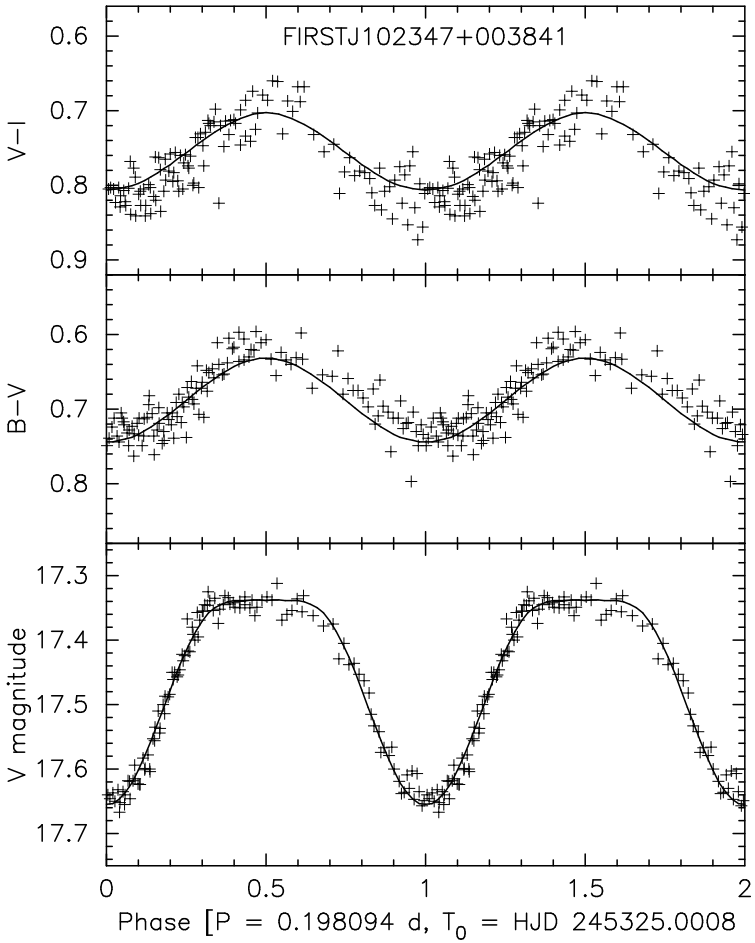



Substantial wander in orbital phase

- No believable long-term orbital period derivative
- No plausible quasi-periodicity

Also seen in: M28I, XSS J12270

# Companion

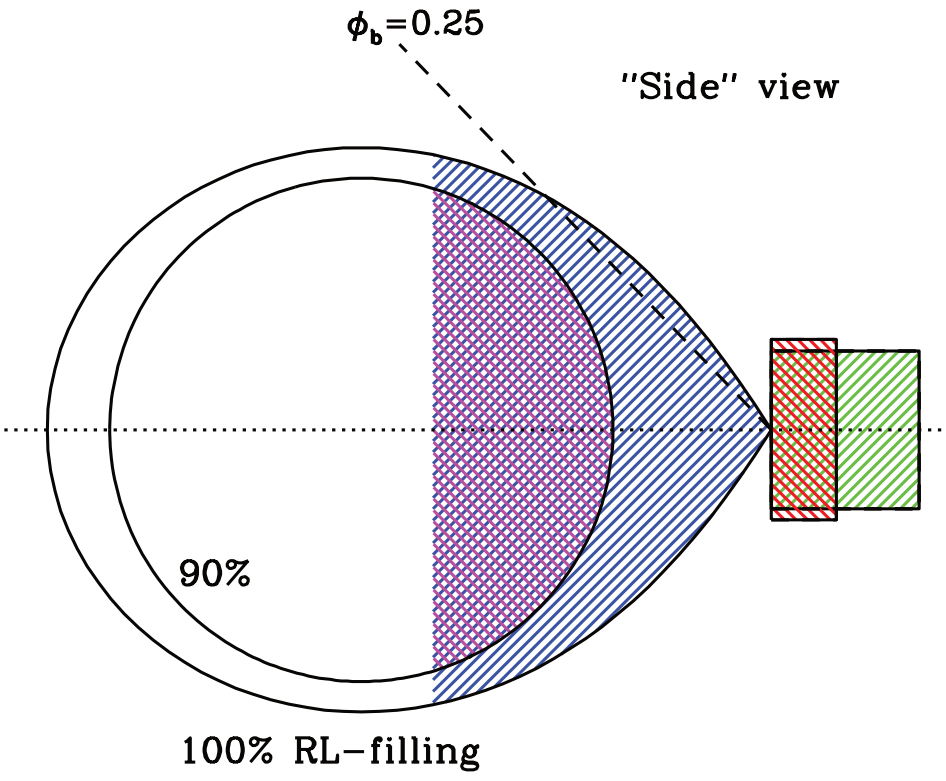



Multicolour light curve from Thorstensen and Armstrong 2005

The companion is unusual:

- 1.8 times the radius expected given the mass
- Mildly irradiated

# X-ray emission

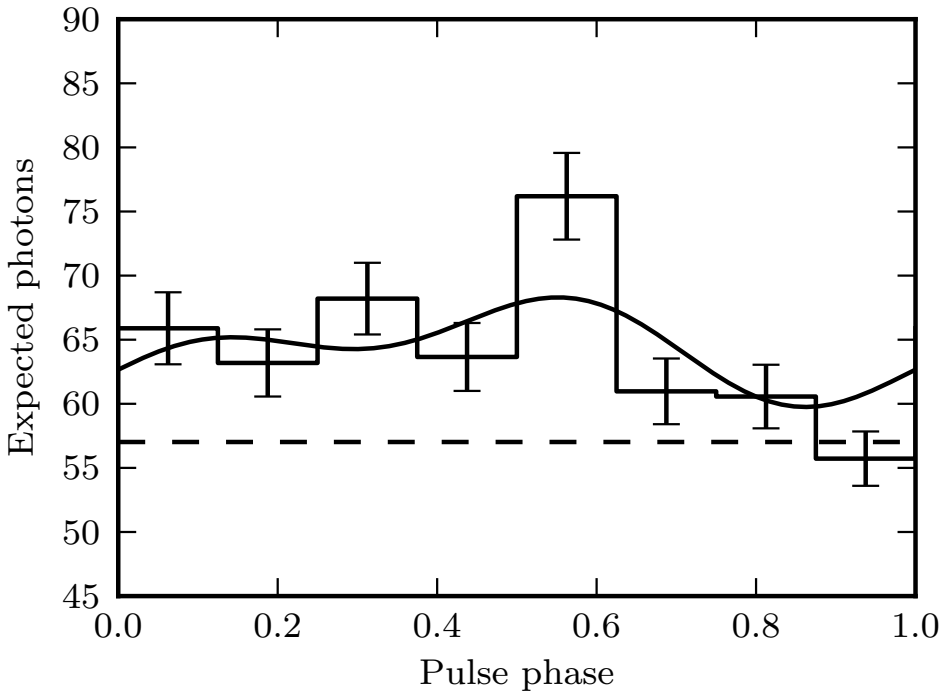



Shock model from Bogdanov et al. 2011

- X-rays in MSP state
  - $L_X = 0.02 L_\odot$ ($10^{32}\,\mathrm{erg\,s^{-1}}$), hard power-law spectrum
- Orbital variability consistent with emission from a shock near L1
  - Reprocessing allows X-rays to explain irradiation

Also seen in: XSS J12270

# $\gamma$-ray emission

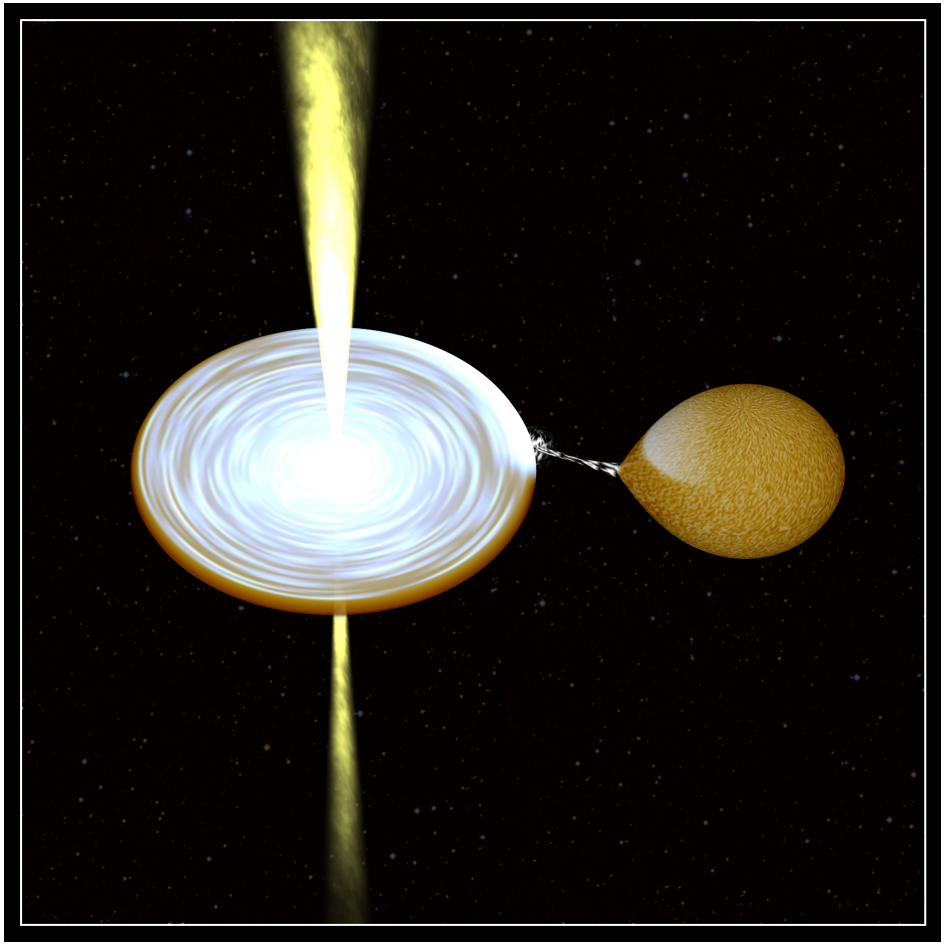



- J1023 is a $\gamma$-ray source
  - $0.3L_\odot$
  - $3.7\sigma$ evidence for pulsations at the pulsar period

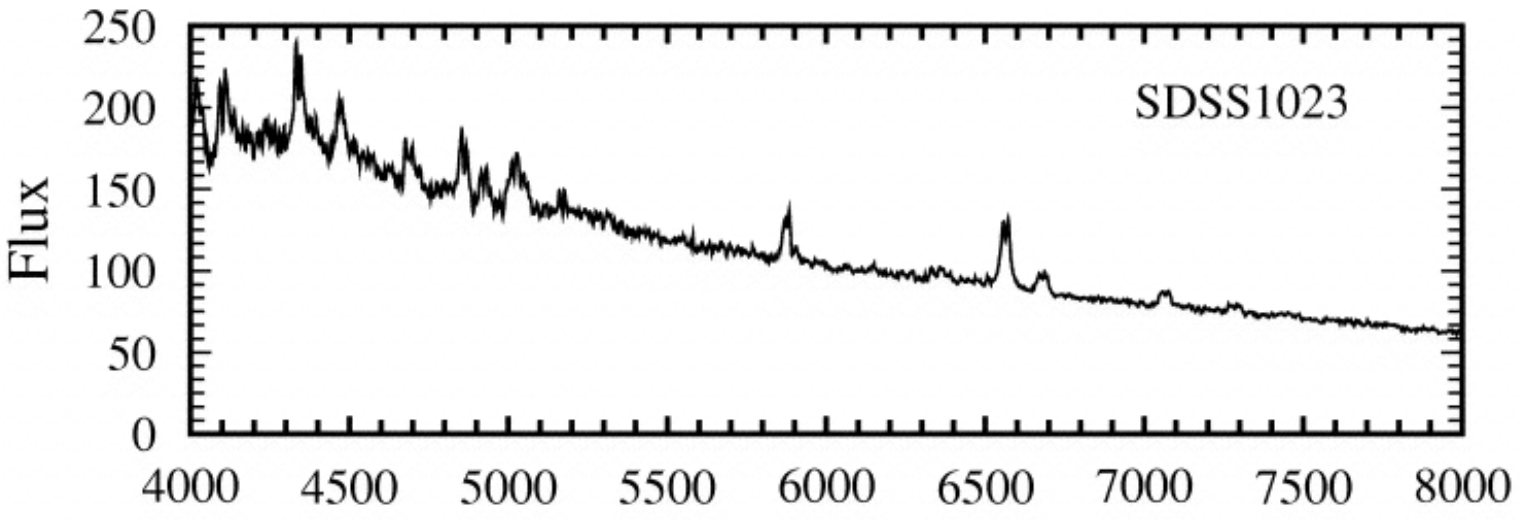
This is fairly typical for a MSP with $\dot{E} = 4 \times 10^{34}$ erg s$^{-1}$ ($12L_\odot$).

Also seen in: XSS J12270

# Accretion



# Optical evidence for an accretion disc




Spectrum from Szkody et al. 2003

- Grew brighter and bluer
- Spectrum developed double-peaked emission lines
- Increased orbital modulation (heating increased by a factor $\sim$3)

Also seen in: XSS J12270

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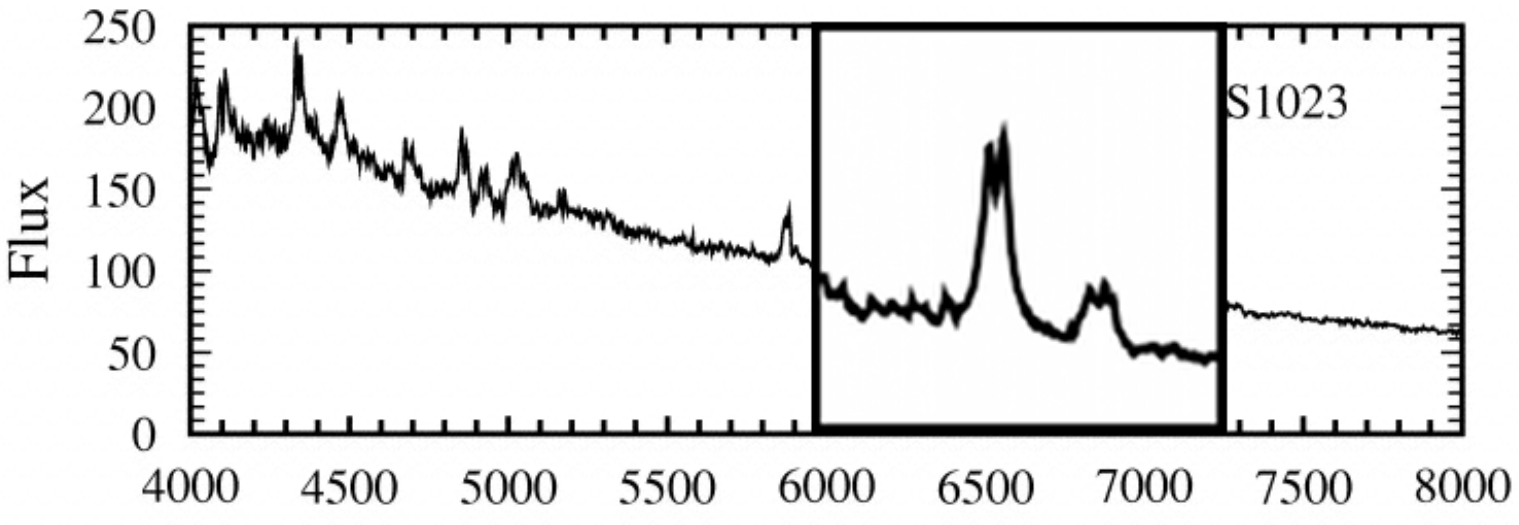


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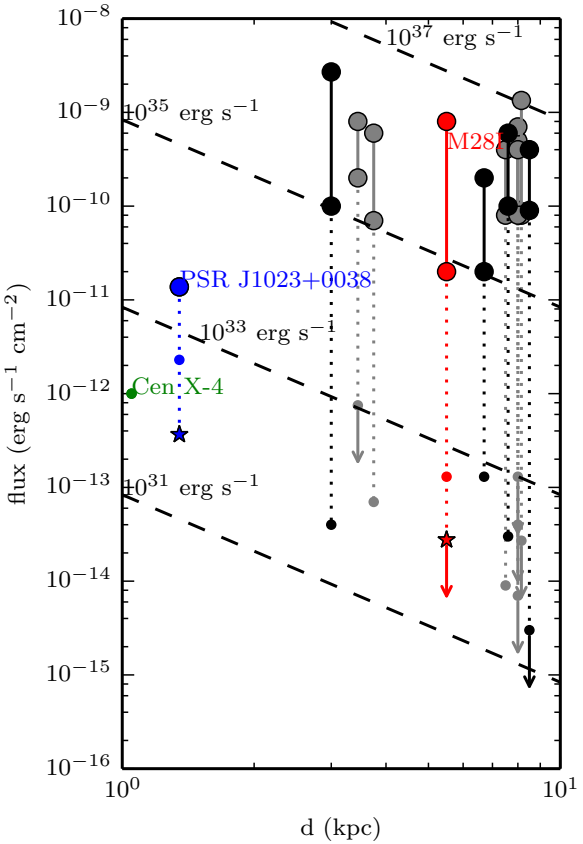
# Low X-ray luminosity




- X-ray luminosity $\sim 3 \times 10^{33}\,\mathrm{erg\,s^{-1}}$
  - Drastically lower than other systems known to accrete
  - "Quiescent"
- X-ray pulsations detected
  - Typical of AMXPs
- Low-luminosity pulsations hard to explain in terms of accretion flows

Also seen in: XSS J12270, M28I (sometimes)

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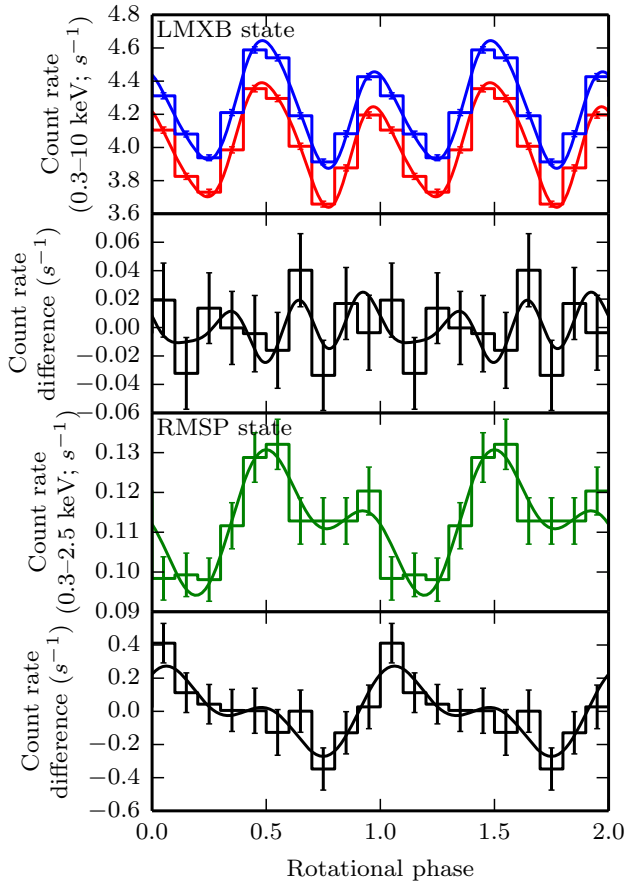


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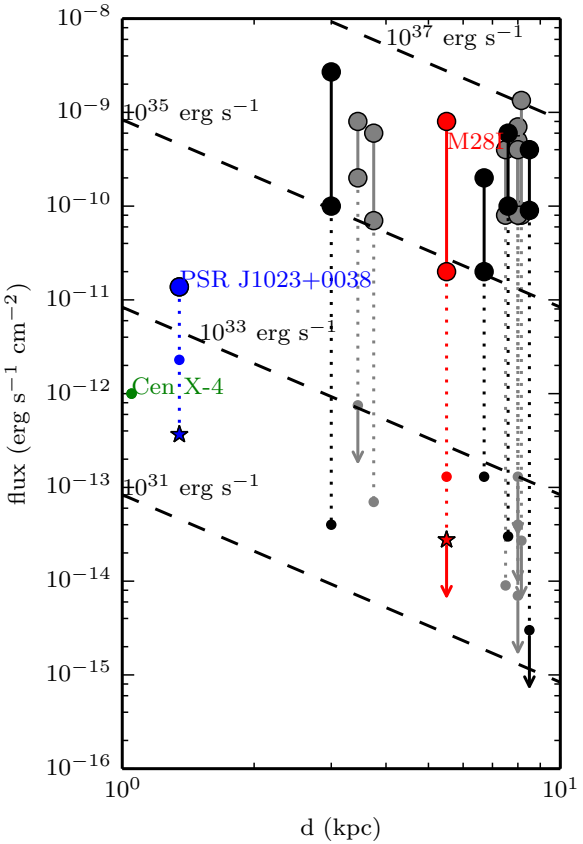


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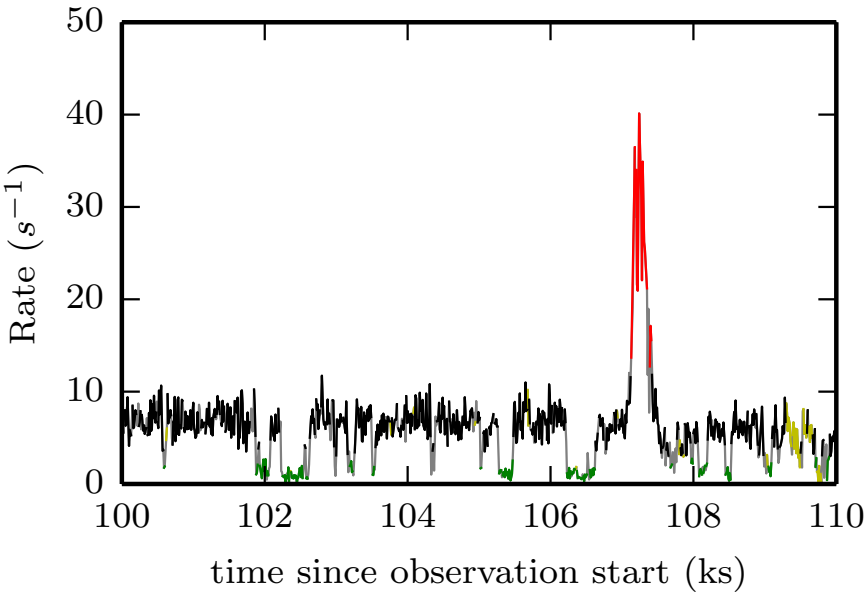
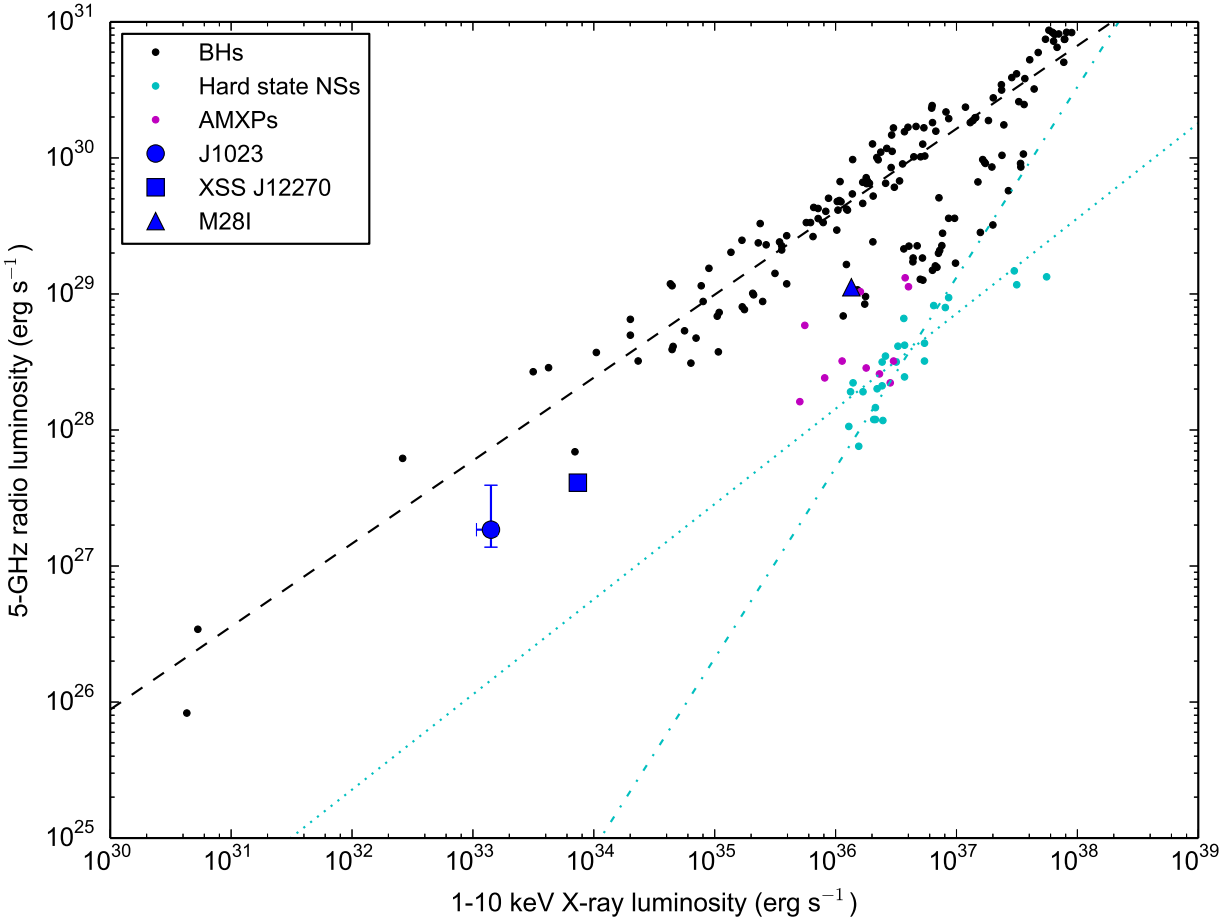



X-ray emission switches between three "modes":

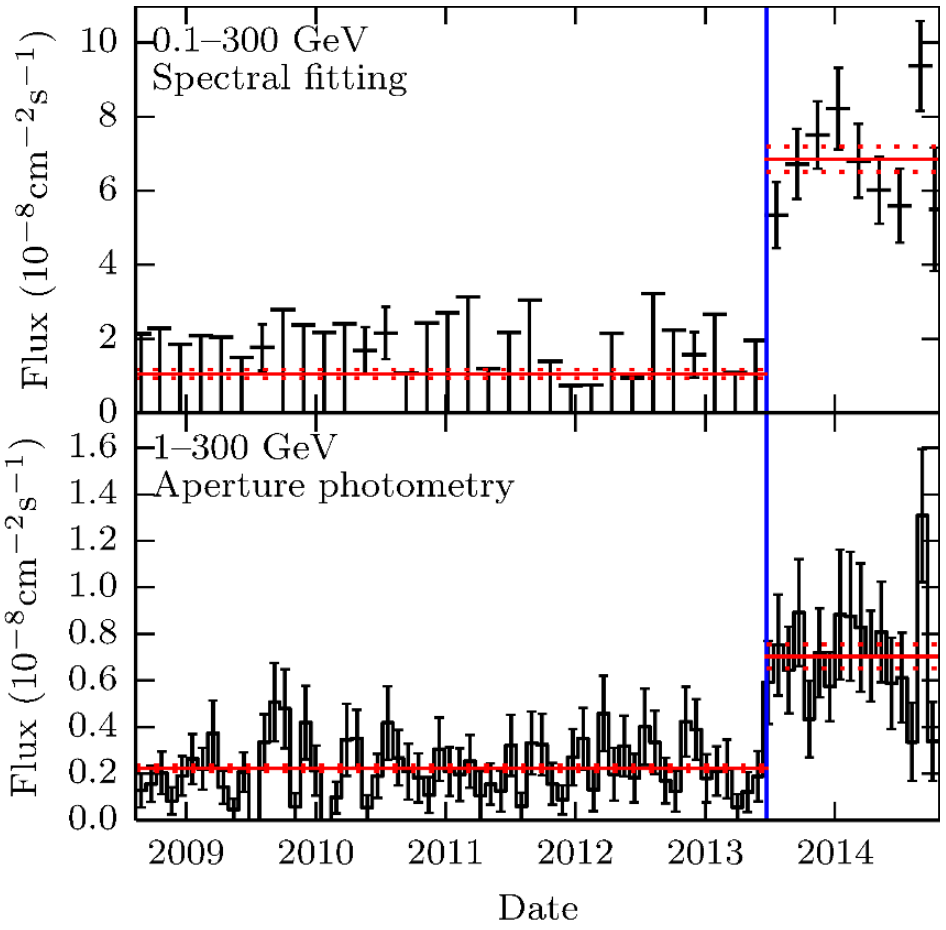
- Low
  - $5 \times 10^{32}\,\mathrm{erg\,s^{-1}}$, stable
  - No pulsations
  - Small fraction of the time; minutes
- High
  - $3 \times 10^{33}\,\mathrm{erg\,s^{-1}}$, stable
  - Pulsations
  - Majority of the time
- Flare
  - $\sim 10^{34}\,\mathrm{erg\,s^{-1}}$, variable
  - No pulsations
  - Occasional; minutes to hours

Also seen in: M28I, XSS J12270




- J1023 shows flat-spectrum variable radio emission
- $L_R/L_X$ more typical of a black hole than a NS

Also seen in: M28I, XSS J12270

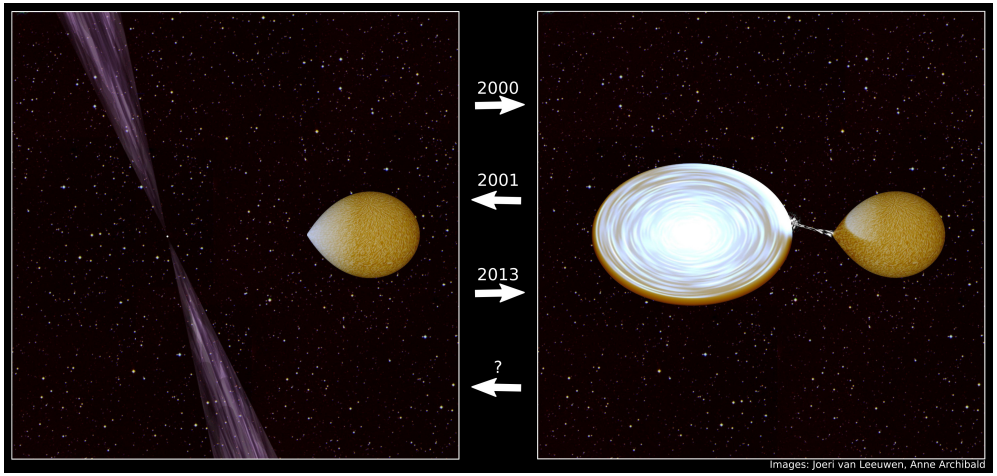



In the accretion-disc state the $\gamma$-ray flux increased by a factor of $\sim$5.

- No evidence for orbital modulation
- Unable to test for pulsations
  - Pulsars are among the very few non-variable Fermi sources

Also seen in: XSS J12270

# Key features



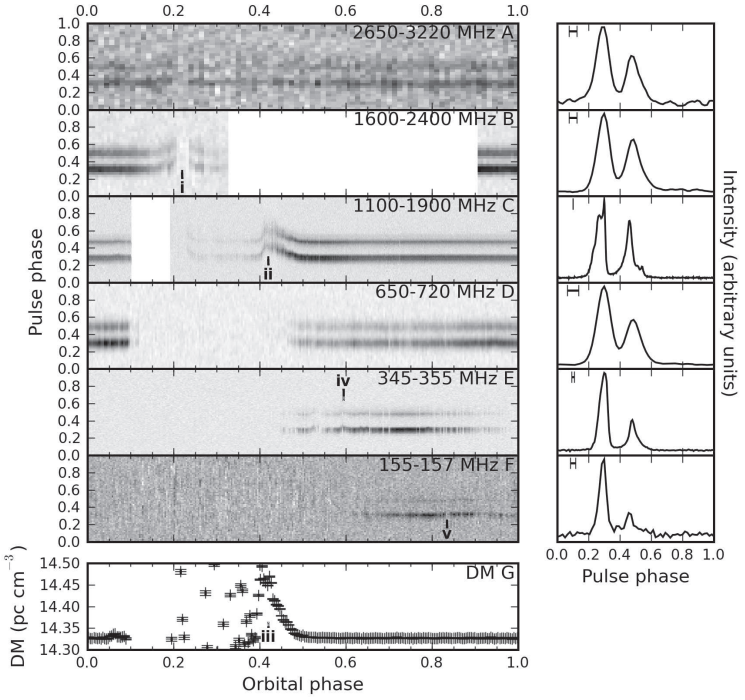

In MSP state:

- Radio eclipsing
- Orbital period variations
- Orbitally modulated X-rays
- Irradiated Roche-lobe-filling companion

In accretion-disc state:

- Underluminous in X-rays
- X-ray mode switching
- X-ray pulsations
- Flat-spectrum radio continuum emission
- $\gamma$-ray brightening

# Radio pulsar emission




- Eclipses
  - Variable
  - Longer at lower frequency
  - Occasionally not near 0.25
- Extra DM
  - Usually near eclipse
  - Sometimes at random phases
  - Varies from observation to observation

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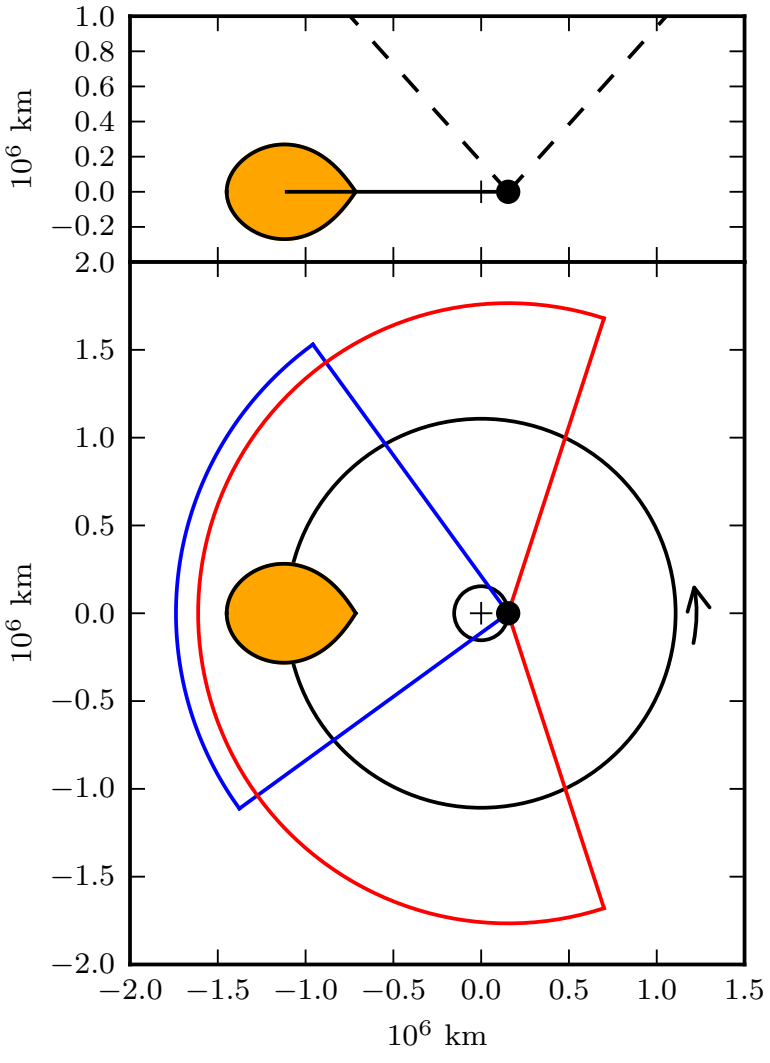


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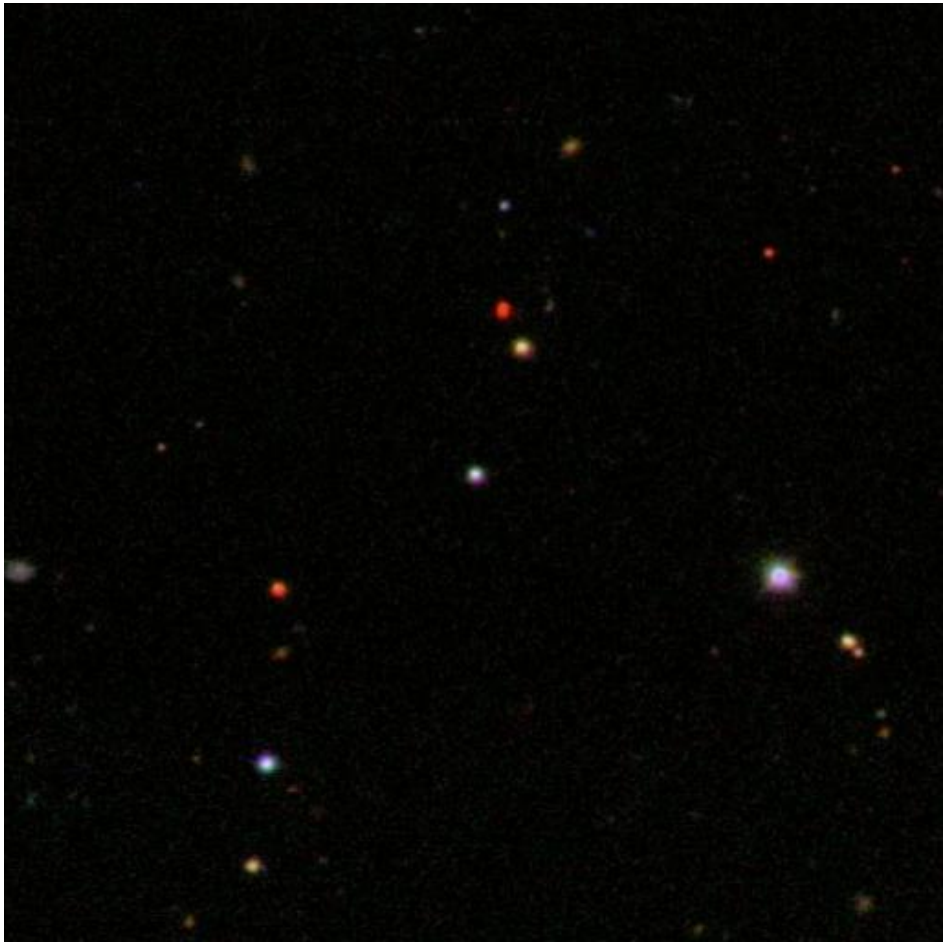
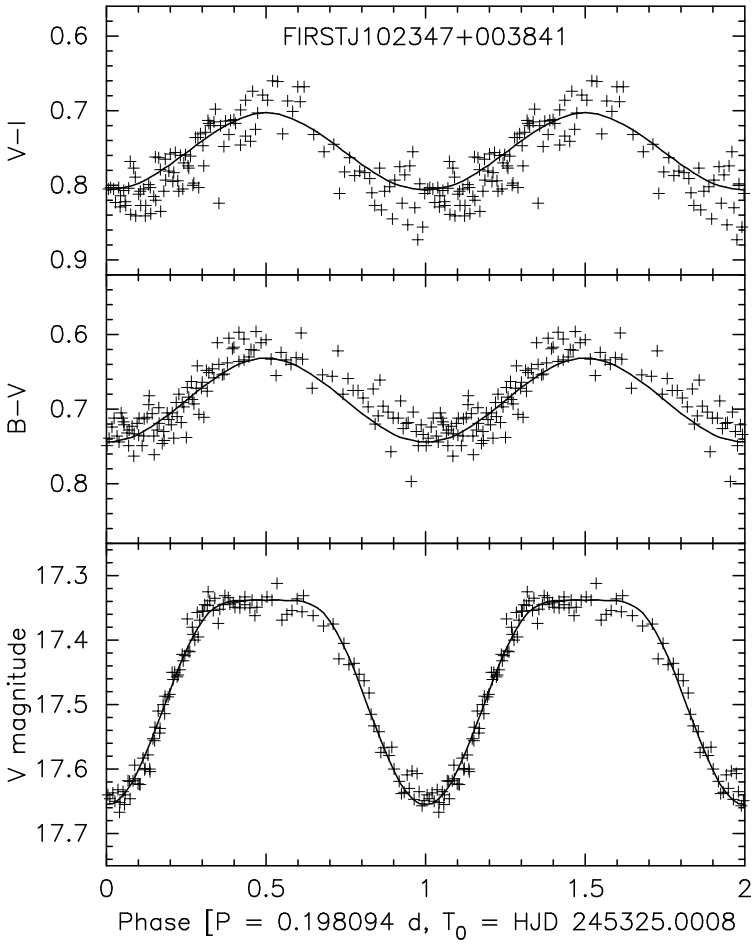


SDSS cutout

The companion is unusual:

- 1.8 times the radius expected given the mass
- Possibly hydrogen-stripped/helium-enhanced
- Not even spherical
- May be magnetic

# Companion irradiation




Multicolour light curve from Thorstensen and Armstrong 2005

Thorstensen and Armstrong (2005) modelled the companion:

- Companion average temperature 5700 K
- Near side hotter by 400 K
- Well-fit by model with $2L_{\odot}$ isotropic primary