Credit: CSIRO/John Sarkissian

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22 Years of a Pulsar-Be Binary System:
From Parkes to the Heavens (Fermi)

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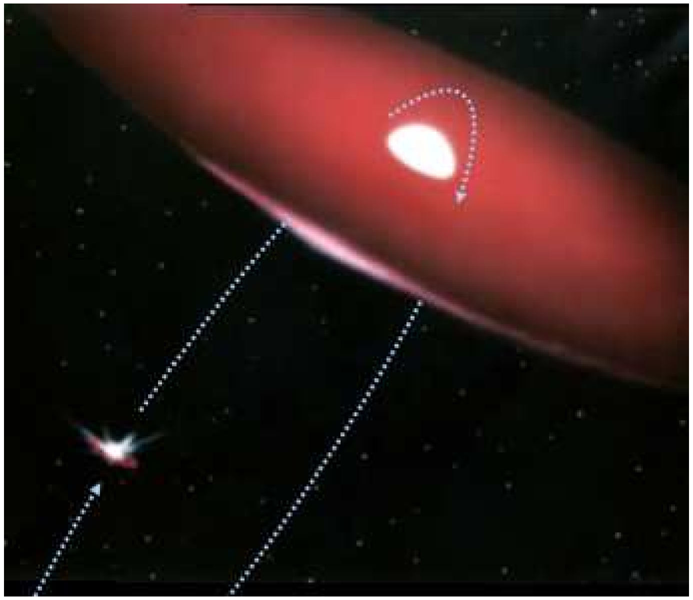
Big Picture and Talk Outline

- **Long term timing:** We have a phase coherent solution showing evidence for coupling between the **spin** of the Be star companion and the **orbit** of the pulsar.

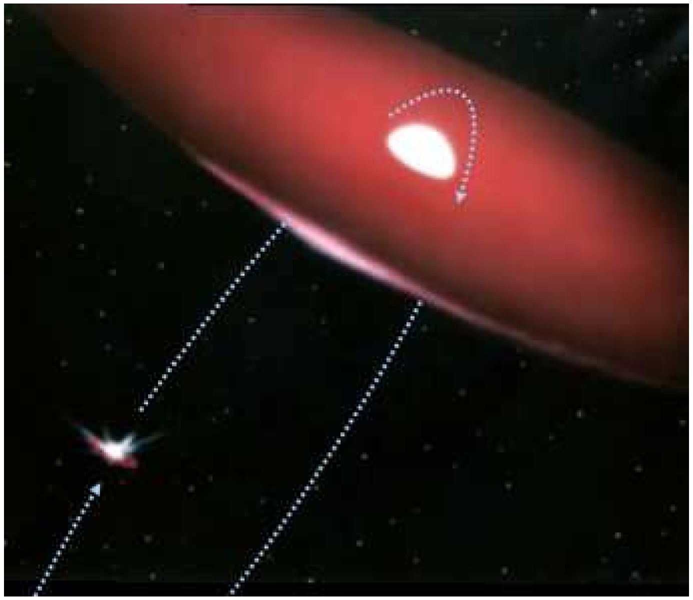
- **Transient emission** close to periastron passage can be used to probe the interactions between pulsar wind and Be-star wind.



Credit: NASA/JPL

The odd couple

- Young (48 ms) pulsar
  - Discovered in 1400 MHz survey of Galactic plane (Johnston, Manchester et al.)
  - ~ 2.5 kpc distant
- Be star companion (SS 2883)
  - Rapidly rotating
  - Be star produces disk and stellar wind
- Very eccentric orbit
  - Distance between PSR and Be star: 0.7 AU to 70 AU
- Pulsar eclipsed close to periastron passage
  - Normal pulsar emission disappears for 30 days
  - Other types of emission appear (second part of talk)



HESS/ MPIfK

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Origins of the system

- Two massive stars “P”, and “C” ($M_P > M_C$)
- P commences post-main sequence evolution
- Mass transfer from P to C
  - Spins up C
  - C becomes the Be companion
- P goes supernova, becoming the pulsar
  - Combination of mass loss asymmetric explosion causes eccentric orbit

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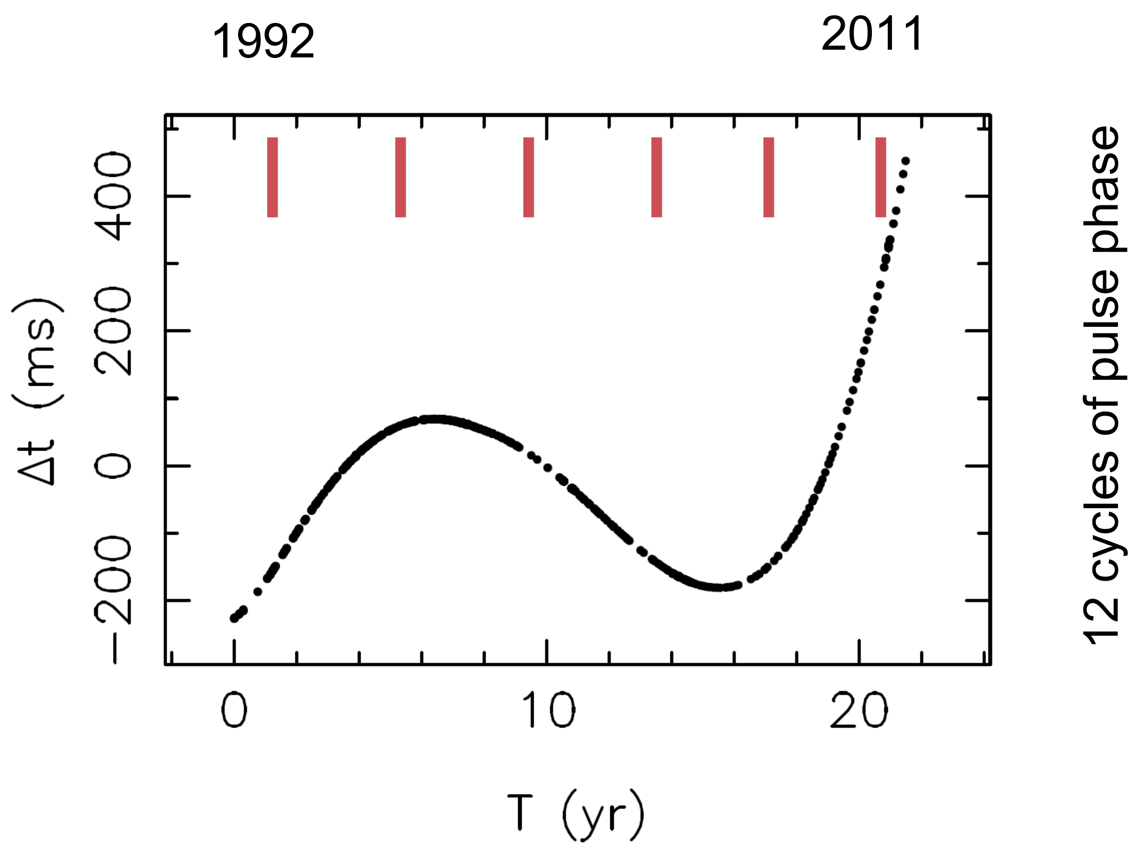
Time of Arrival Analysis

- Pulsar has been regularly observed at Parkes since its discovery in 1992
- Observations cover six periastron passages
- Issues in producing and analysing timing solution
  - Pulsar shows large levels of timing noise
  - One glitch, occurring close to one of the eclipses
  - Correct for DM variations pulse shape distortions close to periastron passage.
- No missing cycles of phase through eclipse



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Spin orbit coupling

Pre-fit TOA perturbations

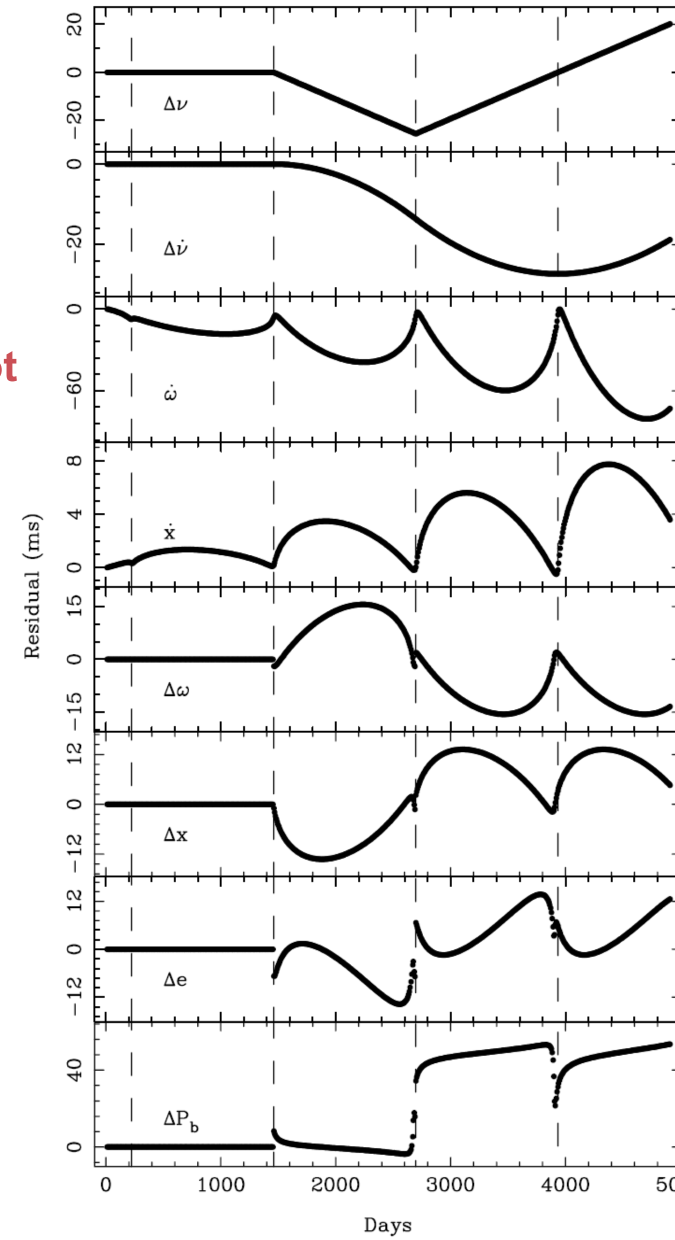
- Expect transfer of angular momentum between **orbit (L)** and **spin (S)** of the oblate B star companion

- Level of coupling
  - Measure the alignment of **S** and L (Geometry of the system)
  - Measure quadrupole moment of the Be star

- Consequences of S-L coupling
  - Graduate change in longitude of periastron passage (omegadot)
  - Change in inclination of orbit, manifested as a change in projected semimajor axis of orbit (xdot)

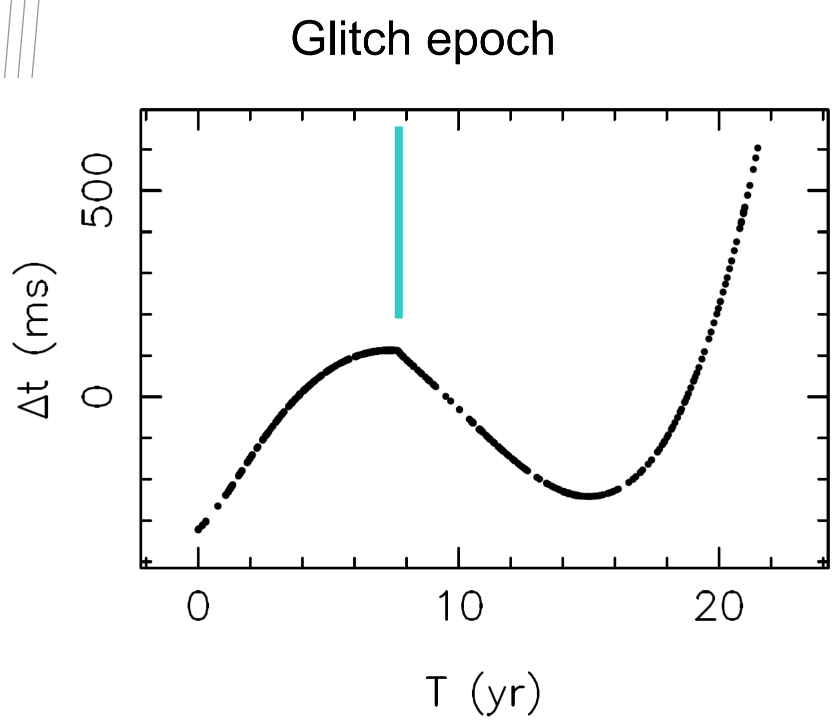
omegadot

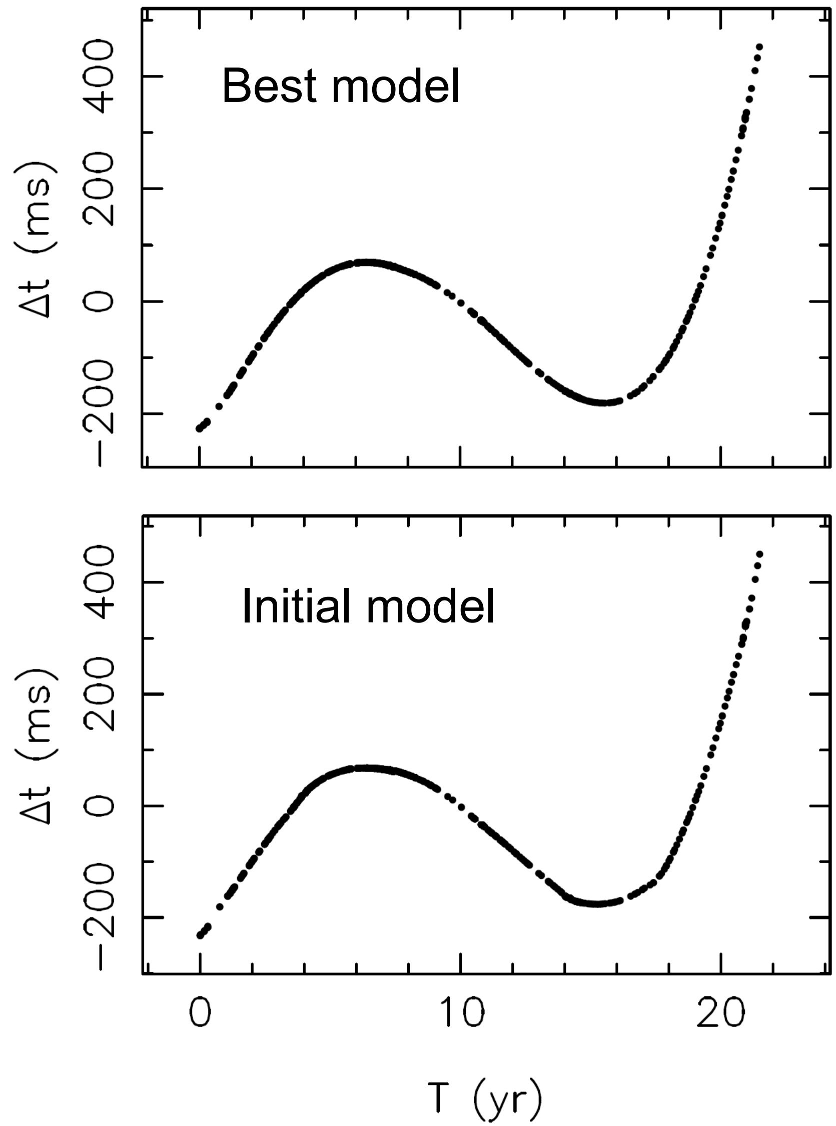
xdot



Wang et al 2004

First comparison of timing solutions

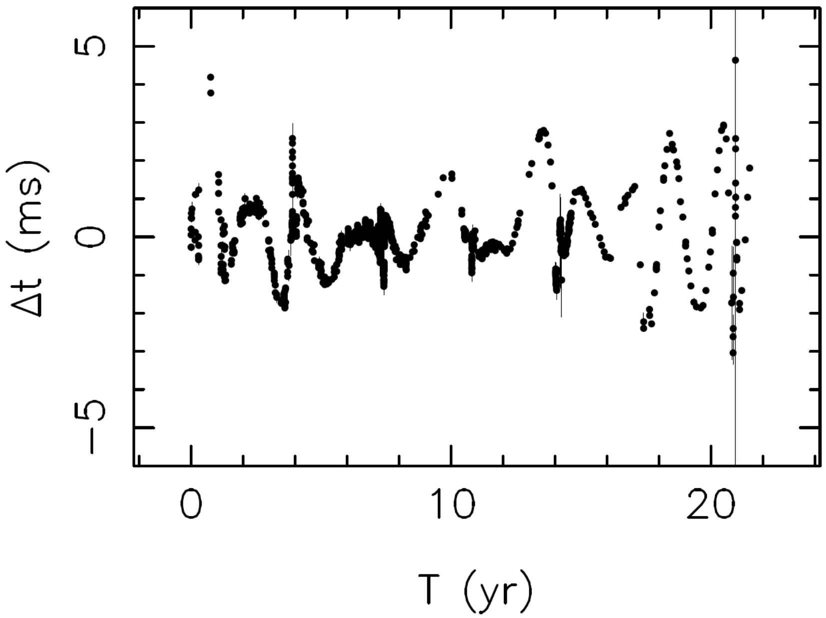




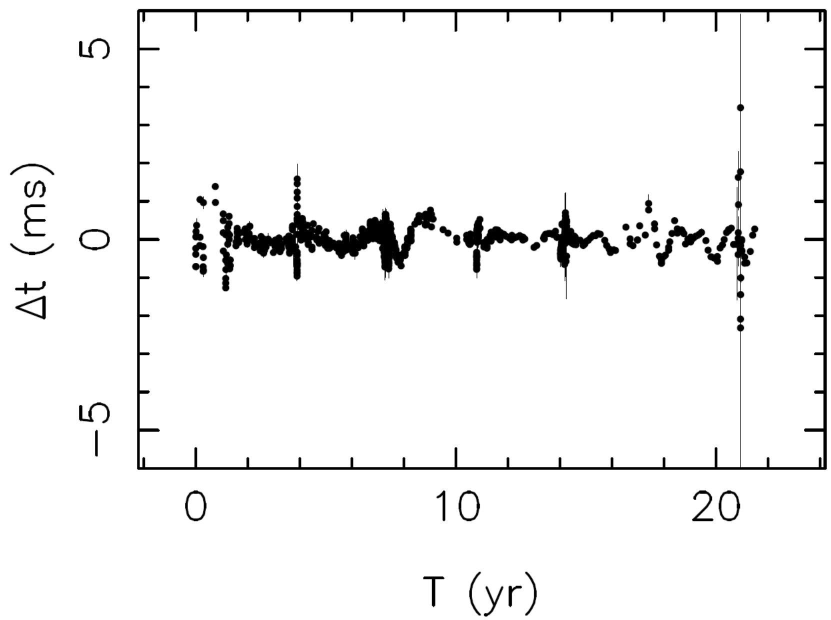
Evidence for secular variations in Orbital parameters

- Previous studies: couldn’t distinguish between different classes of variations (best solution had discrete changes in x at periastron passages, Wang et al 2004).
    - Fewer orbits + glitch?
- Revised analysis: Use “harmonic whitening” method for modeling timing noise.
- Significant improvement to residuals when xdot and omegadot are included.

No evolution



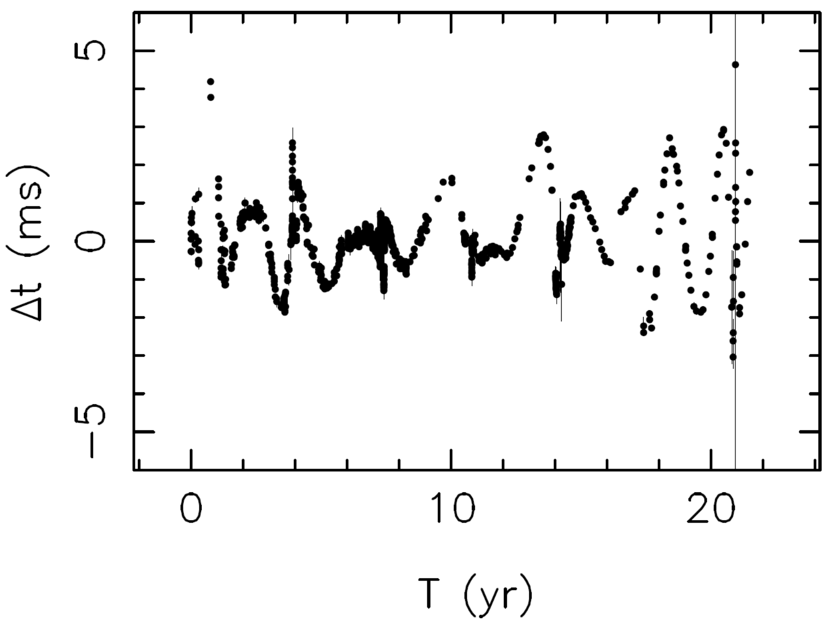
Best solution: (xdot, omegadot)



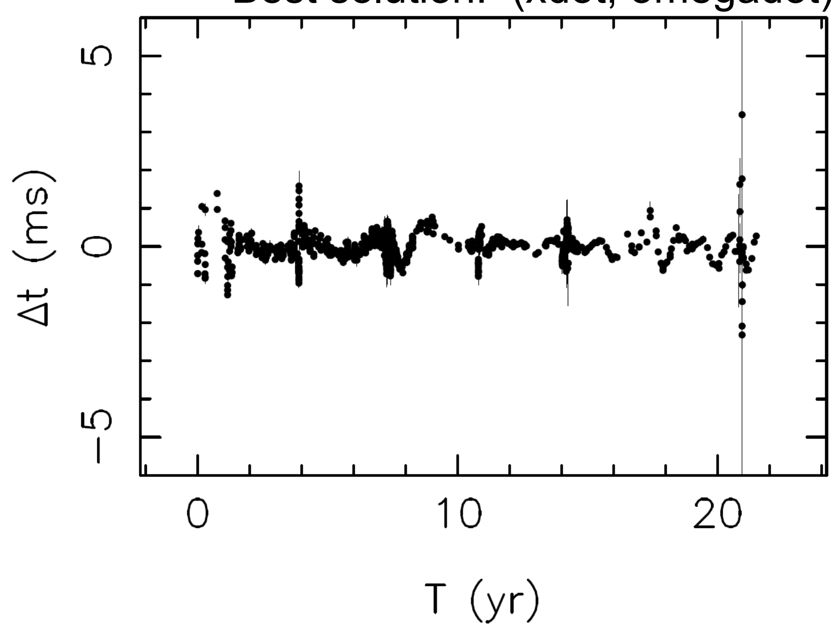
Implications: Secular changes in orbital parameters

- Use Wex (1998) model for orbital evolution
- Measure significant, xdot, omegadot, but not Pbdot
  - omegadot (6.84±0.09) x 10^{-5} deg/yr
    - (GR contribution to omegadot: 3 x 10^{-5} deg/yr)
  - xdot (1.76±0.09) x 10^{-11}

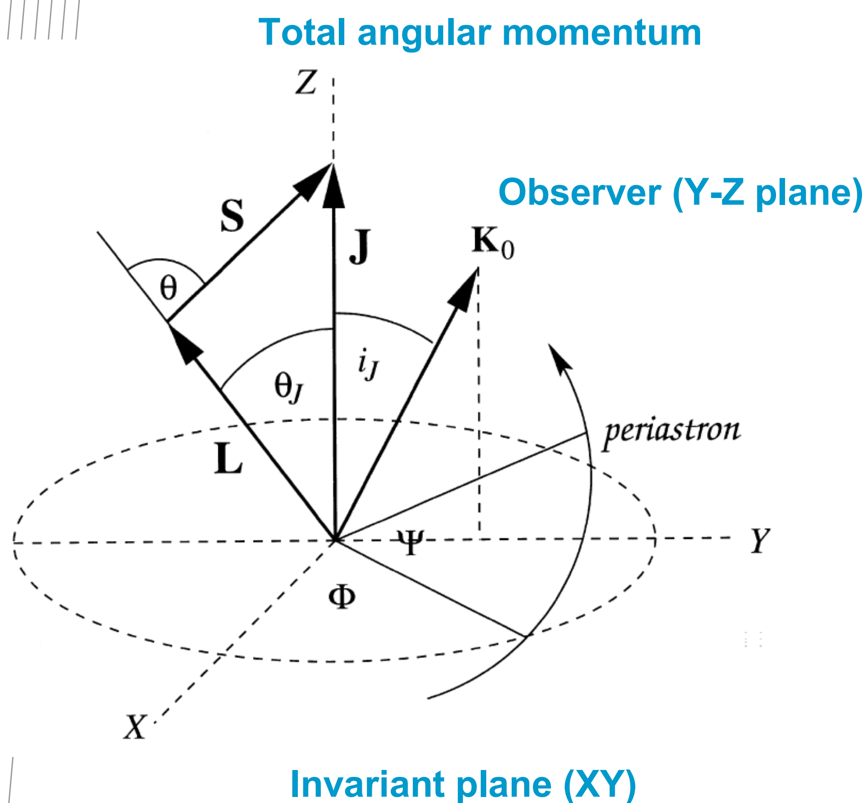
No secular evolution



Best solution: (xdot, omegadot)



Implications: Secular changes in orbital parameters



Use the Wex (1998) model for secular changes.

Recent optical observations of companion Negueruela et al. (2011)

-Reclassified as O9.5 Ve
-Increased Mass to 30 M_{sun}
-Revised inclination of orbit w.r.t. line of sight. i ~ 25^o.

Can radio timing observations be used to verify this re-classification?

Constraint on system geometry

$$\frac{\dot{\omega}_Q x}{\dot{x}_Q} \sin\Phi - \cos\Phi = \frac{1 + 3\cos 2\theta}{2\cot i \sin 2\theta}$$

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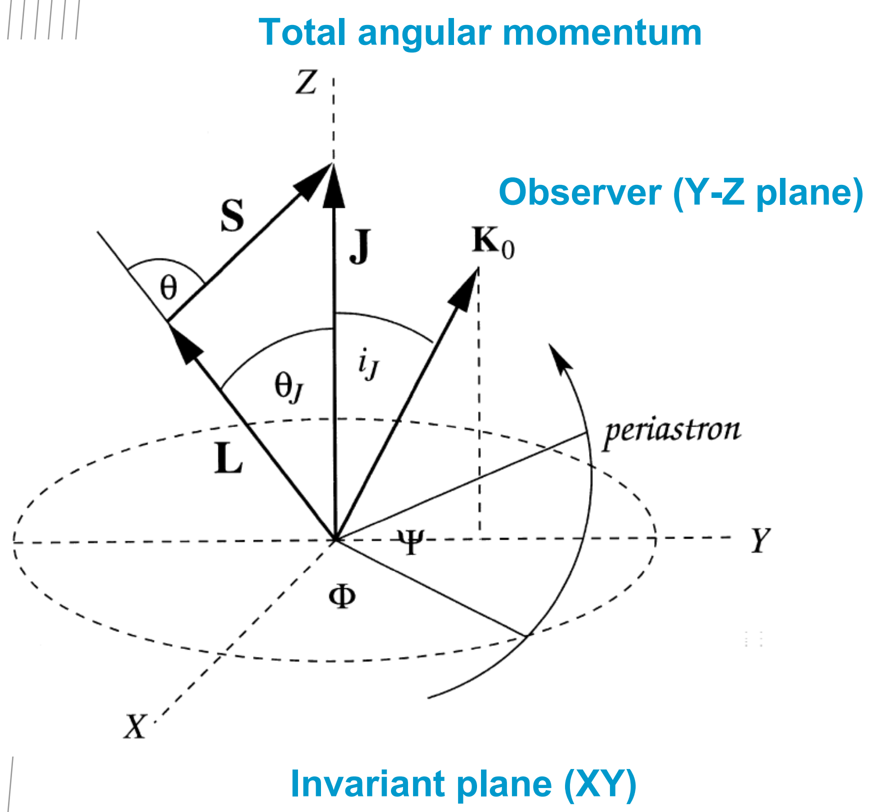
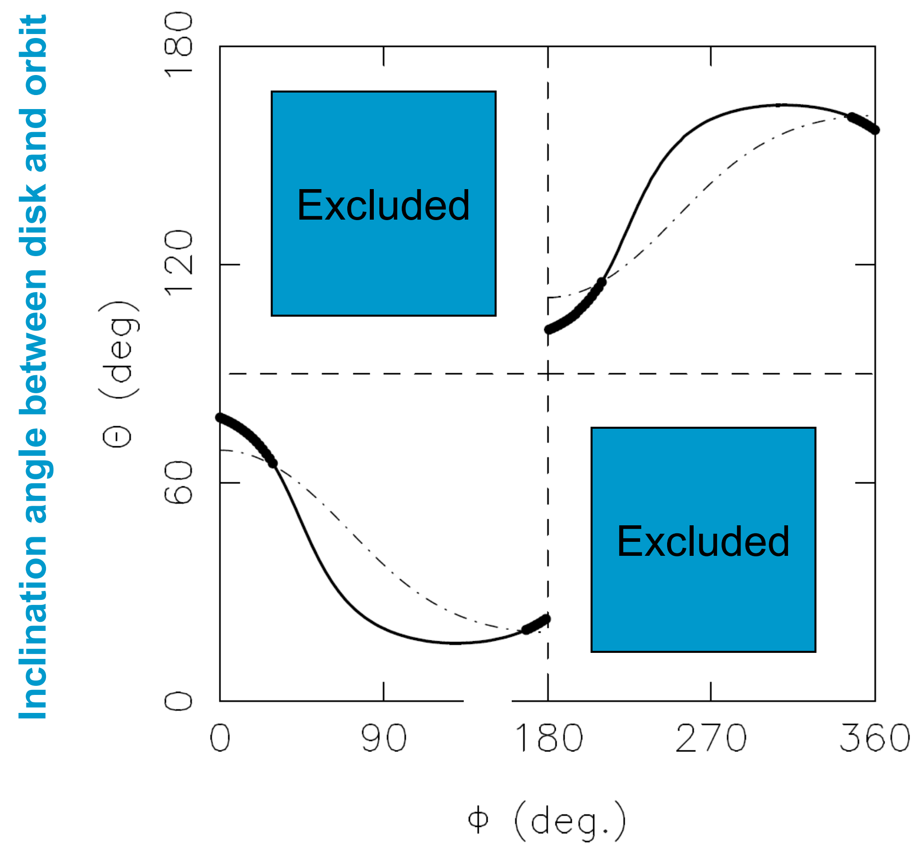
Implications: Secular changes in orbital parameters





Longitude of ascending node with respect to invariant plane

$$\frac{\dot{\omega}_Q x}{\dot{x}_Q}\sin\Phi - \cos\Phi = \frac{1+3\cos 2\theta}{2\cot i \sin 2\theta}$$

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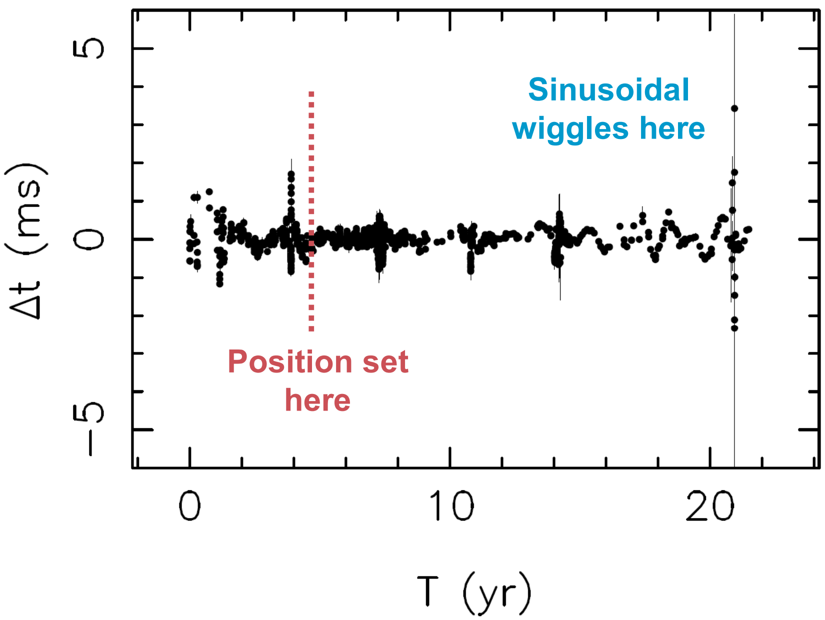
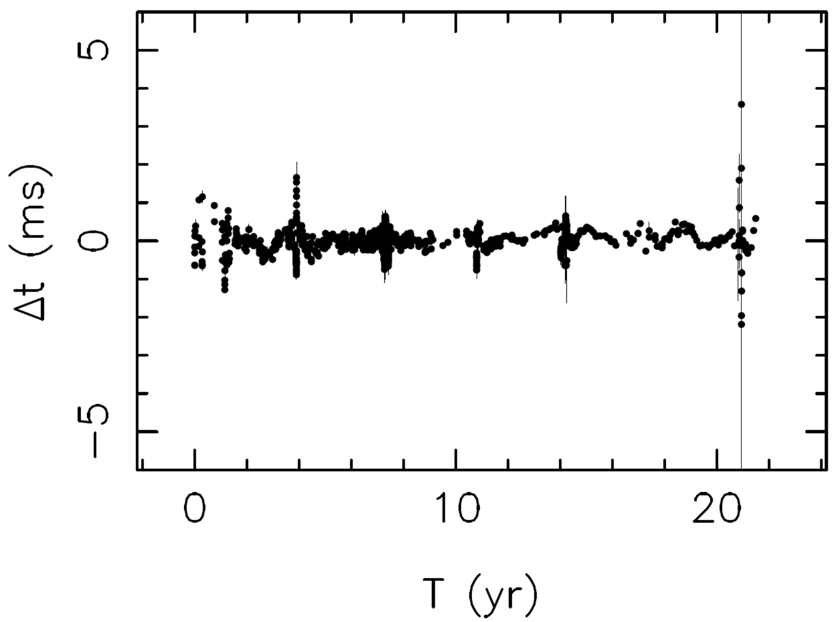
Evidence for System Proper Motion

- Method: Use additional (higher frequency) sinusoids to model timing noise

- Significant proper motion
  - PM_{α}: -12±2 mas/yr
  - $PM_{\delta:}$ -7±2 mas/yr
  - Consistent with Hipparcos constraints for LS 2883 $|PM_{\alpha}|$, $|PM_{\delta}|$ < 22 mas/yr





Evidence for System Proper Motion

- Method: model timing noise down to 1.5 year period (can't use solution to model orbital variations).

- Significant proper motion
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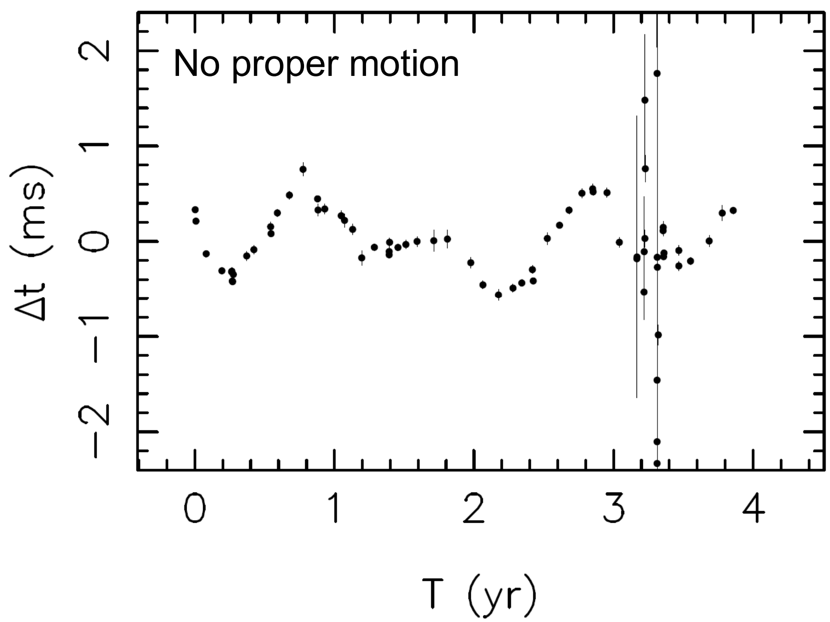
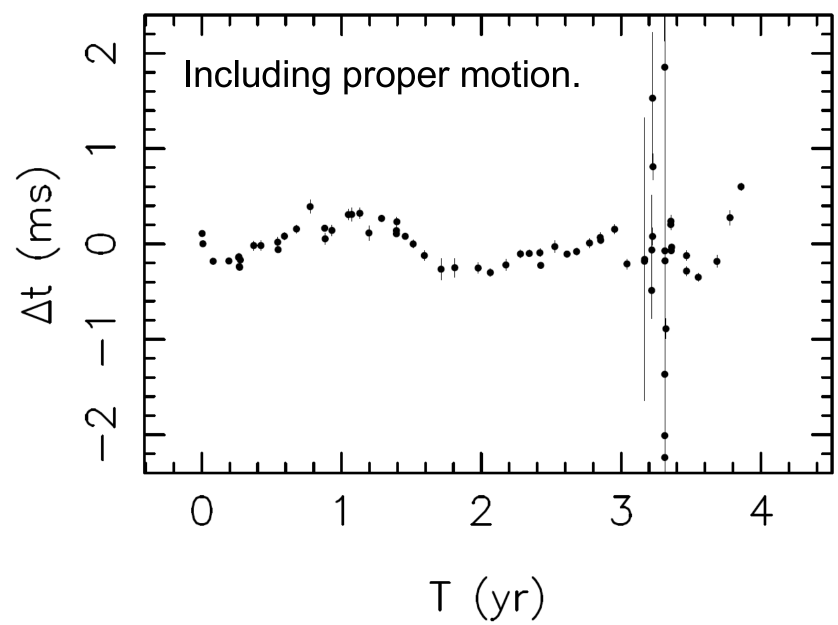
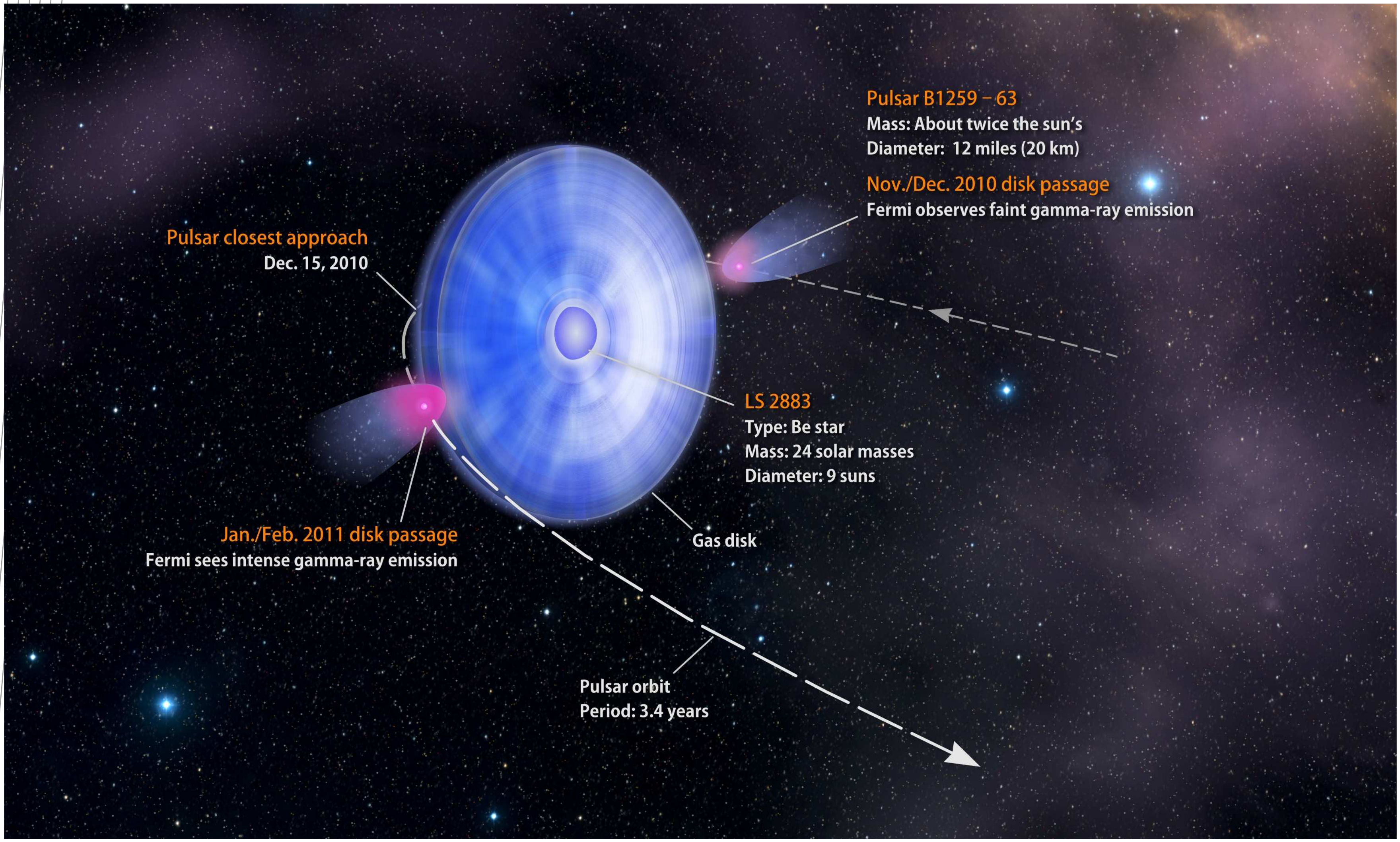




Implications of Proper Motion

- Inferred velocity: ~ 70 km/s (normal-ish for pulsars)
- System origin thought to be in *Cen OB1* association.
  - PM has it moving in correct direction
- Kinematic age: 300 kyr
  - Assuming origin at centre of OB association
- Spin-down age: 330 kyr
  - Proper motion measurement not out of line

Emission around Periastron Passage



Credit: NASA/GSFC

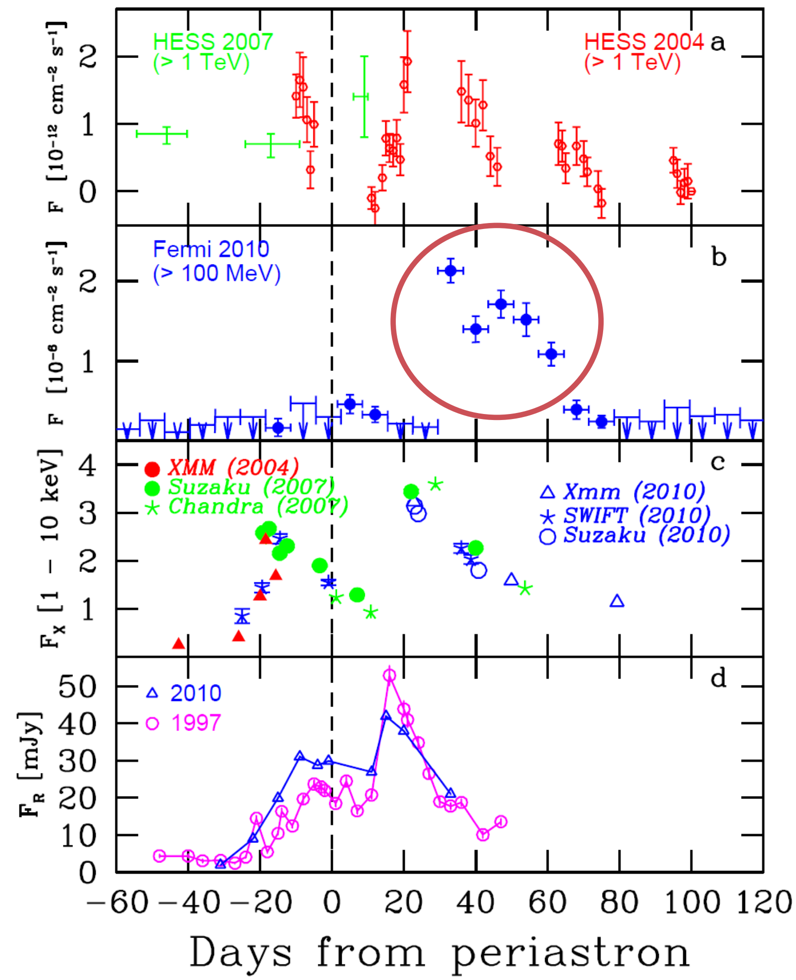
Transient emission close to periastron passage

- Interaction between energetic particles and pulsar wind (e.g., Dubus 2006)

- TeV gamma-rays
  - Inverse Compton scattering of Be star photons

- X-rays and nonpulsed radio emission
  - Synchrotron

- GeV Gamma-rays?
  - Crazy flare!



Abdo et al. (2011)

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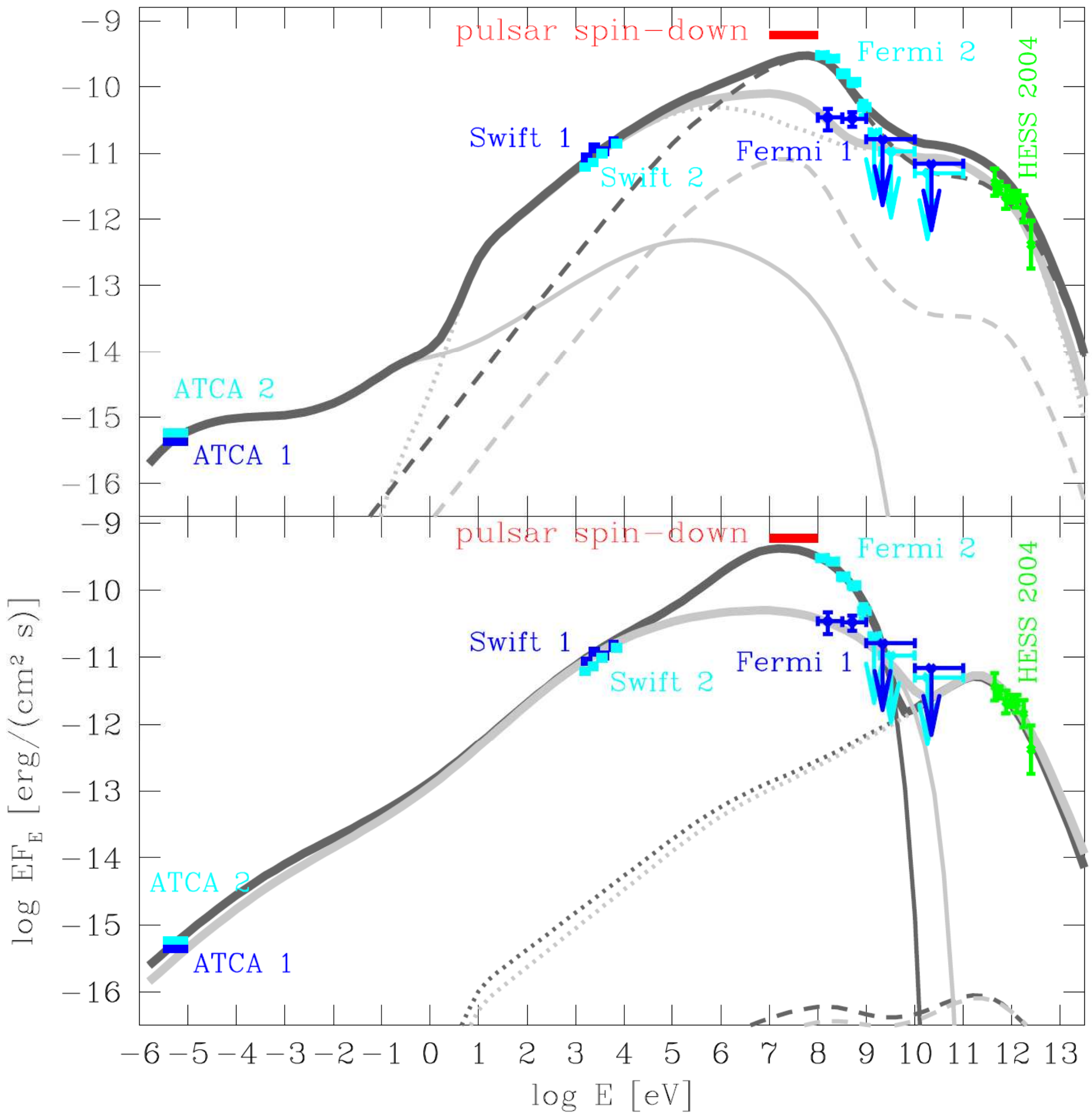
Electromagnetic Spectrum of Flares

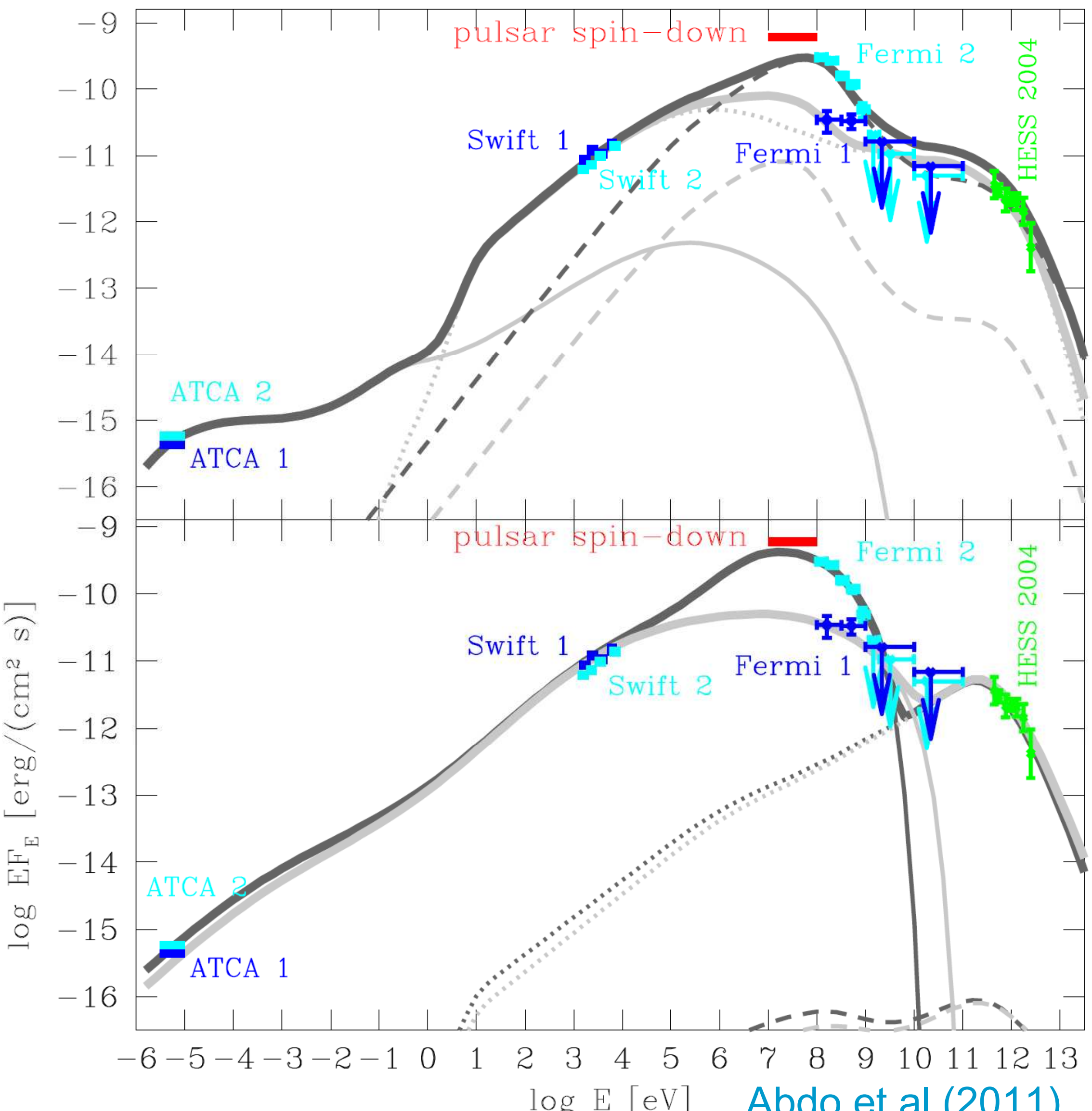
- Interaction between energetic particles and pulsar wind (e.g., Dubus 2006)
- TeV gamma-rays
  - Inverse Compton scattering of Be star photons
- X-rays and nonpulsed radio emission
  - Synchrotron
- GeV Gamma-rays?
  - Crazy flare!



Electromagnetic Spectrum of Flares

Two plausible models for transient emission.

- Top panel: particles escape at the speed of pulsar wind (Chernyakova & Illarionov 1999).
  - Slow escape: cooling of electrons via bremsstrahlung/Coulomb loss mechanisms.
- Bottom panel: Particles escape at c/3. (Tavani & Arons 1997).

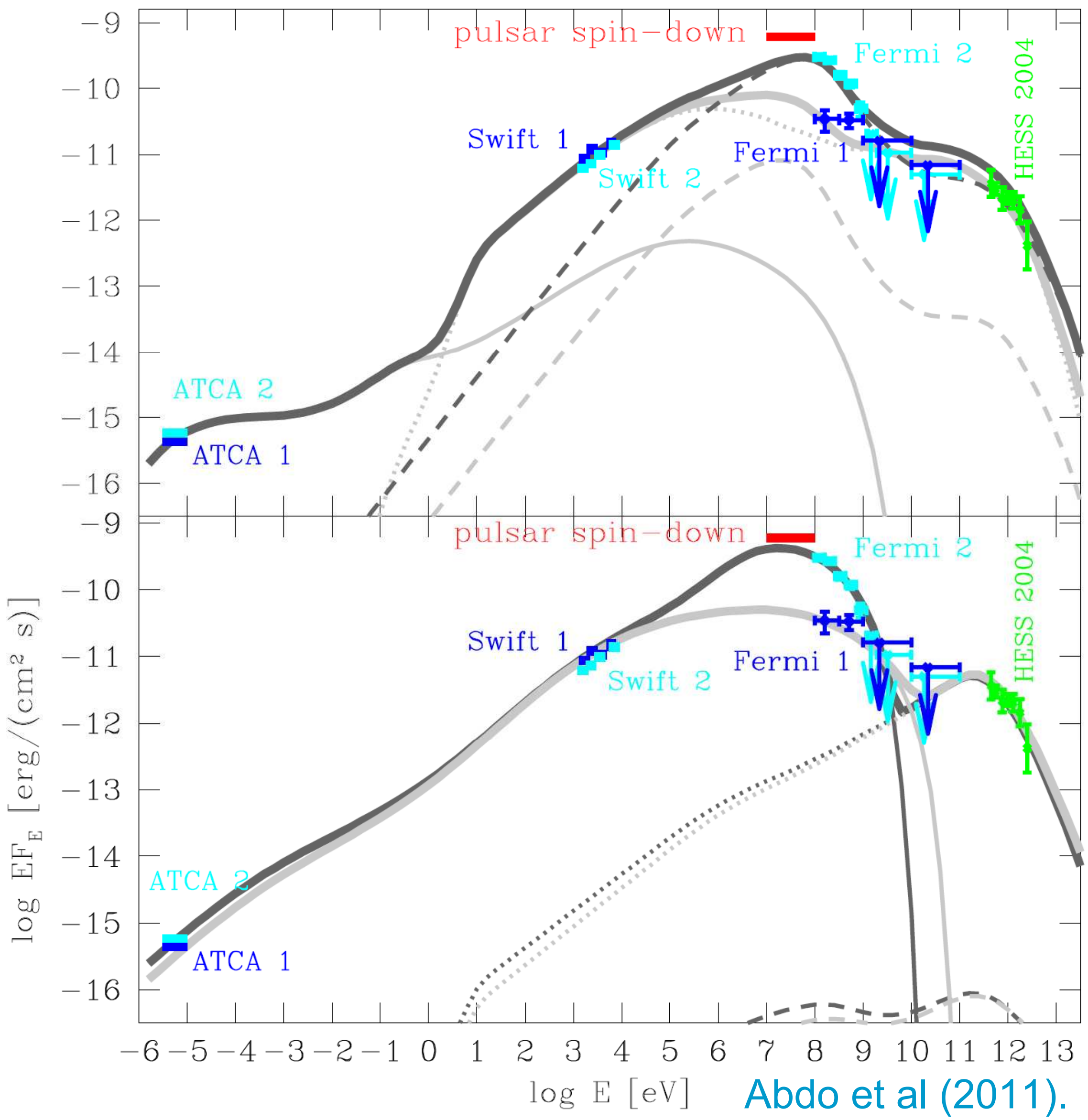


Abdo et al (2011).

Electromagnetic Spectrum of Flares

- Solid: Synchrotron
- Dotted: Inverse Compton (IC)
- Dashed: Bremsstrahlung

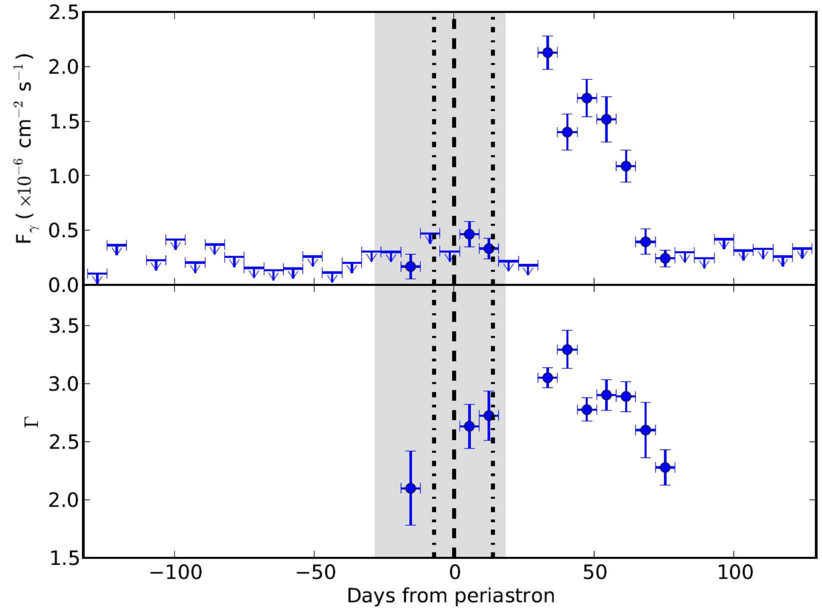
- Dark: Pre-periastron:
- Lighter: Post periastron:



Abdo et al (2011).

Gamma-ray emission from 2010-2011 Passage

- Strong flare observed in Gev energy band with Fermi after pulsar emerged from disk
- **Flare really large:** gamma-ray luminosity comparable to pulsar spin-down luminosity.
  - Spectral index steeper during flare
- Possible mechanisms:
  - Anisotropy of pulsar wind/ stellar wind (need factor of 10 variation).
  - Beaming of radiation: Synchroton cooling time comparable to gyroradius



Abdo et al (2011)

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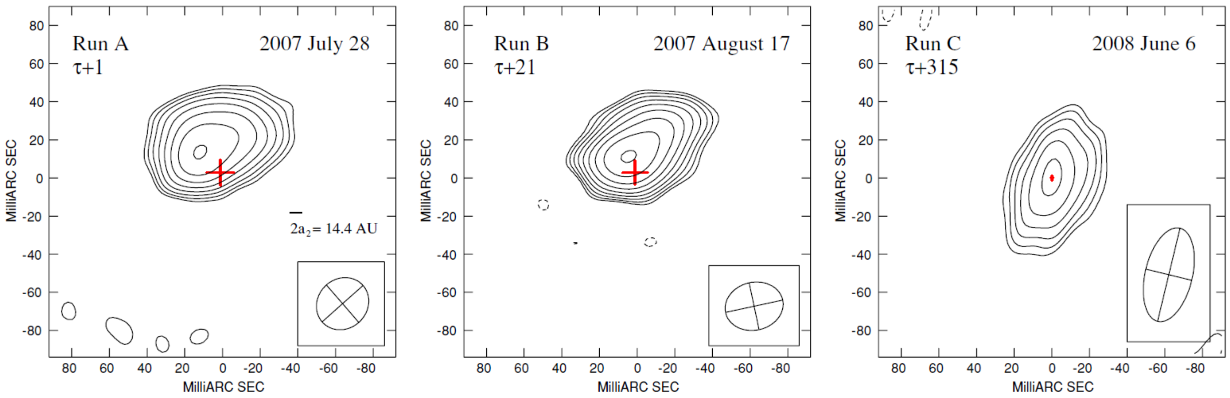
Variability oberved in radio as well



- LBA observations of system during 2007 passage (Moldon et al 2010).
- Transient radio emission offset from pulsar
- Challenging to model with only two epochs.
- LBA observations during 2010 passage currently being processed.

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The future

- Continue monitoring system at Parkes
  - Determine if measured values of xdot, omegadot pass the test
  - Does the proper motion measurement agree with LBA observations?
- Multi-wavelength observations close to periastron passage
  - Full reduction of Jan 2011 multi-wavelength campaign.
  - Another observing campaign mid 2014?
  - Use scintillation/ emission measure properties to probe inhomogeneities in disk/wind (e.g. McClure Griffiths et al. 1996)

Conclusions

- Long term monitoring of the system at Parkes has enable the first convincing detection of S-L coupling in the system.

- Phase coherent timing solution
    - Evidence for spin orbit coupling
    - Evidence for proper motion

- Surprising gamma-ray flare post Jan 2011 periastron passage

- Happy Birthday, Parkes, from B1259-63 (and Ryan)!

Extra slides