Learning about neutron stars from pulsar precession observations

NewCompStar, Istanbul, 2016

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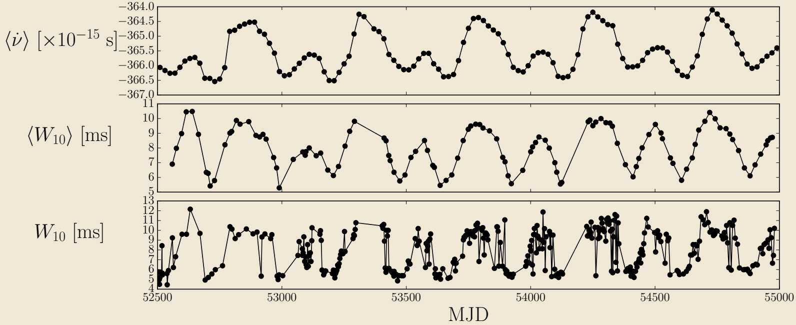
PSR B1828-11: spin-down and beam-width



Data courtesy of Lyne at al. (2010): *Switched Magnetospheric Regulation of Pulsar Spin-Down*

Potential explanations:

- **Precession**: conflict with vortex-pinning of superfluid core
- **Magnetospheric switching**

We would like to quantify how well the two models fit the data. To do this we will use Bayes theorem:

$$P(\mathcal{M}|\mathbf{y}_{\text{obs}}) = P(\mathbf{y}_{\text{obs}}|\mathcal{M})\frac{P(\mathcal{M})}{P(\mathbf{y}_{\text{obs}})}.$$

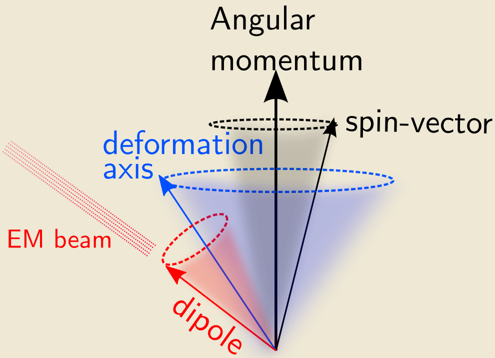
The odds ratio:

$$\mathcal{O} = \frac{P(\mathcal{M}_A|\mathbf{y}_{\text{obs}})}{P(\mathcal{M}_B|\mathbf{y}_{\text{obs}})} = \frac{P(\mathbf{y}_{\text{obs}}|\mathcal{M}_A)}{P(\mathbf{y}_{\text{obs}}|\mathcal{M}_B)} \underbrace{\frac{P(\mathcal{M}_A)}{P(\mathcal{M}_B)}}_{=1}$$

Calculate the *marginal-likelihood* $P(\mathbf{y}_{\text{obs}}|\mathcal{M}_A)$ using Markov chain Monte-Carlo method.

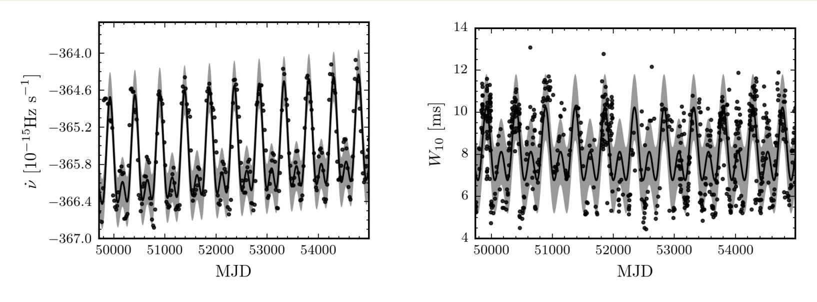
Define the model: precession

- Precession is a geometric effect in non-spherical bodies where the spin-vector is misaligned from the angular momentum
- It will produce periodic modulations of:
  - the beam width
  - the spin-down rate
- Complicated interaction with the EM torque can amplify the spin-down modulations



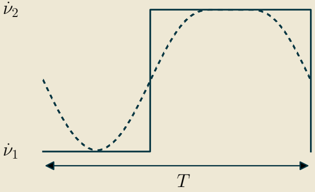
See for example: *Jones & Andersson (2001), Link & Epstein (2001), Akgun et al. (2006) Zanazzi & Lai (2015), Arzamasskiy et al. (2015)*

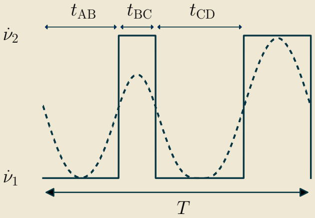
Fitting the model: precession



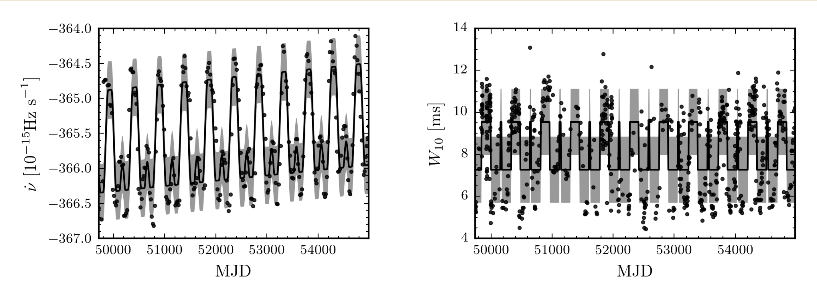
Define the model: switching

- Lyne et al. (2010): the magnetosphere undergoes periodic switching between two states
- The smooth modulation in the spin-down is due to time-averaging of this underlying spin-down model
- To explain the *double-peak*, Perera (2015) suggested four times were required





Fitting the model: switching



Results of precession vs switching

- Results published in *arXiv:1510.03579* with a conclusion

$$\frac{P(\text{precession}|\text{data})}{P(\text{switching}|\text{data})} = 10^{2.7\pm0.5},$$

  favouring the precession interpretation

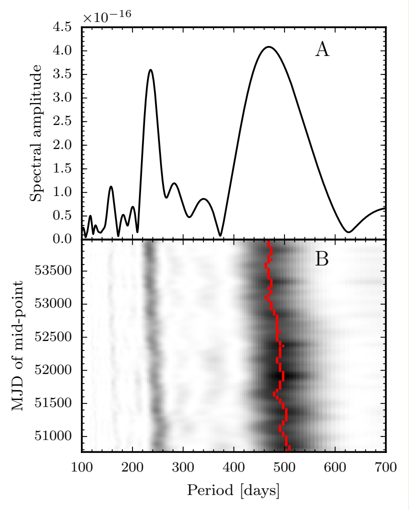
- This odds-ratio is for *simple* models with unbiased priors

- Questions for the precession model:
  - Connection with the pinning of the superfluid core
  - Presence of a glitch just after our data ends

- We can extend the models. . .

Evidence for changing modulation period

- We noticed different sections of data gave different modulation periods
- Studied with a *Lomb-Scargle* periodogram
- Finds the expected two peaks
- Precession period decays from 503 to 467 days over a period of 3211 days



Extending the precession model

- Modulation period in the precession model is given by

$$\tau_{\mathrm{p}} = \left|\frac{P}{\epsilon}\right| \cos\theta$$

- Can rule out variation in P due to spin-down: not large enough and makes the precession period longer not shorter
- Can rule out variation in θ as there is no corresponding change in the amplitude of modulations

Secular evolution of $\epsilon(t)$

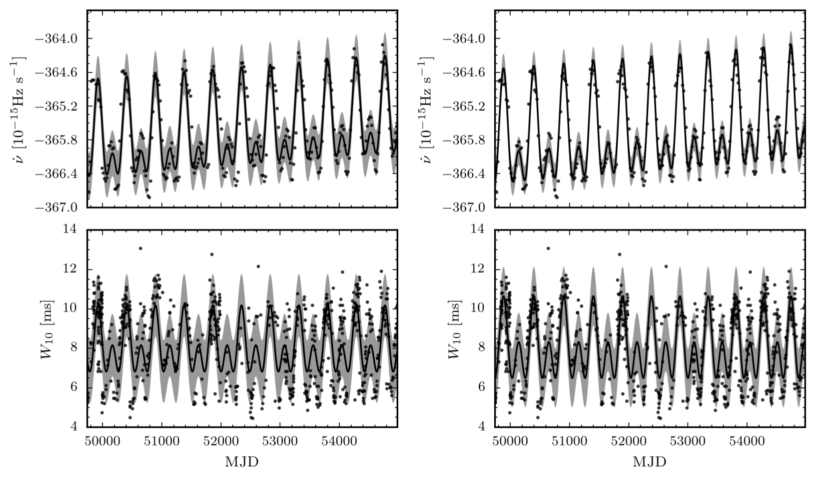
$$\epsilon(t) = \epsilon_0 + \dot{\epsilon} t$$

Discreet jumps in $\epsilon(t)$

$$\epsilon(t) = \epsilon_0 \left(1 + \sum_{j}^{N} H(t, t_j)\Delta_j\right)$$

Secular evolution of $\epsilon(t)$

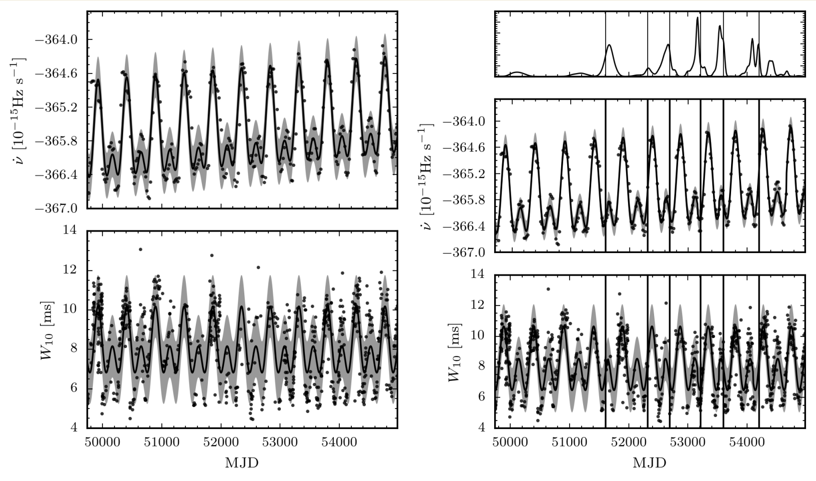
Basic precession | **Secular evolution**



$$\frac{P(\text{secular evolution of } \epsilon(t)|\text{data})}{P(\text{basic precession}|\text{data})} = 10^{74.55\pm0.8}$$

Discreet jumps in $\epsilon(t)$

Basic precessing **N=6 discreet jumps**



$$\frac{P(\text{6 discreet jumps in } \epsilon(t)|\text{data})}{P(\text{basic precession}|\text{data})} = 10^{74.57\pm1.1}$$

Comparing models for $\epsilon(t)$

- Discreet jumps have a 'preference' for the point in the precessional phase with which they occur: rules out external models.
- Fractional size of the jumps is $\sim 10^{-2}$
- The odds-ratio between these models is

$$\frac{P(\text{secular evolution of } \epsilon(t) \,|\text{data})}{P(\text{6 discreet jumps in } \epsilon(t) \,|\text{data})} \approx 1$$

Secular evolution of $\epsilon(t)$

We need a physical model to explain why ϵ changes on a timescale of 200 yrs.

- **Accretion**: from back of the envelope calculation would require $\dot{M} \approx 10^{-11}\ \mathrm{M}_\odot/\mathrm{yr}$.
- **Evolution of the magnetic field**: requires internal magnetic field to vary on a timescale of ~ 400 yr.
- **Evolution of the pinned superfluid**: requires

$$\frac{I_{\text{Pinned superfluid}}}{I_{\text{total}}} \leq 10^{-8}$$

  and the amount of pinned superfluid to *increase* on a timescale of 200 yrs.

Conclusion

Can rule out some models, but *decreasing* modulation period is difficult to understand in the context of precession.

Conclusions

- We have found strong evidence in support of a increasing modulation frequency in PSR B1828-11
- Under the precession interpretation this corresponds to an increase in the deformation $\epsilon(t)$
- Unclear exactly *how* $\epsilon(t)$ is changing
- New physical ideas needed?