Free precession & magnetic stars

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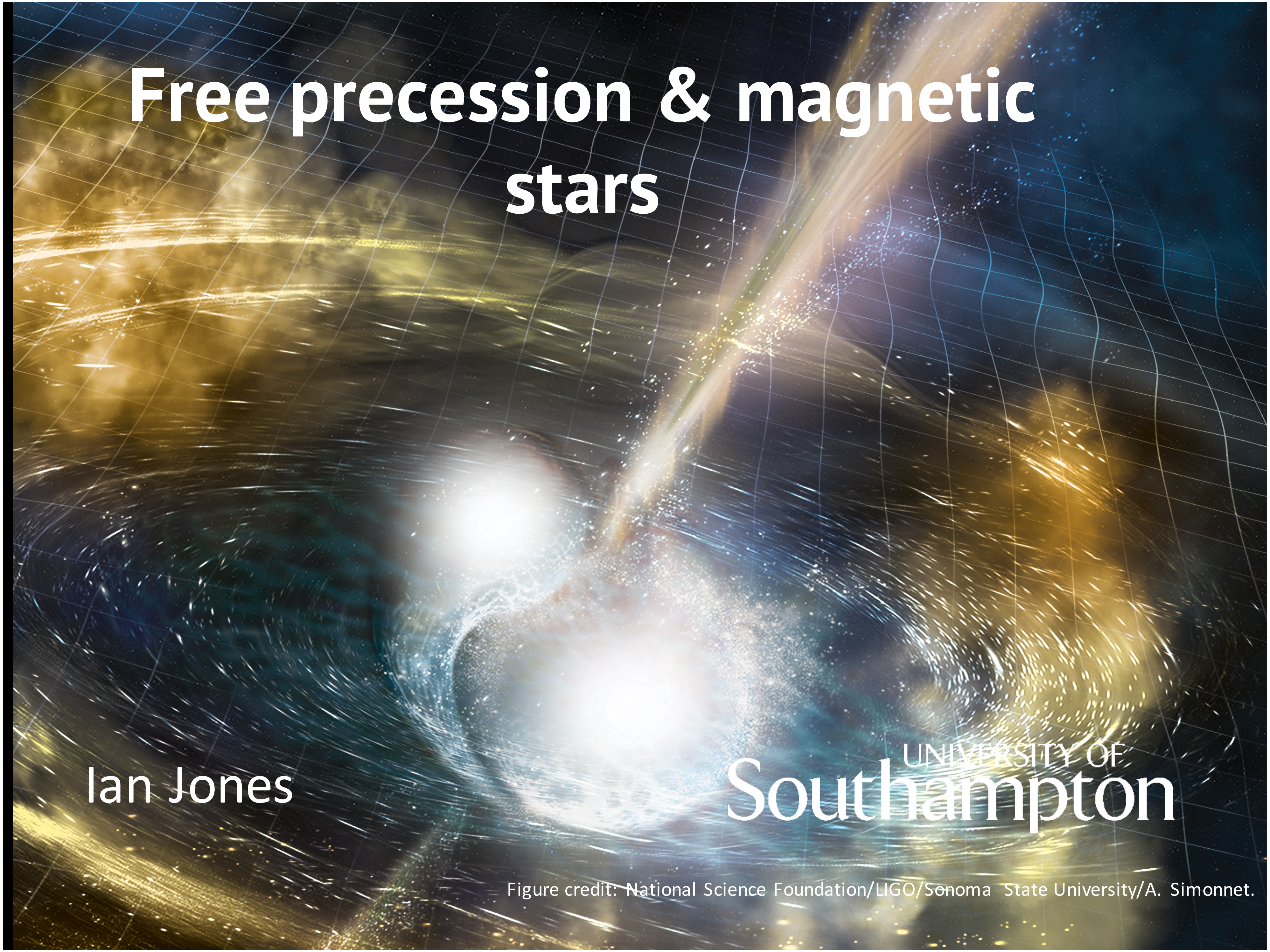
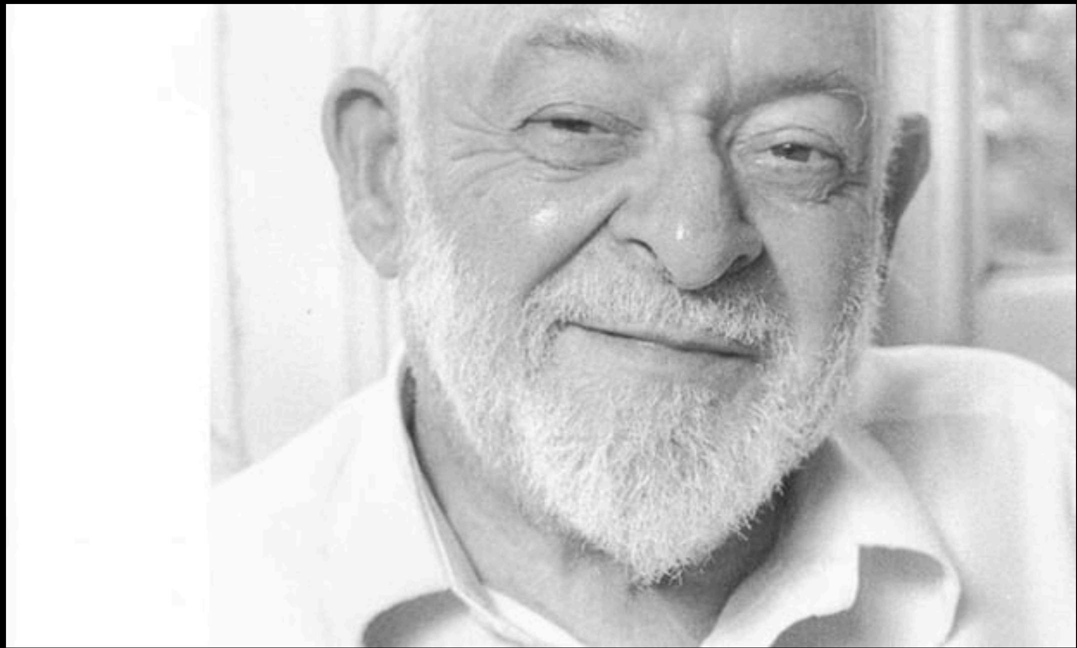
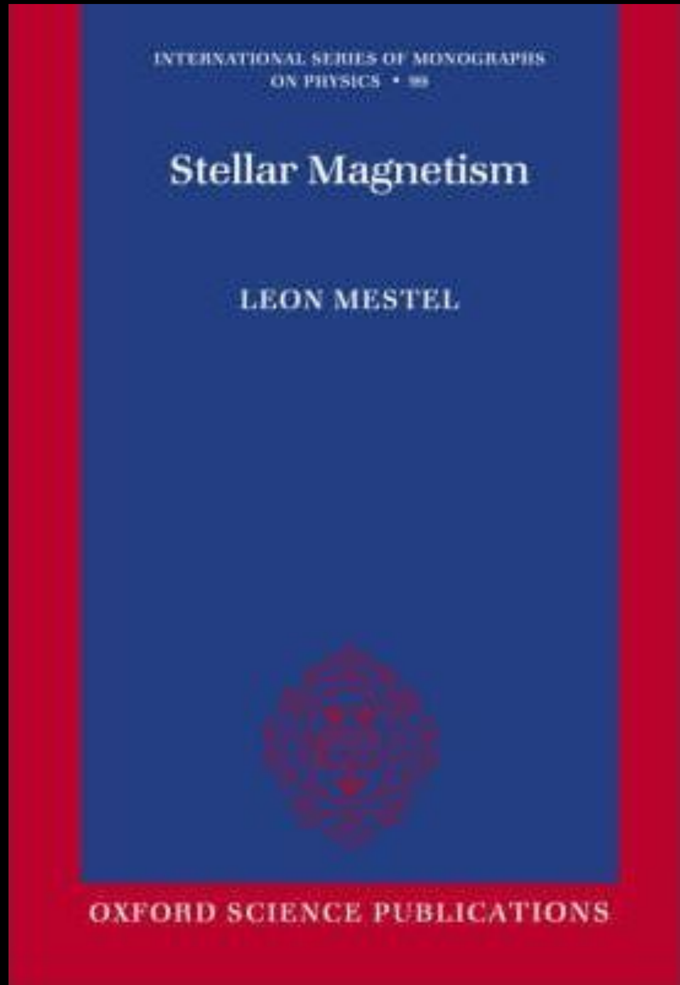


Figure credit: National Science Foundation/LIGO/Sonoma State University/A. Simonnet.

Leon Mestel: 1927 – 2017

Pioneer in the modelling of stellar magnetic fields.





Developed model for precessing *magnetic star.*

Outline

- What is free precession?
- Why is it interesting?
- Does it happen?
- The magnetic precession problem

What is free precession?

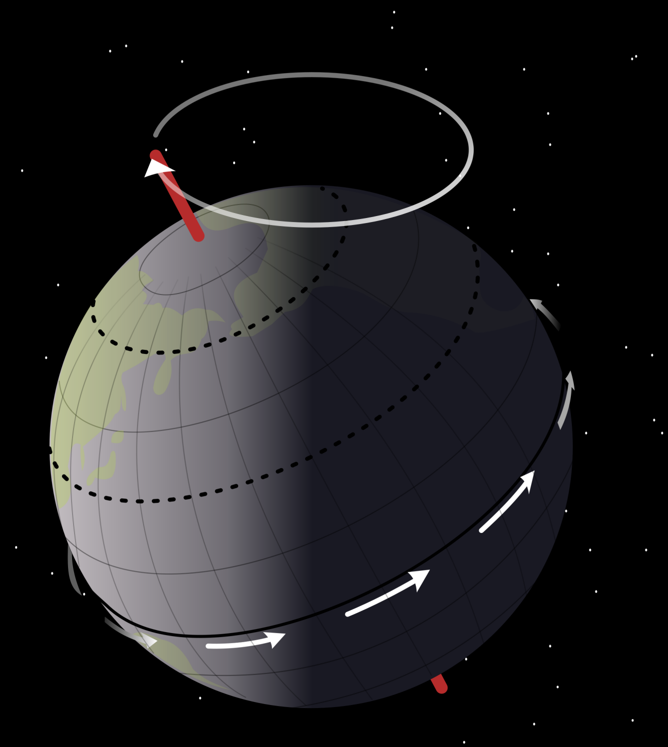
Most general motion of a rigid body.

For biaxial body, motion consists of two superimposed rotations.

Precession period depends upon stellar deformation:

$$\frac{P}{P_{fp}} \sim \frac{\Delta I}{I}$$

Observed for Earth: “Chandler wobble”, $P_{fp} \approx 435$ days.



Why is precession interesting?

1: Constraining stellar structure

For neutron stars, pinned vorticity adds to precession frequency:

$$\frac{P}{P_{fp}} = \frac{\Delta I}{I} + \frac{I_{pin}}{I}$$

ΔI sourced by crustal and/or magnetic strain.

I_{pin} sourced by pinned neutron superfluid.

$\Longrightarrow$ measurement of P_{fp} gives info on stellar structure.

Longevity of excited precession also probes interior.

2: Potential GW source

Precessing biaxial star emits at two harmonics, (f, 2f).

For small wobble angle, lower harmonic dominant:

$$h \sim \frac{1}{r} f^2 \, \Delta I \, \theta$$

Detectability limited not only by finite shear modulus and breaking strain, but also dissipation (DIJ & Andersson 2002).

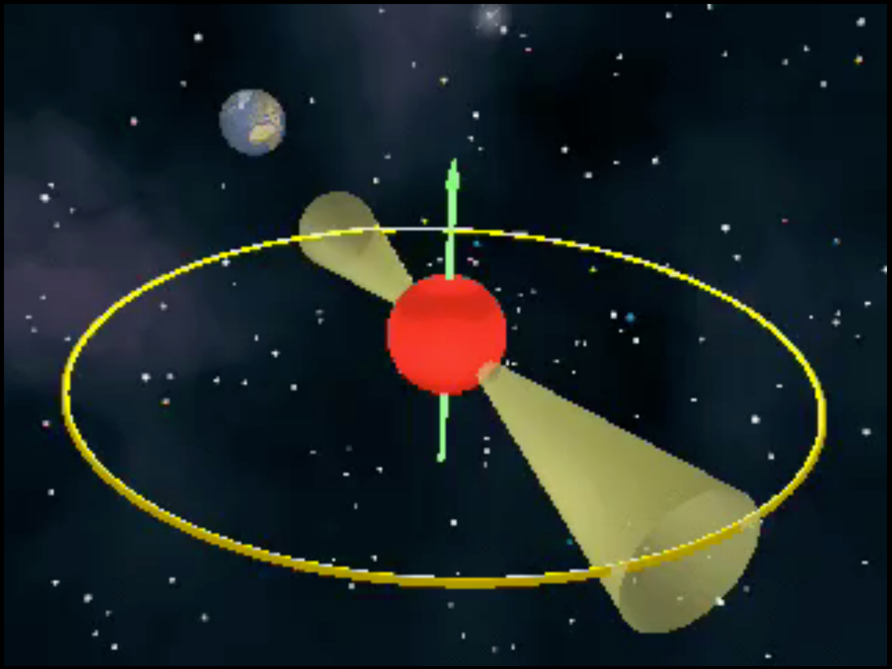
Does free precession occur?

Effect of precession on radio pulsations

Precession will leave imprint on radio data.

Could affect timing, pulse shape and polarization.

Modulations occur on (long) free precession period.



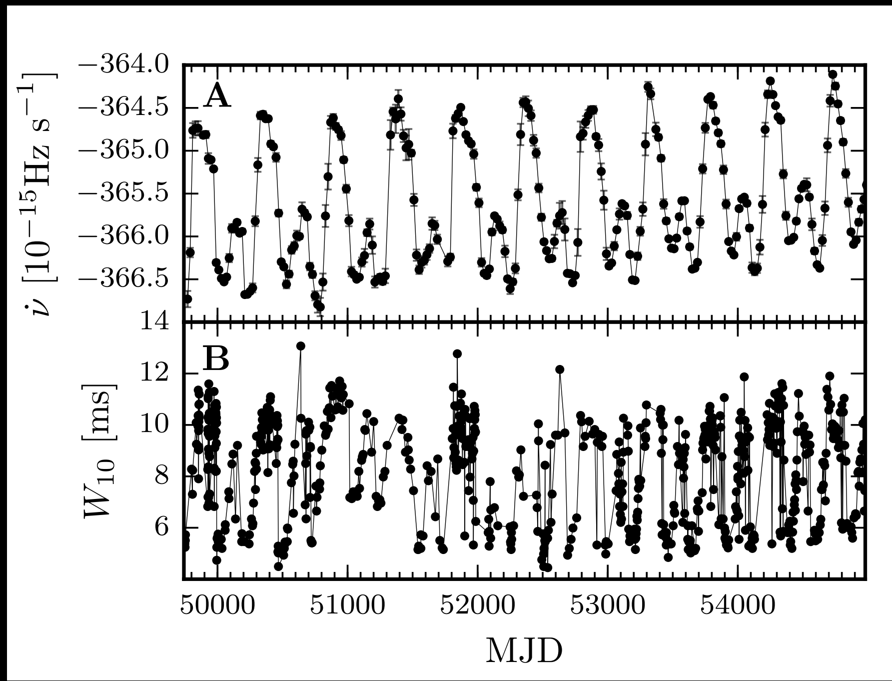
Animation: Jodrell Bank

Pulsar precession?

Quasi-periodicities seen in a handful of pulsars (Lyne+ 2010).

Cleanest candidate B1828-11: correlated timing and pulse shape variations.

Initially interpreted as small angle free precession (Stairs+ ‘00, DIJ & Andersson ‘01, Link & Epstein ‘01)



Data courtesy of Lyne+ (2010)

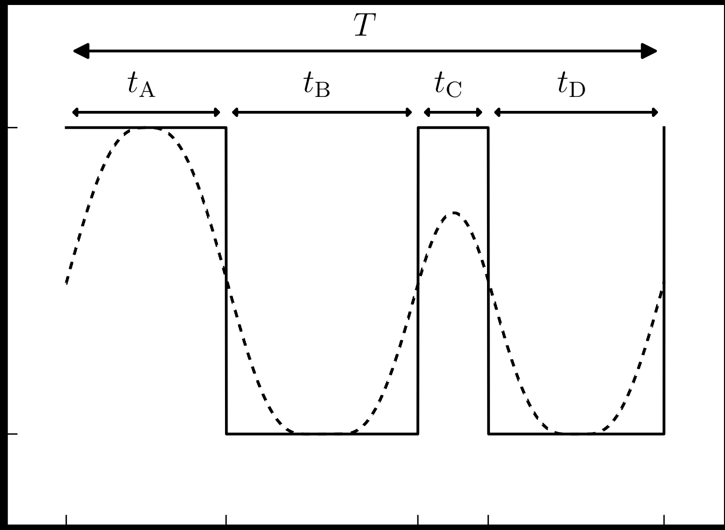
Magnetospheric switching?

Pulse width observed to switch rapidly.

Motivated "magnetospheric switching" (Lyne+ '10).

Smoother variation in observed spin-down and pulse shape to be understood as due to time-averaging.

Provides no model for "clock".

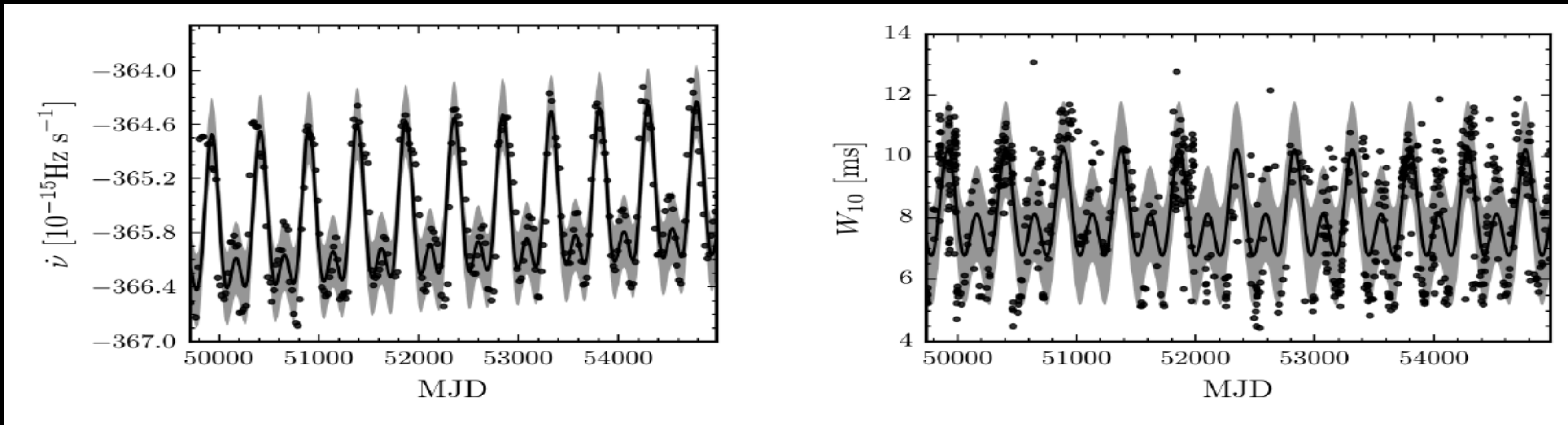


Schematic representation of Perera+ (2015) switching model.

Precession v Switching

Carried out a Bayesian comparison between precession and switching model (Ashton, DIJ & Prix, 2015).

Found precession was significantly better fit (odds ratio $10^{2.7\pm0.5}$).



Selected posterior parameters:

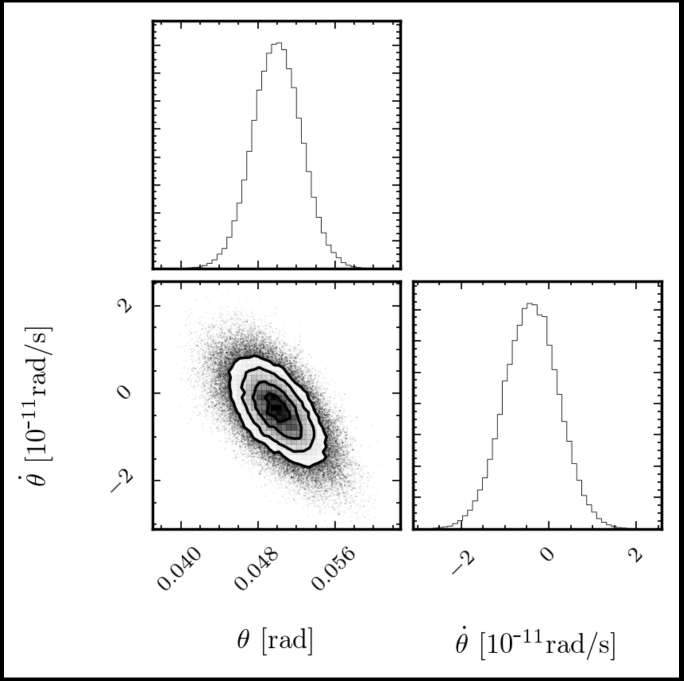
$$\frac{P}{P_{fp}} \sim 10^{-8}, \qquad \theta \sim 2.8^{\circ}, \qquad \chi \sim 88.9^{\circ}$$

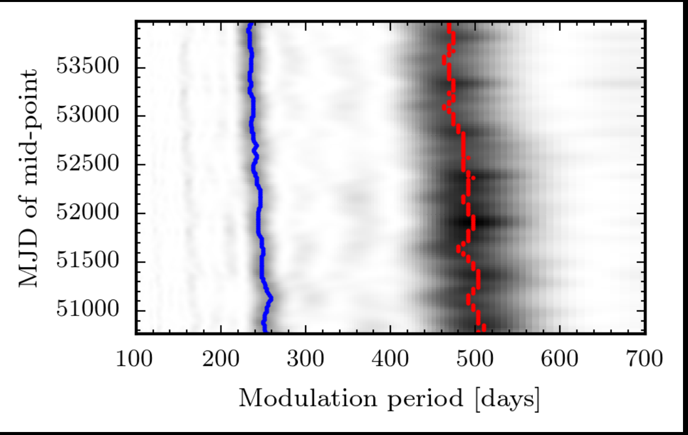
Further analysis…

Refined model to allow for changing θ and P_{fp} (Ashton, DIJ & Prix 2017).

Found no evidence for decay of wobble angle θ…

…but found P_{fp} to be decreasing on timescale ~200 years!





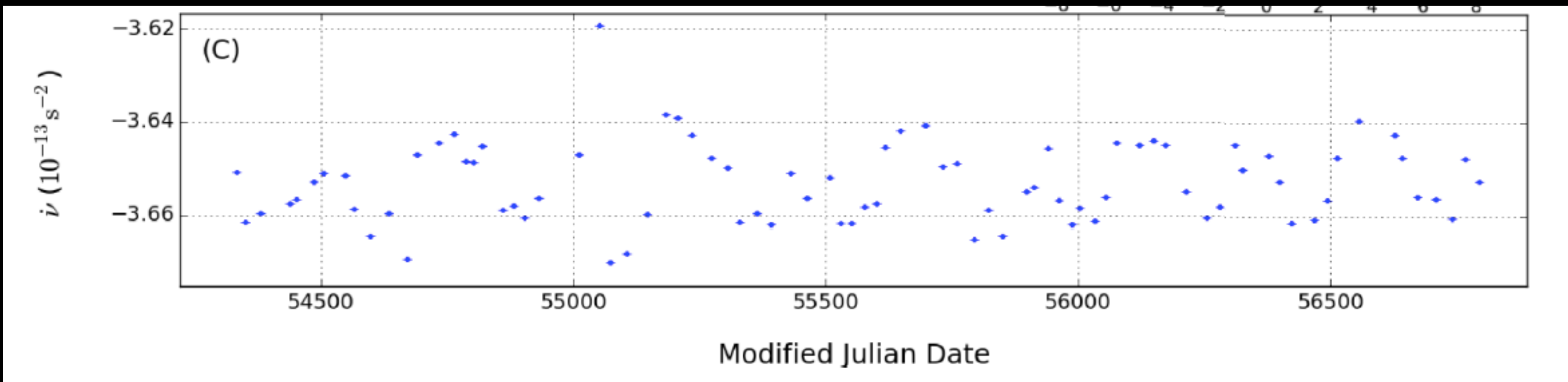
…and a glitch

B1828-11 underwent a glitch in 2009.

DIJ, Ashton & Prix (2017) derived consistency requirements between glitch and precession.

Expect P_{fp} to increase significantly after glitch.

Data suggests otherwise (Brook+ 2016). Problematic!



Magnetic precession problem

Expect even a purely fluid star to be able to precess, if magnetically deformed.

Relevant to:

1. Main sequence stars
2. Newly-formed neutron stars
   - Core collapse supernovae
   - Binary coalescence

Interesting, as may be important for:

1. Gravitational wave emission (especially the "millisecond magnetar" scenario; Paul Lasky's talk).
2. Setting the pulsar spin-dipole inclination angle.

Basic picture

Magnetic field distorts star, giving ellipticity:

$$\epsilon_B \sim \frac{B^2 R^3}{GM^2/R} \sim 10^{-6} \left(\frac{B}{10^{15}\,\mathrm{G}} \right)^2$$

This then sets the precession period:

$$P_{\mathrm{fp}} \sim \frac{P}{\epsilon_B} = 10^6\,\mathrm{seconds} \left(\frac{P}{1\,\mathrm{second}} \right) \left(\frac{10^{15}\,\mathrm{G}}{B} \right)^2$$

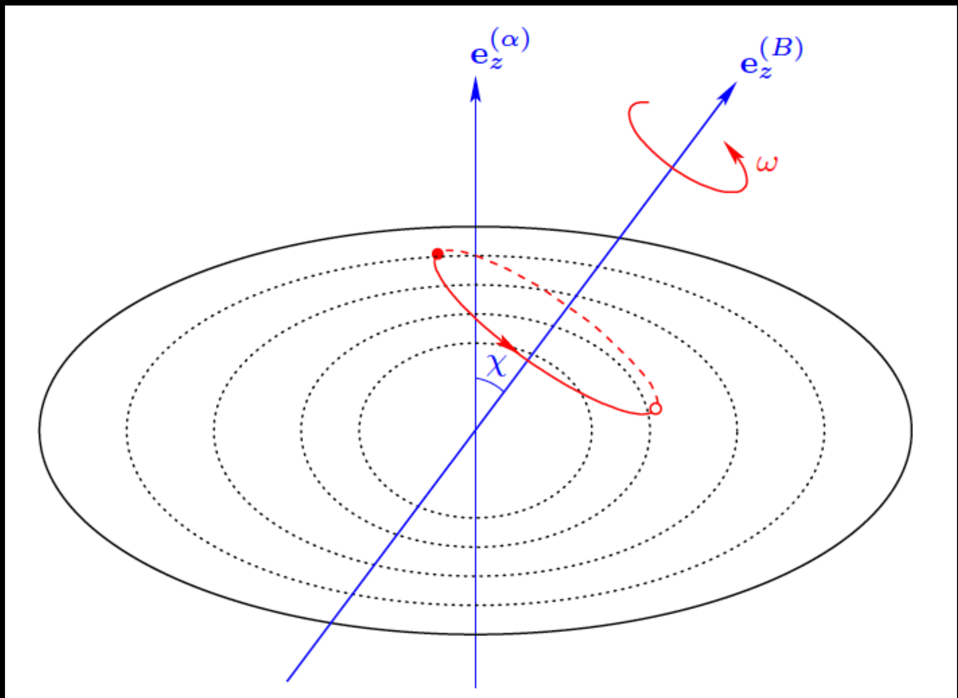
Precession consists of rapid spin of magnetic axis about fixed angular momentum axis…

…plus slow superimposed rotation about magnetic axis.

Non-rigid response

Spin axis traces out a cone of half-angle χ as viewed from rotating star.

But spin axis defines centrifugal bulge, of size:



$$\epsilon_\Omega \sim \frac{I\Omega^2}{GM^2/R} \sim 0.1 \left(\frac{f}{\mathrm{kHz}}\right)^2$$

$\Longrightarrow$ have density wave propagating around star

Non-rigid response: “xi-motions”

Time-varying density perturbation will induce displacement motion in the stellar fluid, Mestel’s “xi-motions”.

Crucial for calculating dissipation rates (e.g. due to shear & bulk viscosities), and hence evolution in wobble angle.

Must satisfy continuity equation:

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho \vec{v}), \qquad \vec{v} = \frac{\partial \vec{\xi}}{\partial t}$$

But this isn’t sufficient to compute ξ.

Solution: Lander & DIJ 2017

Take full set of PDEs, and exploit smallness of ϵ_Ω and ϵ_B:

$$\rho \frac{d\vec{v}}{dt} = -\nabla P - \rho \nabla \Phi + \frac{1}{4\pi}(\nabla \times \vec{B}) \times \vec{B},$$

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho \vec{v}),$$

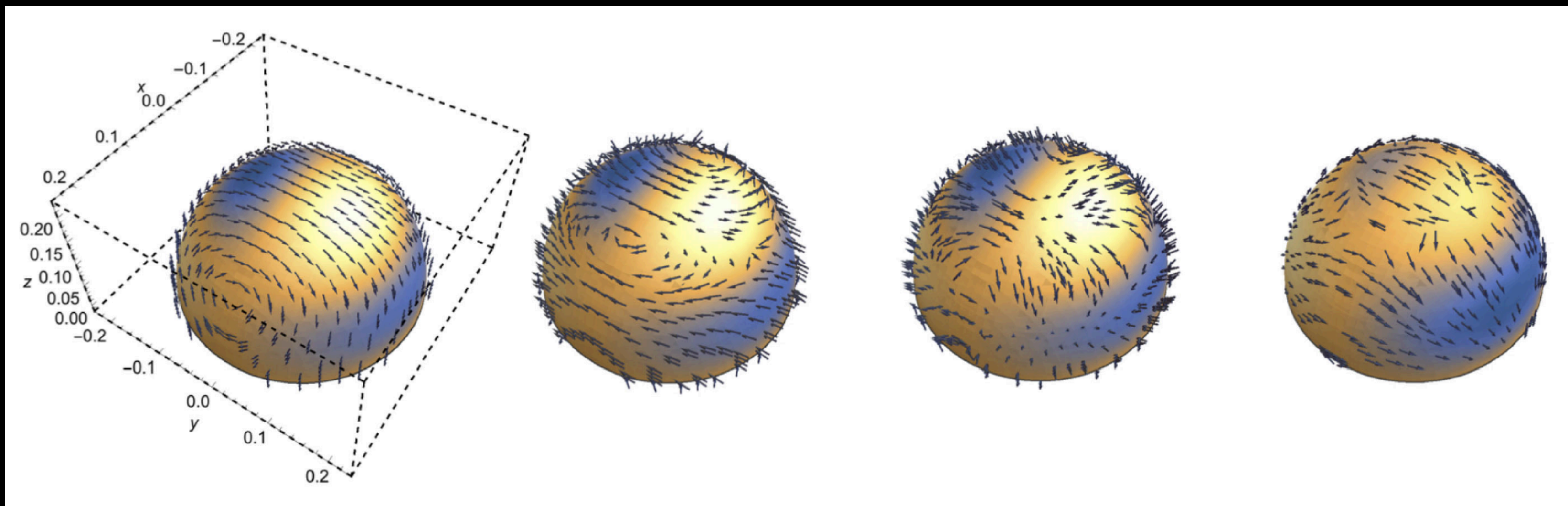
$$\nabla^2 \Phi = 4\pi G \rho,$$

$$\frac{\partial \vec{B}}{\partial t} = \nabla \times (\vec{v} \times \vec{B}),$$

$$P = P(\rho),$$

$$\nabla \cdot \vec{B} = 0.$$

- Zeroth order: spherical star
- Order ϵ_Ω: rotational deformed star
- Order ϵ_B: magnetically deformed star
- Order $\epsilon_\Omega \epsilon_B$: xi-motions!



Application: newly born NSs

Imagine NS born with some non-zero inclination angle.

Set of coupled ODEs:

Temperature: $\frac{dT}{dt} = -neutrino\ cooling$

Spin frequency: $\frac{d\Omega}{dt} = -EM\ spindown$

Inclination angle: $\frac{d\chi}{dt} = \pm viscous\ dissipation - EM\ alignment$

Oblate ($\epsilon_B > 0$): alignment

Prolate ($\epsilon_B < 0$):counteralignment, aka "Mestel-Jones spin-flip"

Spin-flip with EM torque

For prolate star, get competition between bulk viscosity and EM torque.

Bulk viscosity frequency dependent (Lindblom & Owen 2002):

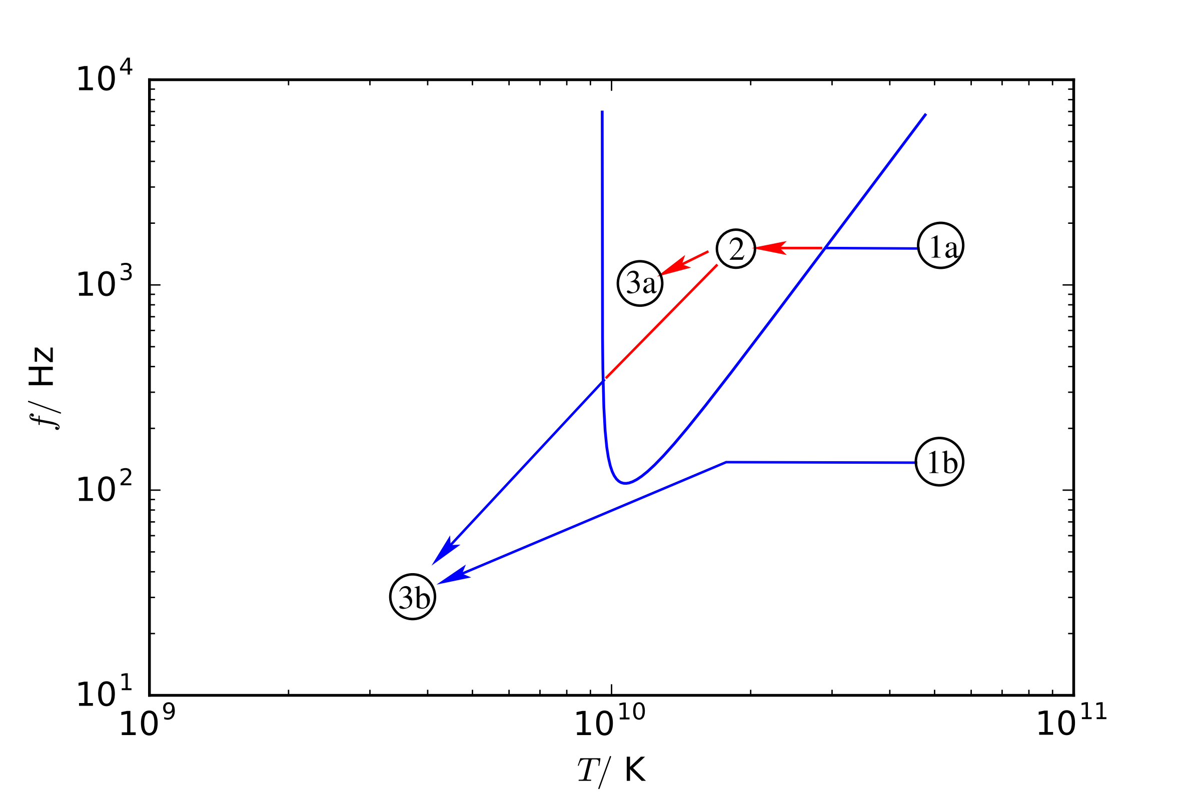
$$\zeta \sim \frac{\tau}{1 + (\omega\tau)^2}$$

$\tau \sim T^{-6}$, microphysical reaction rate
$\omega \sim f\epsilon_B \sim fB^2$, precession frequency → Complex interplay

EM torque $\sim f^3\ B^2$

“Orthogonalisation” curve

Can use back-of-the-envelope formulae to estimate curve in (f, T) plane above which spin-flip active:

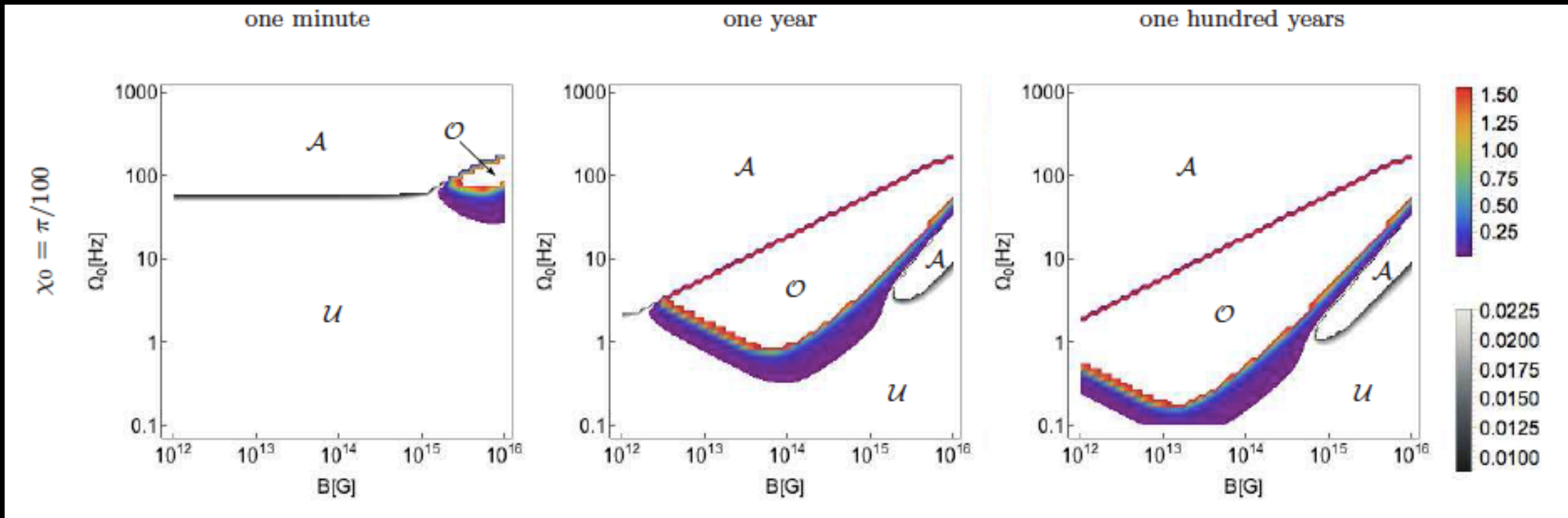


B = 10^{16} G

Time evolutions

Time evolutions of coupled ODEs show rich structure.

In early stages of interpreting results (Lander & DIJ 2018 in prep).



Summary

- Free precession potentially unique probe of NS structure…
- …and possible source of gravitational waves.
- Not clear if active in observed pulsar population.
- Magnetic precession may be important in early life of NS.