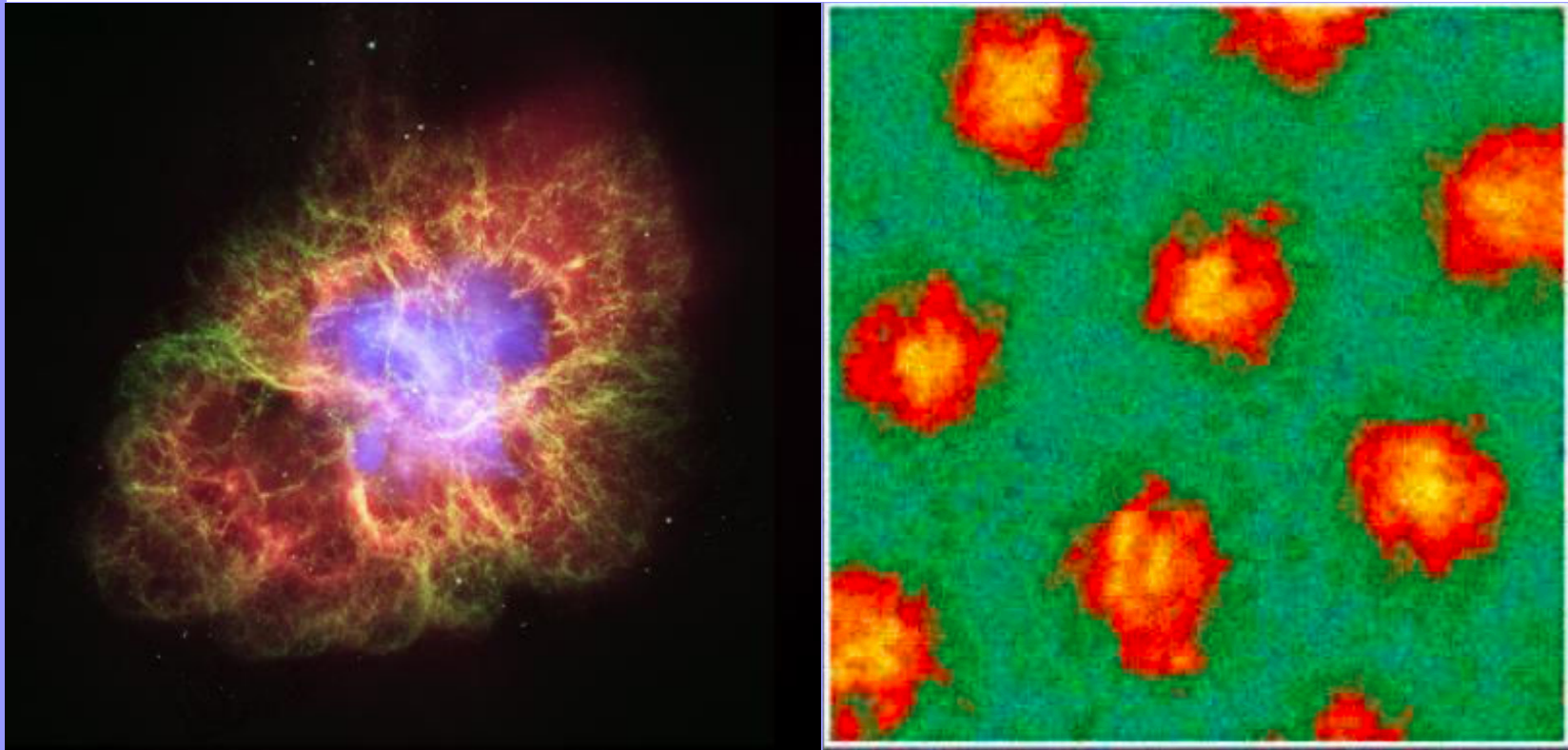


Nonlinear Superfluid Dynamics - Evidence in Pulsars

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Neutron star dynamics is governed by the motion of quantized **vortex lines** in the neutron superfluid.

What determines the motion of vortex lines:

(i) **Continuous interaction** of vortex lines with ambient normal matter.

(ii) **Pinning** at sites attractive for the vortex line. Vortex motion as statistical average of pinning and unpinning : **vortex creep**, and sporadic vortex discharges \rightarrow **glitches**.

Pinning to nuclei in the neutron star crust, $I_i / I \sim 10^{-3}$, and to flux lines in the neutron star core (Gügercinoglu & Alpar, 2014).

VORTEX CREEP

Equations of motion:

$$I_c \, d\Omega_c / dt + I_s \, d\Omega_s / dt = N_{\text{ext}}$$

$$d\Omega_s / dt = - n\kappa \langle v_r \rangle / r = - 2\Omega_s \langle v_r \rangle / r$$

$$\langle v_r \rangle = f (\Omega_s - \Omega_c) \rightarrow \text{two-fluid hydrodynamics.}$$

steady state:

$$d\Omega_s / dt = d\Omega_c / dt = N_{\text{ext}} / (I_c + I_s) = (d\Omega / dt)_{\infty}$$

Vortex creep:

Pinning: superfluid is rotating faster.

If vortex lines move outward superfluid will spin down. It is energetically favourable to reduce differential rotation between normal matter and superfluid. So there is an energy bias favouring vortex motions that are radially outward.

Pinning energy at each pinning site = E_p

Energy bias: $\Delta E = E_p (\Omega_s - \Omega_c) / \omega_{cr} = E_p (\omega / \omega_{cr})$

$$\begin{aligned} \langle v_r \rangle &= v_0 \{ \exp - [(E_p - \Delta E) / kT] - \exp - [(E_p + \Delta E) / kT] \} \\ &= 2 v_0 \exp (- E_p / kT) \sinh [E_p (\omega / \omega_{cr}) / kT] \end{aligned}$$

Depending on the $\langle v_r \rangle$ value required in the steady state,

$$d\Omega_\infty / dt = - 2\Omega_s \langle v_r \rangle / r ,$$

vortex creep has linear and nonlinear regimes:

Linear: $\sinh [E_p (\omega / \omega_{cr}) / kT] \sim E_p (\omega / \omega_{cr}) / kT$

Nonlinear: $\sinh [E_p (\omega / \omega_{cr}) / kT] \sim \frac{1}{2} \exp [E_p (\omega / \omega_{cr}) / kT] .$

Pulsar spindown, glitches and postglitch response involves nonlinear as well as linear creep.

As a pulsar ages $T(t)$ and $|d\Omega/dt|$ both decrease, in such a way that more and more of the neutron star pinning spectrum $E_p(r)$ falls in the nonlinear creep regime: **pulsars go nonlinear as they mature.**

Linear regime:

$$\begin{aligned}d\Omega_s / dt &= - 2\Omega_s \langle v_r \rangle / r \\ &= - (4 \Omega_s v_0 / r) \exp(-E_p / kT) \cdot [E_p (\omega / \omega_{cr}) / kT] \\ &= - \omega / \tau \\ &= - (\Omega_s - \Omega_c) / \tau,\end{aligned}$$

defining a linear creep relaxation time

$$\tau = (4 \Omega_s v_0 / r)^{-1} [kT \omega_{cr} / E_p] \exp(E_p / kT) .$$

In the linear regime the pinned superfluid behaves like a superfluid with continuous drag forces. Linear response to glitch induced perturbations \rightarrow exponential relaxation.

Nonlinear regime:

In the opposite regime we have a very non-linear response to perturbations. The response of a non-linear creep region k to the glitch will be (Alpar et al. 1984a)

$$\Delta\dot{\Omega}_{c,k} = -\frac{I_k}{I}|\dot{\Omega}|_{\infty} \left[1 - \frac{1}{1 + (e^{t_{0,k}/\tau_{nl}} - 1)e^{-t/\tau_{nl}}} \right]. \quad (2)$$

At the time of glitch, creep in those regions which show non-linear response can stop temporarily. These regions decouple from rest of the star, so that external torque acts on less moment of inertia. Creep restarts after a waiting time of $t_0 = \delta\omega/|\dot{\Omega}|_{\infty}$, since the external torque restores the glitch-induced decrease in angular velocity lag. The relaxation time is

$$\tau_{nl} = \frac{kT}{E_p} \frac{\omega_{cr}}{|\dot{\Omega}|_{\infty}}.$$

Nonlinear response is essential in understanding interglitch behaviour. Any perturbation $\delta\omega$ to the superfluid-normal matter lag ω can effectively stop creep, until the spindown of the normal component restores steady state creep conditions on a timescale $t_0 = \delta\omega / |d\Omega/dt|$.

Response time-width $\tau_{nonlinear} = (kT/E_p) (\omega_{cr} / |d\Omega/dt|)$

This is the signature observed in $d\Omega/dt$ if the glitch introduced a constant $\delta\omega$ throughout the pinned superfluid: Fermi function \rightarrow

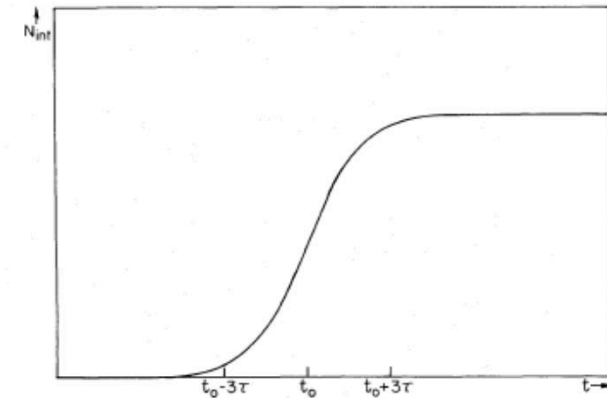


FIG. 4.—The internal torque for the case $t_0 \gg \tau$. Note the characteristic Fermi function behavior.

What happens if the glitch induced offset is not uniform throughout the pinned superfluid?

Nonlinear response to a ‘mean field’ uniform density of unpinned vortices: stacked Fermi functions \rightarrow

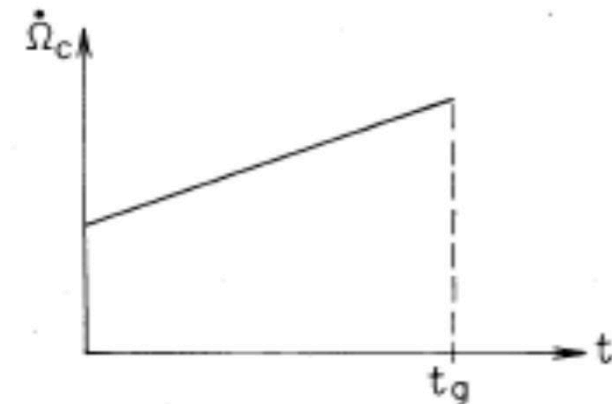
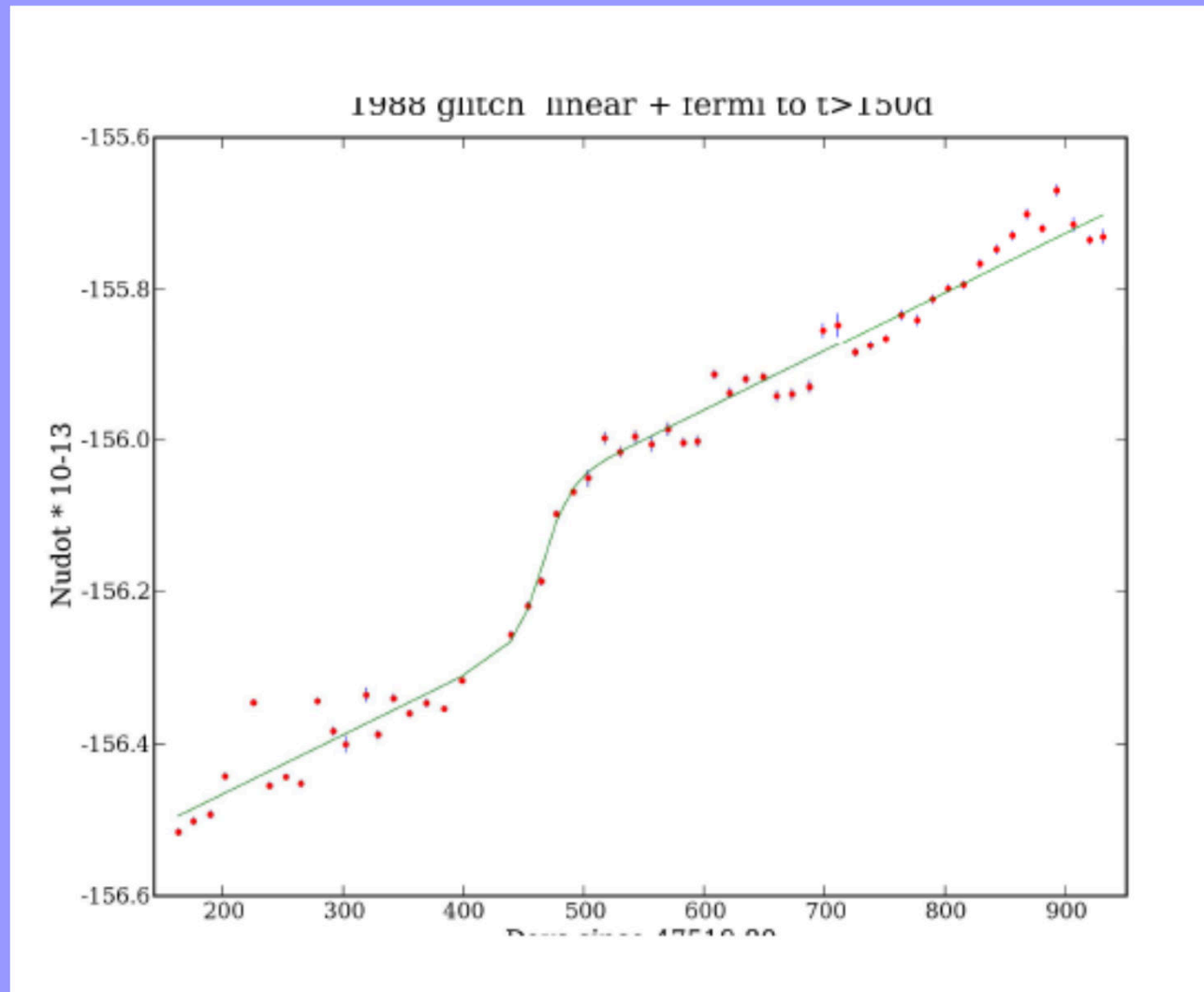


FIG. 4c

$$\frac{\Delta \dot{\Omega}_c(t)}{\dot{\Omega}_c} = \frac{I_A}{I} \left(1 - \frac{t}{t_0} \right)$$

Claire Flanagan (in «Lives of the Neutron Stars», Proc. NATO ASI, Kemer, Turkey, 1995)



It seems there is a universal behaviour regarding glitches of pulsars of all ages.

The constant $d^2 \Omega/dt^2$ interglitch behavior seems universal among all older pulsars with glitch/interglitch data.

(Alpar and Baykal 2006)

ABSTRACT

Almost all pulsars with anomalous positive $\ddot{\Omega}$ measurements (corresponding to anomalous braking indices in the range $5 < |n| < 100$), including all the pulsars with observed large glitches ($\Delta\Omega/\Omega > 10^{-7}$) as well as post-glitch or interglitch $\ddot{\Omega}$ measurements, obey the scaling between $\ddot{\Omega}$ and glitch parameters originally noted in the Vela pulsar. Negative second derivative values can be understood in terms of glitches that were missed or remained unresolved. We discuss the glitch rates and a priori probabilities of positive and negative braking indices according to the model developed for the Vela pulsar. This behaviour supports the universal occurrence of a non-linear dynamical coupling between the neutron star crust and an interior superfluid component. The implied lower limit to dynamical energy dissipation in a neutron star with spindown rate $\dot{\Omega}$ is $\dot{E}_{\text{diss}} > 1.7 \times 10^{-6} \dot{E}_{\text{rot}}$. Thermal luminosities and surface temperatures due to dynamical energy dissipation are estimated for old neutron stars which are spinning down as rotating magnetic dipoles beyond the pulsar death line.

Key words: pulsars: general.

$$\ddot{\Omega} = \frac{I_A}{I} \frac{\dot{\Omega}^2}{\delta\Omega} = (\beta + 1/2)(\Delta\dot{\Omega}/\dot{\Omega})_{-3}^2 / (\Delta\Omega/\Omega)_{-6}(\dot{\Omega}^2/\Omega). \quad (10)$$

This is equivalent to the positive 'anomalous' braking index

$$n = (\beta + 1/2)(\Delta\dot{\Omega}/\dot{\Omega})_{-3}^2 / (\Delta\Omega/\Omega)_{-6}. \quad (11)$$

Sarah Buchner : 20 glitches with $\Delta\dot{\Omega}(t) \cong \Delta\dot{\Omega}(0) (1 - t/t_0)$
related to the glitch parameters in the way expected.

Akbal et al. ongoing work

Characterising the rotational irregularities of the Vela pulsar from 21 yr of phase-coherent timing

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8 glitches:

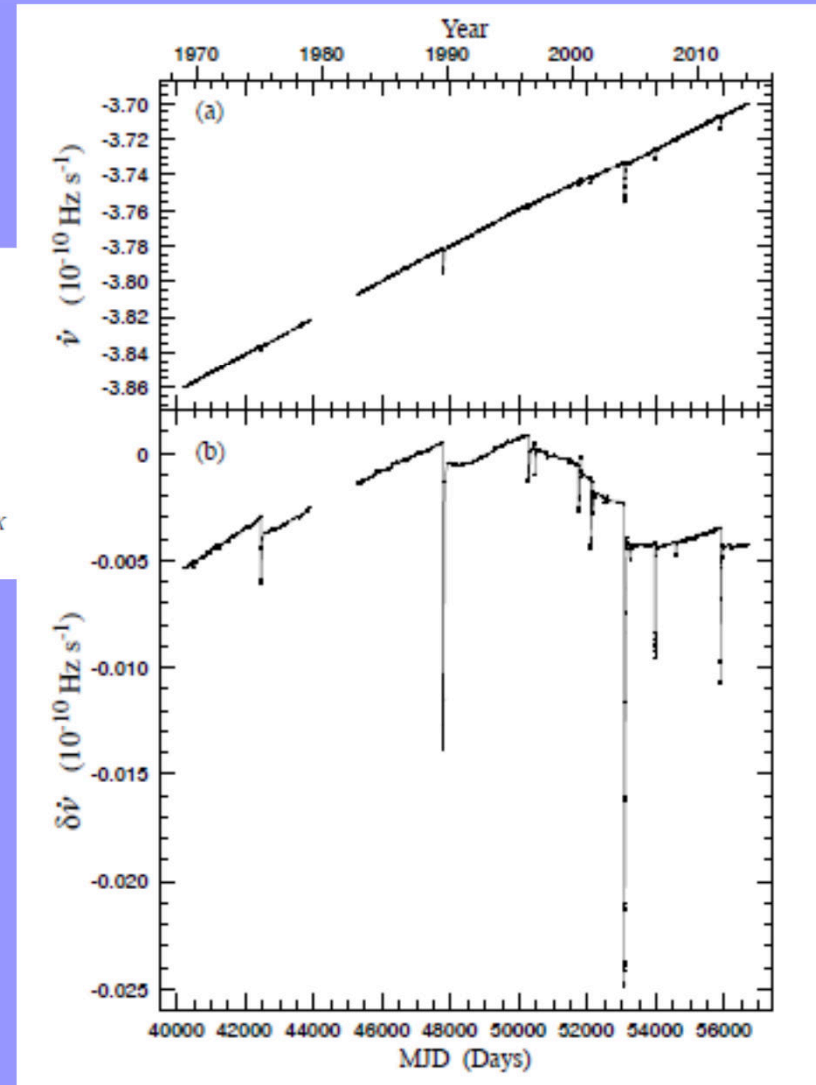
$$\Delta\dot{\Omega}(t) = \Delta\dot{\Omega}(0) (\exp - t / \tau), \text{ with } \tau = 1300 \text{ d.}$$

$$\Delta\dot{\Omega}(t) \cong \Delta\dot{\Omega}(0) (1 - t / \tau) \text{ but not related to glitch parameters.}$$

45 Years of Rotation of the Crab pulsar

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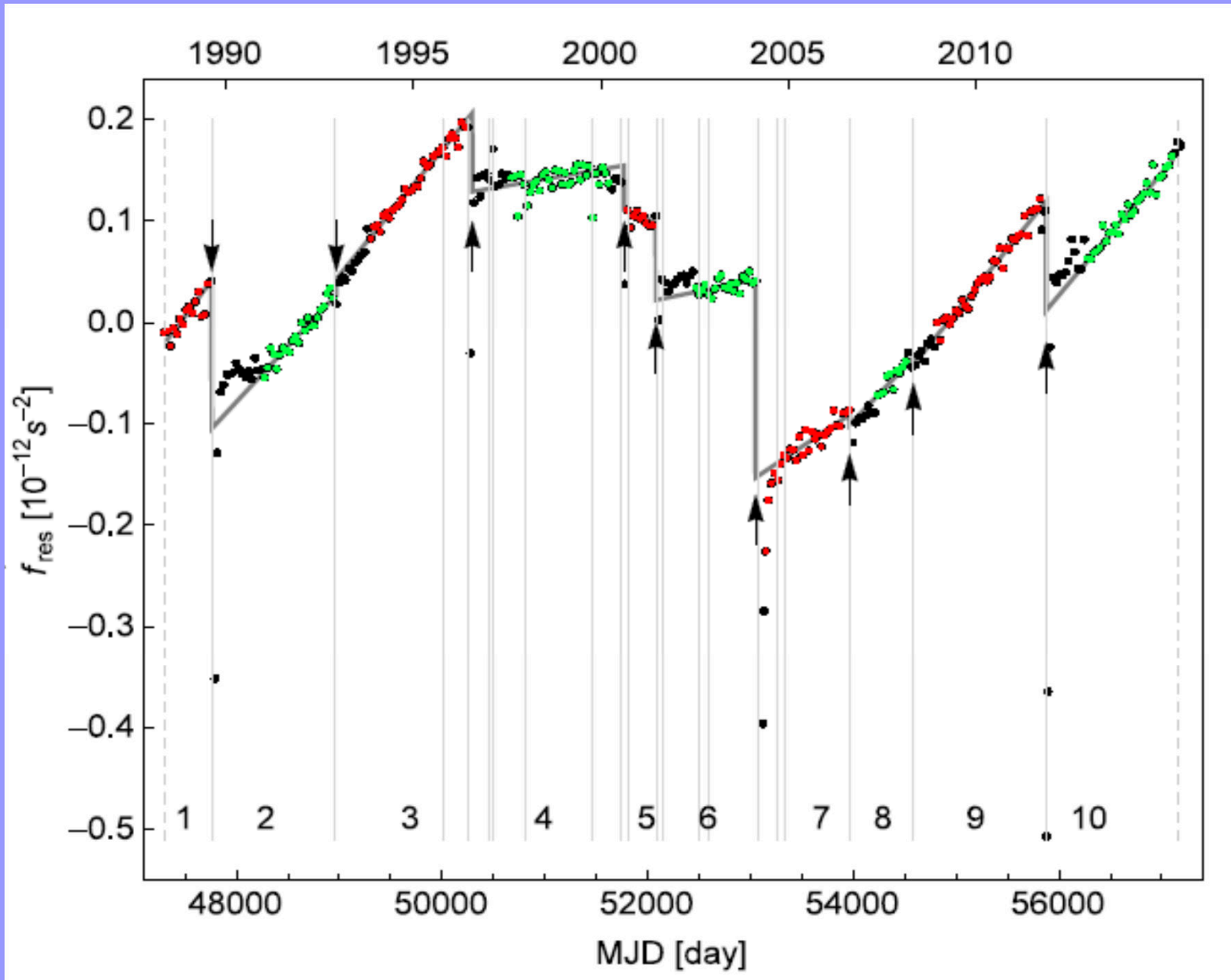
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What brakes the Crab pulsar?

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ON THE BRAKING INDEX OF THE UNUSUAL HIGH- B ROTATION-POWERED PULSAR PSR J1846–0258

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Draft version August 18, 2015

ABSTRACT

PSR J1846–0258 is an object which straddles the boundary between magnetars and rotation powered pulsars. Though behaving for many years as a rotation-powered pulsar, in 2006, it exhibited distinctly magnetar-like behavior – emitting several short hard X-ray bursts, and a flux increase. Here we report on 7 years of post-outburst timing observations of PSR J1846–0258 using the *Rossi X-ray Timing Explorer* and the *Swift* X-ray Telescope. We measure the braking index over the post-magnetar outburst period to be $n = 2.19 \pm 0.03$. This represents a change of $\Delta n = -0.46 \pm 0.03$ or a 14.5σ difference from the pre-outburst braking index of $n = 2.65 \pm 0.01$, which itself was measured over a span of 6.5 yr. So large and long-lived a change to a pulsar braking index is unprecedented and poses a significant challenge to models of pulsar spin-down.

A HIGH BRAKING INDEX FOR A PULSAR

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ABSTRACT

We present a phase-coherent timing solution for PSR J1640–4631, a young 206 ms pulsar using X-ray timing observations taken with *NuSTAR*. Over this timing campaign, we have measured the braking index of PSR J1640–4631 to be $n = 3.15 \pm 0.03$. Using a series of simulations, we argue that this unusually high braking index is not due to timing noise, but is intrinsic to the pulsar's spin-down. We cannot, however, rule out contamination due to an unseen glitch recovery, although the recovery timescale would have to be longer than most yet observed. If this braking index is eventually proven to be stable, it demonstrates that pulsar braking indices greater than 3 are allowed in nature, hence other physical mechanisms such as mass or magnetic quadrupoles are important in pulsar spin-down. We also present a 3σ upper limit on the pulsed flux at 1.4 GHz of 0.018 mJy.