Glitches as Probes of Neutron Star Internal Structure and Dynamics

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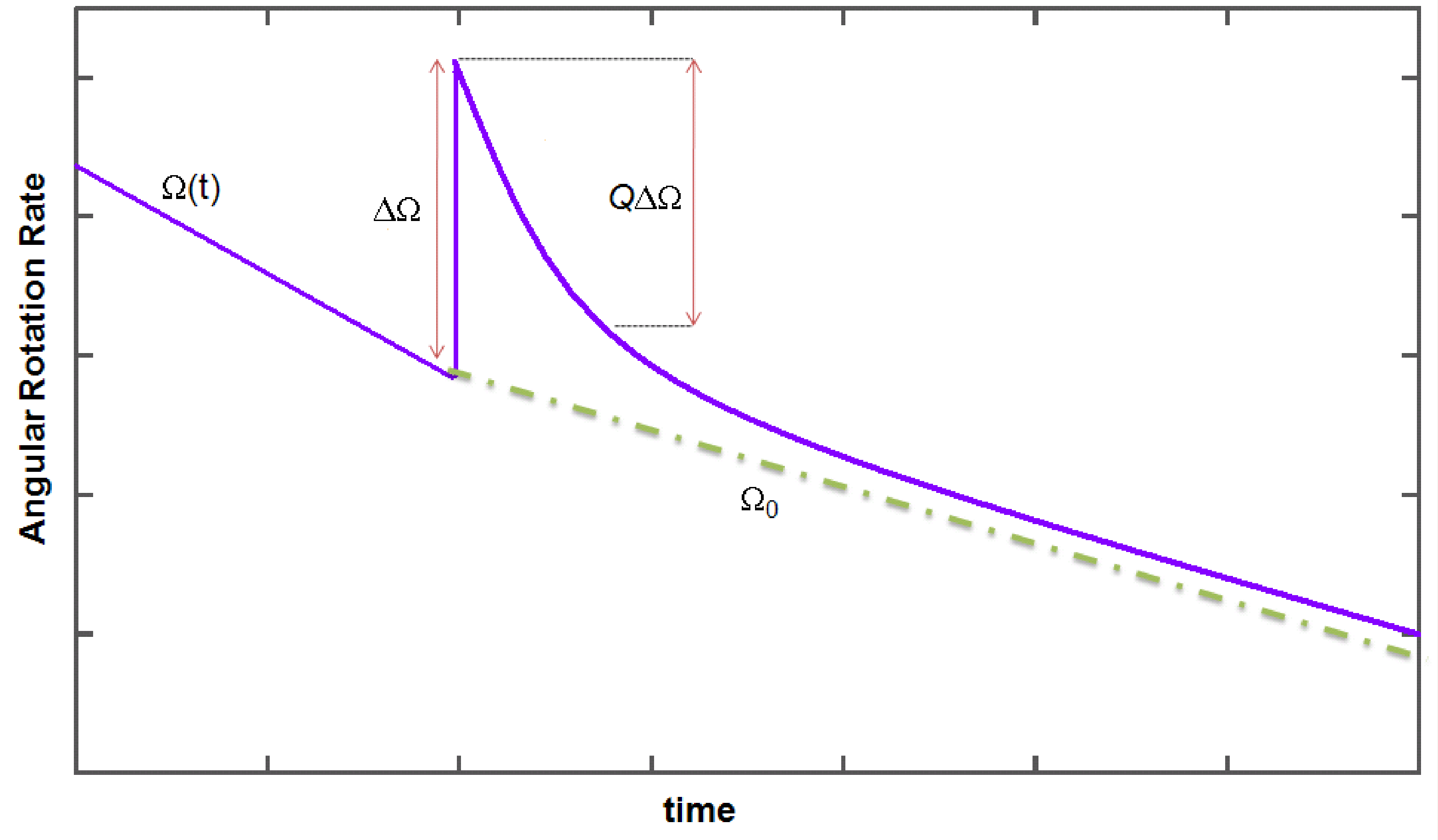
Pulsar Glitches



- Glitch ⟶ sudden increase in pulsar rotation and spindown rates.

$$\frac{\Delta\Omega}{\Omega} = 10^{-12} - 10^{-5}, \quad \frac{\Delta\dot{\Omega}}{\dot{\Omega}} = 10^{-4} - 10^{-1}$$

- Rapid spin-up and long recovery ⟶ bulk superfluid manifestation.

Glitches as Probes of Neutron Star Structure

In literature

- Crust-core coupling (Abney et al. 1996),
- Redistribution of excess angular momentum within different layers (Howitt et al. 2016),
- Spin-up in neutral and charged superfluids (Easson 1979),
- Constraining the bulk properties of neutron star matter (Van Eysden & Melatos 2010),
- Equation of State (Link et al. 1999).

In this work

- Internal magnetic field configuration,
- Temperature evolution.

Standard Glitch Model and Challenge

- Crustal superfluid and crust are coupled via thermally activated creep.
- At the time of a glitch (Alpar et al. 1984),
  - Large number of vortices unpin and impart angular momentum to crust
  - Spin up glitch → coupling decreases → superfluid decouples
  - Torque acts on smaller moment of inertia → spin-down increases
  - Recovery → superfluid recouples to some other regions of the crust.
- Theoretical challenge

_Chamel (2012) band theory calculations reveal that scattering of dripped neutrons from crystal reduces superfluid mobility.

_ Decrease in angular momentum reservoir $\sim (m_{\rm n}/m_{\rm n}^*) I_{\rm s} \delta\Omega_{\rm s}$

- **Way out:** Involvement of core superfluid in glitches.

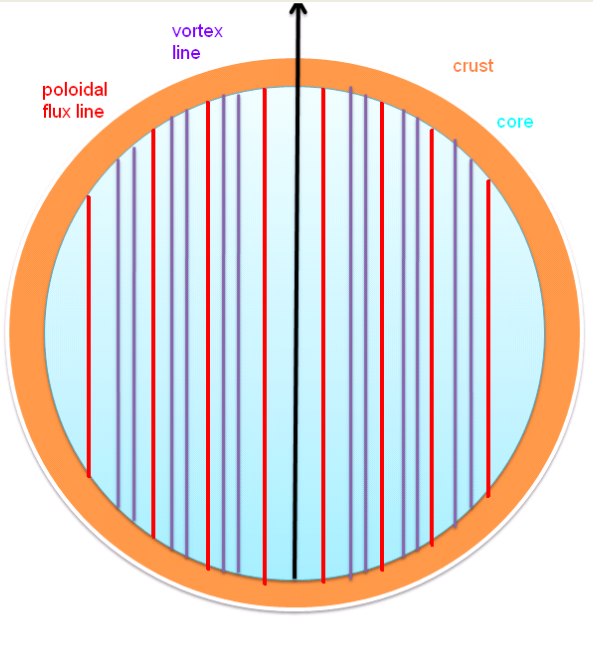
_ $\frac{\Delta\Omega_{\rm c}}{\Omega_{\rm c}} = \frac{I_{\rm s}}{I_{\rm c}} \left(\frac{m_{\rm n}}{m_{\rm n}^*} \right) \frac{\delta\Omega_{\rm s}}{\Omega_{\rm c}}$ ☺ I_s/I_c can increase by

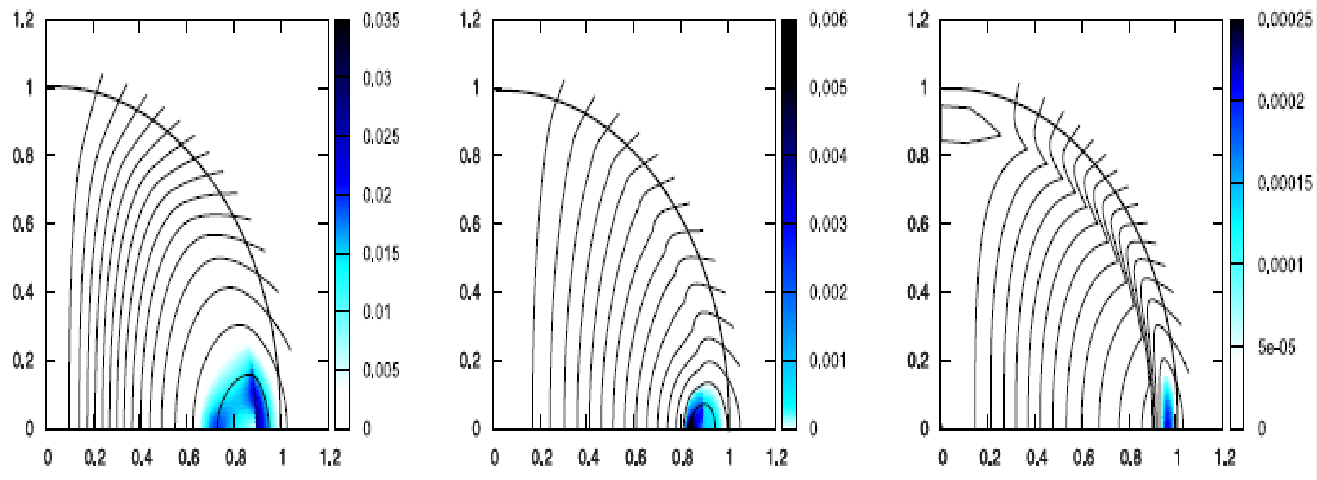
1) Superfluid decoupling from external torque (Gügercinoğlu & Alpar 2014)

2) Core superfluid participation (Gügercinoğlu & Alpar 2016)

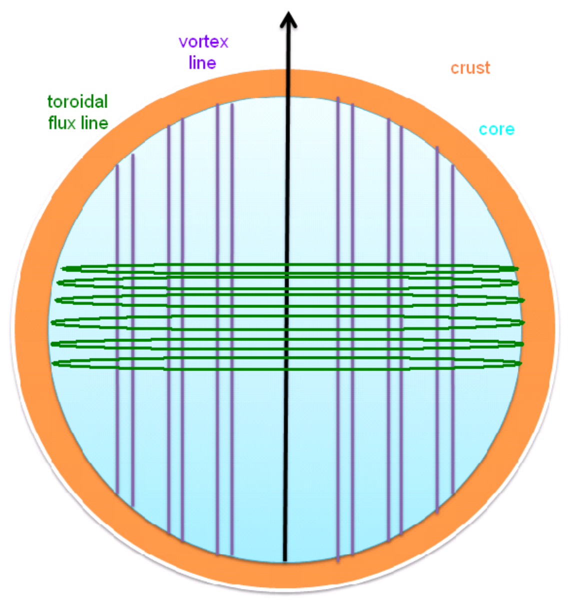
Vortex Pinning and Creep Against Flux Tubes

- Flux tubes provide pinning/creep sites for vortex lines (Sidery & Alpar 2009).
- If flux tubes have poloidal configuration, pinning and creep will depend on the angle between rotation and magnetic axes.
- Toroidal arrangement of flux tubes inevitably constrain the motion of the vortices.





Lander (2014)

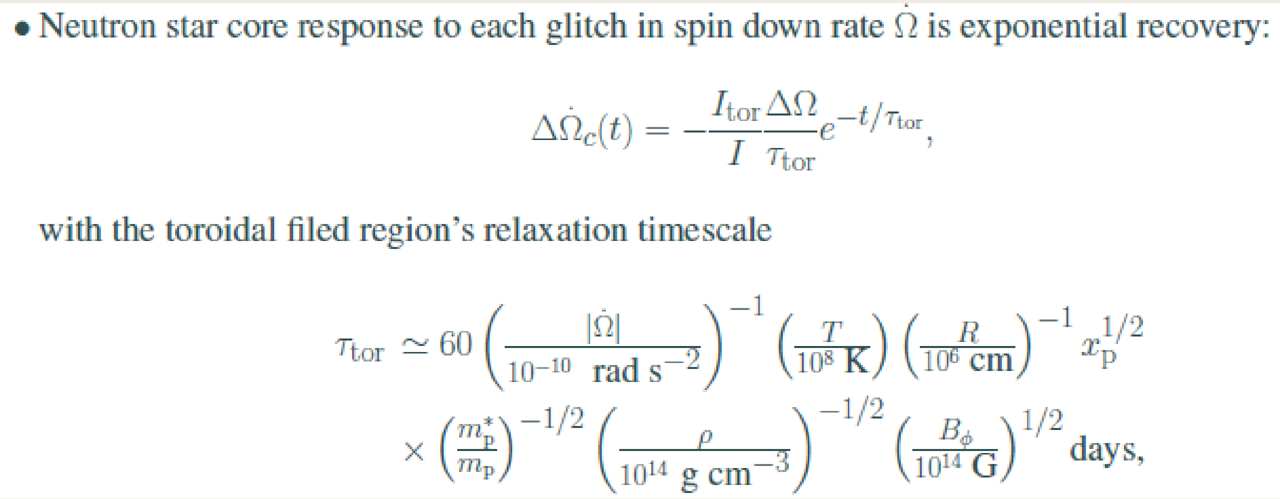


Vortex Creep Across Flux Tubes Model

Gügercinoğlu & Alpar (2014, 2016)

Predictions:

- Only the toroidal field region (a rather small portion of core) participates in glitches ⟶ accounts for why glitch magnitudes are tiny.

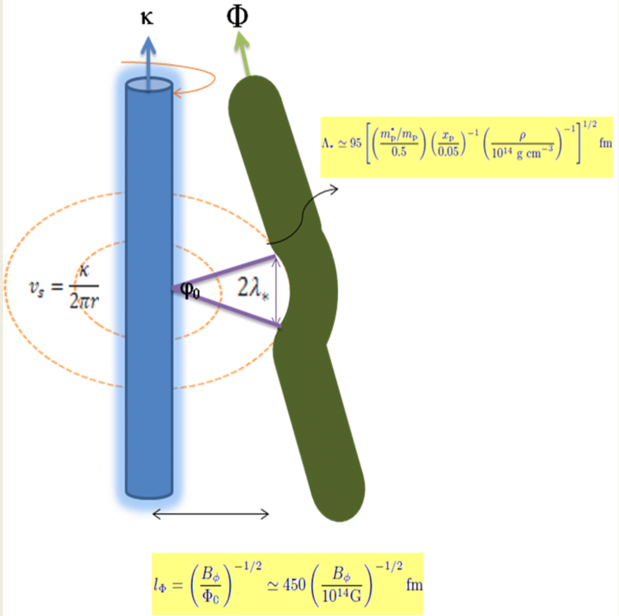


- Neutron star core response to each glitch in spin down rate $\dot{\Omega}$ is exponential recovery:

$$\Delta\dot{\Omega}_c(t) = -\frac{I_{\rm tor}}{I}\frac{\Delta\Omega}{\tau_{\rm tor}}e^{-t/\tau_{\rm tor}},$$

with the toroidal filed region's relaxation timescale

$$\tau_{\rm tor} \simeq 60\left(\frac{|\dot{\Omega}|}{10^{-10} \ \ {\rm rad\ s^{-2}}}\right)^{-1}\left(\frac{T}{10^{8}\ {\rm K}}\right)\left(\frac{R}{10^{6}\ {\rm cm}}\right)^{-1}x_{\rm p}^{1/2}$$
$$\times\left(\frac{m_{\rm p}^{*}}{m_{\rm p}}\right)^{-1/2}\left(\frac{\rho}{10^{14}\ {\rm g\ cm^{-3}}}\right)^{-1/2}\left(\frac{B_{\phi}}{10^{14}\ {\rm G}}\right)^{1/2}{\rm days},$$



$$\Lambda_{*} \simeq 95\left[\left(\frac{m_{\rm p}^{*}/m_{\rm p}}{0.5}\right)\left(\frac{x_{\rm p}}{0.05}\right)^{-1}\left(\frac{\rho}{10^{14}\ {\rm g\ cm^{-3}}}\right)^{-1}\right]^{1/2}\ {\rm fm}$$

$$l_{\Phi} = \left(\frac{B_{\phi}}{\Phi_{0}}\right)^{-1/2} \simeq 450\left(\frac{B_{\phi}}{10^{14}{\rm G}}\right)^{-1/2}\ {\rm fm}$$

- As a pulsar ages relaxation timescale becomes longer ⟶ glitches resemble step like changes ⟶ supported by observations (Espinoza et al. 2011, Yu et al. 2013).

Observations vs Model

- $\Delta\dot{\nu}(t) = -\frac{\Delta\nu_{\mathrm{d}}}{\tau_{\mathrm{d}}} e^{-t/\tau_{\mathrm{d}}} + \Delta\dot{\nu}_{\mathrm{p}} = -\frac{Q\Delta\nu_{\mathrm{g}}}{\tau_{\mathrm{d}}} e^{-t/\tau_{\mathrm{d}}} + \Delta\dot{\nu}_{\mathrm{p}}$ Observation
- $\Delta\dot{\nu}(t) = -\frac{I_{\mathrm{tor}}}{I} \frac{\Delta\nu_{\mathrm{g}}}{\tau_{\mathrm{tor}}} e^{-t/\tau_{\mathrm{tor}}}$ Model
- $\tau_{\mathrm{tor}} \approx \tau_{\mathrm{d}}$ then $I_{\mathrm{tor}} / I \sim Q$.
- $\tau_{\mathrm{tor}} \gg \tau_{\mathrm{d}}$ then $I_{\mathrm{tor}} / I \leq 1 - Q$ can be said.
- So, glitch observations bring constraints into magnetic field configuration.
- 41 pulsars underwent 76 glitches with exponential decay.
- Of these, 60 glitches with one exponential decay component, 14 glitches with two exponential decay components and 2 glitches with three exponential decay components were detected.

- **Model 1:** Akmal et al. (1998) EOS.
  Cooling behavior Yakovlev et al. (2011).
  Torus extends to $R=0.6R_*$.
  SF-SC coupling parameters from Chamel (2008).

- **Model 2:** Lattimer & Swesty (1991) EOS.
  Cooling behavior Yakovlev et al. (2011).
  Toroid region’s response at $R=0.9R_*$.
  SF-SC coupling parameters from Borumand et al. (1996).

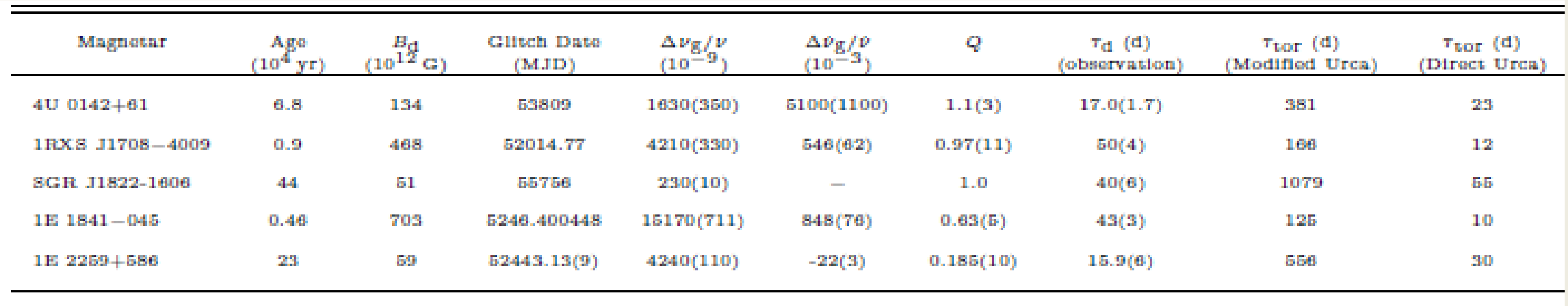
- **Model 3:** Douchin & Haensel (2001) EOS.
  Cooling behavior Aguilera et al. (2008).
  Toroid region’s response at $R=0.8R_*$.
  SF-SC coupling parameters from Chamel (2008).

Magnetar Glitch Pecularities

- Magnetars display unstable spindown and burst like activities.
- Strong evidence that both magnetospheric processes and internal superfluid play an important role in their glitches.
- Anomalous *Q* values → overshooting or relaxation.
- Due to magnetic field decay magnetar spindown rates are low (Dall’Osso et al. 2012).
- As a result of magnetic field decay magnetars have higher temperatures (Beloborodov ve Li 2016).
- Magnetars behave different from radio pulsars.
- Magnetar glitches require diffrent physical explanation.

Results for Magnetar Glitches

- Toroidal field component carry over some of its magnetic energy to the poloidal field so that in magnetars $B_\phi \lesssim 0.01B_{\rm p}$ Fujisawa & Kisaka (2014) .
- If the density of the core exceeds a critical threshold direct Urca cooling takes place.
- Magnetar surface thermal emisson can be explained by a cooler core + a heater in the crust (Kaminker et al. 2009, Beznogov & Yakovlev 2015).
- Variable external torque and superfluid coupling results in extra terms in Q values (Gügercinoğlu & Alpar 2017).



Magnetar	Age (10^4 yr)	B_d (10^{12} G)	Glitch Date (MJD)	$\Delta\nu_g/\nu$ (10^{-9})	$\Delta\dot\nu_g/\dot\nu$ (10^{-3})	Q	τ_d (d) (observation)	$\tau_{\rm tor}$ (d) (Modified Urca)	$\tau_{\rm tor}$ (d) (Direct Urca)
4U 0142+61	6.8	134	53809	1630(350)	6100(1100)	1.1(3)	17.0(1.7)	381	23
1RXS J1708−4009	0.9	468	52014.77	4210(330)	546(62)	0.97(11)	50(4)	166	12
SGR J1822-1606	44	51	55756	230(10)	—	1.0	40(6)	1079	55
1E 1841−045	0.46	703	5246.400448	15170(711)	848(76)	0.63(5)	43(3)	125	10
1E 2259+586	23	59	52443.13(9)	4240(110)	-22(3)	0.185(10)	15.9(6)	556	30

Conclusions

- Pulsar glitch observations can be used to place stringent constraints on the equation of state.
- Post-glitch exponential decay observations provide indirect measure for internal magnetic field configuration.
- Magnetar glitch observations are best explained by a core in which direct Urca cooling operates.
- Glitches with external torque variation implies a strong coupling between the internal superfluid and spinning down or up magnetospheric or accretion torques.
- Details can be found in Gügercinoğlu 2017, MNRAS, 469, 2313.

Thank You for Attention…