Glitches as Probes of Neutron Star Internal Structure and Dynamics

Erbil Gügercinoğlu

Sabancı University, Faculty of Engineering and Natural Sciences

egugercinoglu@gmail.com

Abstract

Glitches, sudden spin-up of pulsars with comparatively longer recovery, provide us with a unique opportunity to investigate various physical processes, including the crust-core coupling, distribution of reservoir angular momentum within different internal layers, spin-up in neutral and charged superfluids and constraining the equation of state of the neutron star matter. In this work, depending on the dynamic interaction between the vortex lines and the nuclei in the inner crust and between the vortex lines and the magnetic flux tubes in the outer core various types of the relaxation behaviors are obtained and confronted with the observations. It is shown that the glitches have strong potential to deduce information about the cooling behavior and interior magnetic field configuration of neutron stars. Some implications of the relative importance of the external spin-down torques and the superfluid internal torques for recently observed unusual glitches are also discussed.

Introduction

Glitches, as implied by rapid angular momentum transfer and comparatively long relaxation behavior (see Figure 1), provides indirect observational evidence for bulk superfluidity in neutron star matter [3]. The standard model, i.e. vortex creep model by Alpar et. al [2] invokes the interaction of vortex lines of neutron star inner crust with crystal nuclei to explain both the glitch occurrence and post-glitch relaxation.

Theoretical challenge–Recent band theory calculations of Chamel [1] revealed that Bragg scattering of dripped (free) neutrons from crystal somewhat reduces the mobility of crustal superfluid neutrons and accordingly the angular momentum reservoir.

Way out $\rightarrow$ This crustal mass entrainment effect suggests involvement of the core superfluid in the glitches. Gügercinoğlu and Alpar [8, 9] have given the first principles of how can superfluid-superconducting core takes place in a glitch.

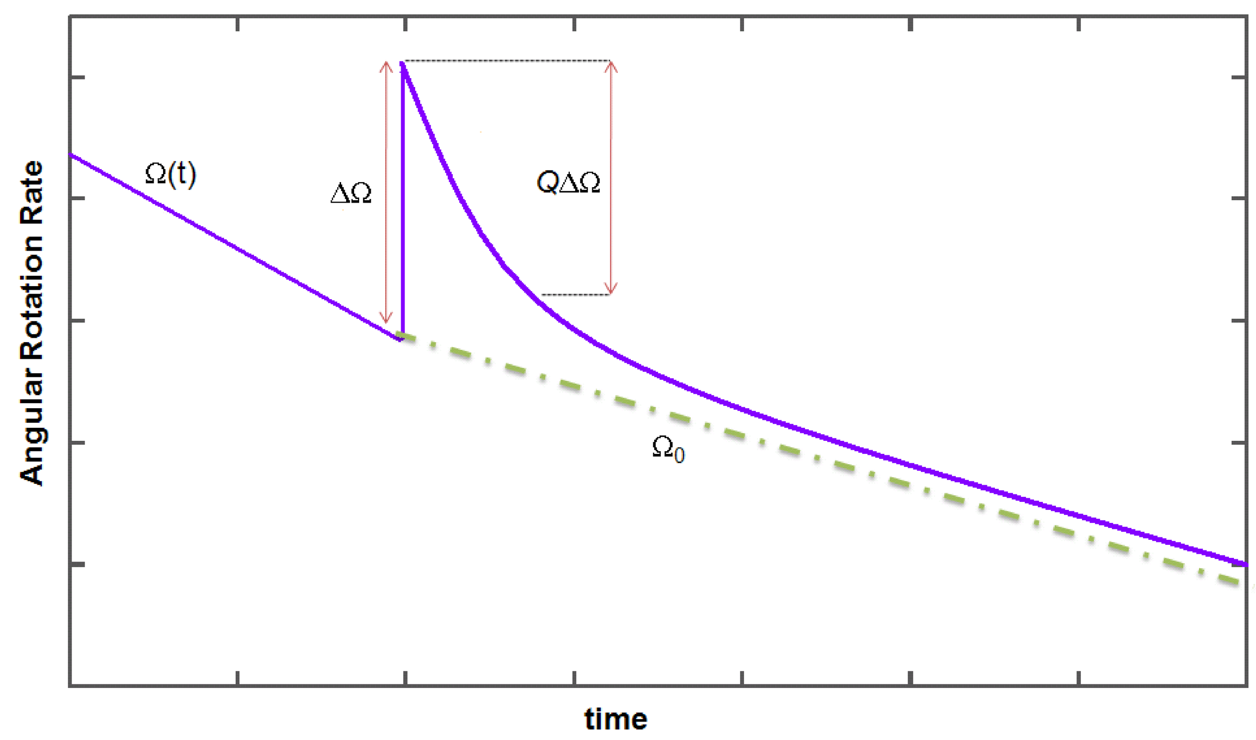

Figure 1: Sketch showing a typical glitch $\Delta\Omega$ in angular rotation rate Ω. A fraction of Q decays in long term but excess angular momentum prevails. From [6].

Materials and Methods

Vortex creep across flux tubes model describes post-glitch relaxation of radio pulsars and magnetars in terms of dynamical interaction of vortex lines and toroidally arranged flux tubes in the outer core.

Model Premises

- Vortex lines' orientation is parallel to the rotation axis while flux tubes array acquires very complicated poloidal plus toroidal structure inherited from the progenitor star after superconducting phase transition.
- Vortex lines inevitably intersect with toroidal flux tubes while the interaction with poloidal flux tubes is highly dependent on inclination angle.
- Due to non zero core temperature vortex lines slowly migrate out pinning potentials sustained by flux tubes (i.e. creep) in accordance with stellar spindown.

Model Predictions

- Only the toroidal field region (a rather small portion of core) participates in glitches via decoupling from external torque. This fact accounts for why glitch magnitudes are tiny.
- Neutron star core response to each glitch in spin down rate $\dot{\Omega}$ is exponential recovery:

$$\Delta\dot{\Omega}_c(t) = -\frac{I_{\rm tor}}{I}\frac{\Delta\Omega}{\tau_{\rm tor}}e^{-t/\tau_{\rm tor}}, \tag{1}$$

with the toroidal field region's relaxation timescale

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

where $I_{\rm tor}/I$ is fractional moment of inertia of toroidal field region, T is temperature, B_{ϕ} is strength of toroidal field component, ρ is mass density, $m_{\rm p}^{*}(m_{\rm p})$ is effective (bare) mass of protons, $x_{\rm p}$ is proton fraction, and R is the radius of the location of the toroidal field region.

- As a pulsar ages relaxation timescale (2) becomes longer so that glitches resemble step like changes which are supported by observations [4, 5].

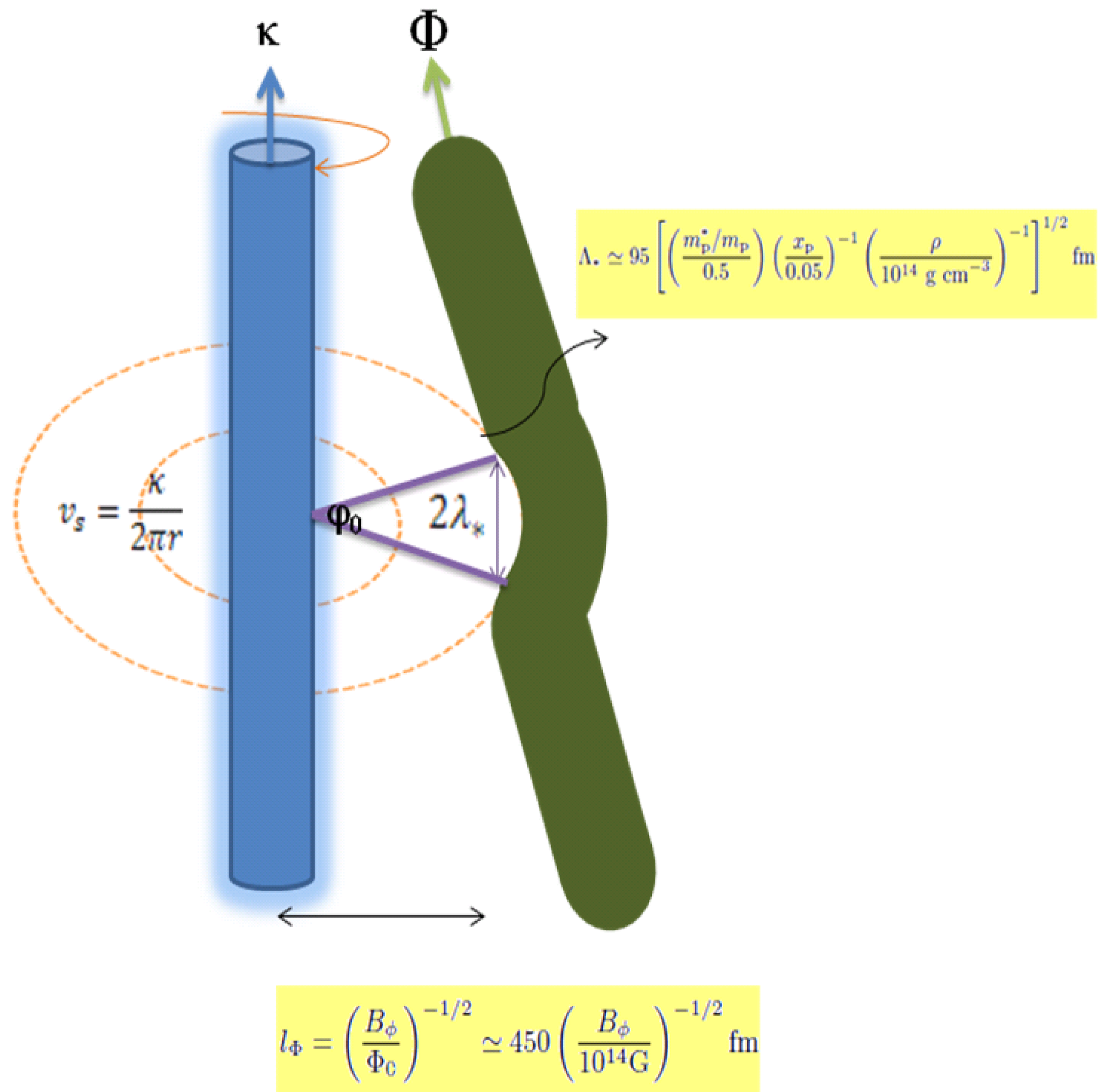

Figure 2: Sketch showing the interaction of a vortex line with single flux tube. From [6].

Results

The change in the spindown rate at the time of a glitch is well described by the fit function [4, 5]

$$\Delta\dot{\Omega}\,(t) = \Delta\dot{\Omega}_{\rm d}\left({\rm e}^{-t/\tau_{\rm d}}\right) + \Delta\dot{\Omega}_{\rm p} = \frac{-Q\Delta\Omega}{\tau_{\rm d}}\left({\rm e}^{-t/\tau_{\rm d}}\right) + \Delta\dot{\Omega}_{\rm p}. \tag{3}$$

Here $\Delta\dot{\Omega}_{\rm d} = -\Delta\Omega_{\rm d}/\tau_{\rm d}$. Upon comparing the fit function (3) with vortex creep across flux tubes model prediction equations (1) and (2) one arrives at three possibilities:

1. If $\tau_{\rm tor} \approx \tau_{\rm d}$, then $I_{\rm tor}/I \sim Q$.
2. If $\tau_{\rm tor} \gg \tau_{\rm d}$ but $Q \ll 1$, then the relaxation of the toroidal field region is not completed yet and one can only say $I_{\rm tor}/I \lesssim 1 - Q$.
3. If $\tau_{\rm tor} \ll \tau_{\rm d}$, then the prompt response of the toroidal flux region is missed from the observations.

Then, post-glitch observations of pulsars enable us to infer macroscopic properties like temperature evolution and internal magnetic field structure, and microscopic traits like equation of state parameters and strength of superfluid-superconductor coupling.

Magnetars, through their unstable spindown and burst like activities, provide strong evidence that both magnetospheric processes and internal superfluid play an important role in their glitches as reflected by anomalous Q values [10]. Model results for magnetars are displayed in Table 1.

Magnetar	Age (10^4 yr)	$B_{\rm d}$ (10^{12} G)	Glitch Date (MJD)	$\Delta\Omega/\Omega$ (10^{-9})	$\Delta\dot{\Omega}/\dot{\Omega}$ (10^{-3})	Q	$\tau_{\rm d}$ (d) (observation)	$\tau_{\rm tor}$ (d) (Modified Urca)	$\tau_{\rm tor}$ (d) (Direct Urca)
4U 0142+61	6.8	134	53809	1630(350)	5100(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

Table 1: Magnetar glitch characteristics and model results for two different cooling laws, namely modified Urca and direct Urca.

Conclusions

- Pulsar glitch observations can be used to place stringent constraints on the equation of state.
- Post-glitch exponential decay provide indirect measure for 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 [7].

References

[1] N. Chamel. *PhRvC*, 85:035801, 2012.
[2] Alpar et al. *ApJ*, 276:325, 1984.
[3] Baym et al. *Nature*, 224:872, 1969.
[4] Espinoza et al. *MNRAS*, 414:1679, 2011.
[5] Yu et al. *MNRAS*, 429:688, 2013.
[6] E. Gügercinoğlu. *The Role of Neutron Star Interior in Pulsar Glitches, PhD Thesis*. Istanbul University, 2016.
[7] E. Gügercinoğlu. *MNRAS*, 469:2313, 2017.
[8] E. Gügercinoğlu and M. A. Alpar. *ApJL*, 788:L11, 2014.
[9] E. Gügercinoğlu and M. A. Alpar. *MNRAS*, 462:1453, 2016.
[10] E. Gügercinoğlu and M. A. Alpar. *preprint*, arXiv:1706.05662, 2017.