Journal of Physics: Conference Series

Glitches as probes of neutron star internal structure and dynamics: Effects of the superfluid-superconducting core

To cite this article: Erbil Gügercinolu 2017 *J. Phys.: Conf. Ser.* **932** 012037

International Conference Physics of Neutron Stars - 2017. 50 years after. IOP Publishing
IOP Conf. Series: Journal of Physics: Conf. Series **932** (2017) 012037 doi:10.1088/1742-6596/932/1/012037

Glitches as probes of neutron star internal structure and dynamics: Effects of the superfluid-superconducting core

Erbil Gügercinoğlu

Faculty of Engineering and Natural Sciences, Sabanci University, Orhanli, Tuzla, 34956 Istanbul, Turkey

E-mail: `egugercinoglu@gmail.com`

Abstract. Glitches, sudden spin-up of pulsars with subsequent 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 (NS) 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 relaxation behavior 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 NSs. 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.

1. Introduction

Pulsars are rapidly rotating NSs. Being exceptionally stable rotators, they rival the best atomic clocks. This fact alone allows to obtain a precise timing solution after observing frequency ν and spin-down rate $\dot{\nu}$. It enables one to predict NS rotational evolution with high accuracy. However, pulsars, especially the young ones, show stochastic wandering, i.e. noise in their phase, rotation period and spin-down rate [1], rendering some level of fluctuations in measurements. Moreover, regular long-term spin-down of pulsars is observed to be occasionally interrupted by sudden spin-ups in their rotation rates $\Omega = 2\pi\nu$, i.e. glitches. Glitches appear in timing data as fractional changes in the rotation rate with $\Delta\Omega/\Omega = 10^{-11} - 10^{-5}$. They are usually accompanied by larger jumps in the spin-down rate, $\Delta\dot{\Omega}/\dot{\Omega} = 10^{-4} - 10^{-1}$ [2–4]. Both changes tend to recover fully or partially on timescales of the order of several days to a few years.

Glitch monitoring demonstrated for the first time that NSs contain superfluid at the highest observable densities and temperatures; since sudden spin-up with long relaxation give indirect evidence for bulk superfluidity in NS matter [5]. Recent observation of decline in surface flux of the 330 yr old Cas A NS also confirmed a transition into superfluid/superconducting state in the core with temperature $T \leq 10^{8-9}$ K [6]. Anderson and Itoh [7] in their seminal paper explained glitches in terms of catastrophic unpinning of vortex lines, i.e. topological defects within a superfluid carrying angular momentum, from ambient normal matter crystal in the NS crust. The standard model, i.e. the vortex creep model by Alpar et al. [8] invokes the interaction of vortex lines of the NS inner crust with the crystal nuclei to account for the glitch occurrence and post-glitch relaxation. In the vortex creep model, the coupling between the superfluid and crust is maintained by the thermally activated migration of vortex lines at a presumed lag $\omega \equiv \Omega_{\rm s} - \Omega_{\rm c}$ between the superfluid and crustal rotational rates. At the time of a glitch, vortex lines rip off from pinning centers and impart their angular momentum to the crust. As a consequence, the crust spins-up and the lag decreases. Hence the coupling weakens. This results in decoupling of that superfluid region from the externally decelerating magnetospheric dipole and/or wind torques. Since the external torque is now acting on a smaller moment of inertia, the spin-down rate increases following a glitch. Post-glitch recovery appears as recoupling of glitch affected superfluid region to the crust.

Various phases of glitch observations have strong potential of constraining and extracting information about NS internal structure and dynamics. In this paper, it is shown how the occurrence, magnitudes and relaxations of glitches observed from canonical radio pulsars and magnetars can be used to probe different physical processes inside NSs.

2. Glitch occurrence as neutron star probe

Surprisingly, the origin of pulsar glitches still remains controversial although it has been intensively studied for about half of an century. Nevertheless, the occurrence of glitches may shed light on the internal structure of NSs. It appears that there are at least two different behaviors and spin-up timescales related to the glitches. The well-known quasi-periodic giant glitcher, the Vela pulsar, undergoes large spin-ups with a timescale less than 40 s [9]. Its glitches initially show abrupt fall off from a large value. Conversely, the glitches typical for the Crab pulsar are somewhat weaker and display a day long comparatively slow, extended spin-up [10]. In the literature, different mechanisms based on superfluid dynamics were proposed to trigger glitches. For instance, crustquake induced vortex unpinning and avalanches from high density vortex traps [11] may account for the Crab and the Vela glitching behaviors, respectively. While studying crustquakes, one can investigate two important parameters, the strain-stress relation and the yield strength of the NS crust [12]. On the other hand, by investigating vortex traps, one can study the impact of crust breaking and impurity on the distribution of vortex lines within the crust [13]. Also, as a crustal-driven mechanism, coupling of vortex oscillations, i.e. kelvons, to lattice phonons was proposed to account for rapid angular momentum exchange between crustal superfluid and charged normal matter [14]. Through this mechanism one can clarify the dependence of phonon spectrum and angular momentum reservoir efficiency on the temperature evolution of the crust. Furthermore, interaction of crustal magnetic field with flux tubes in the outer core may give rise to extra pinning barrier for vortex lines [15]. This mechanism may help to understand the effects of transition into superconducting state and expulsion of magnetic field in the form of Meissner currents [16].

3. Glitch magnitudes as neutron star probe

In the vortex creep model, as well as in other models, glitch magnitudes in the rotation rate $\Delta\Omega/\Omega$ and in the spin-down rate $\Delta\dot{\Omega}/\dot{\Omega}$ are directly related to the superfluid region(s) involved in glitches. Thus, the glitch magnitudes are a measure of the glitch affected crustal superfluid moment of inertia and the equation of state [8,17,18]. This picture has been challenged theoretically [19]. Recent band theory calculations by Chamel [20] revealed that Bragg scattering of free neutrons on crystal somewhat reduces the mobility of crustal superfluid neutrons and, accordingly, the angular momentum reservoir [21,22]. This crustal mass entrainment effect suggests involvement of the core superfluid in the glitches. Gügercinoğlu and Alpar [23,24] have conducted the first principles calculations of glitches in the superfluid-superconducting core.

Vortex creep across flux tubes model [25] 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. In NSs, vortex lines' orientation is parallel to the rotation axis while flux tube 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 of pinning potentials sustained by flux tubes (i.e. creep) in accordance with the stellar spin-down. Model predictions can be summarized as follows:

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

$$\Delta\dot{\Omega}_{\rm c}(t) = -\frac{I_{\rm tor}}{I}\frac{\Delta\Omega}{\tau_{\rm tor}}\exp\left(-\frac{t}{\tau_{\rm tor}}\right), \tag{1}$$

with the toroidal field relaxation timescale [23]

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

where $I_{\rm tor}/I$ is fractional moment of inertia of the toroidal field region, T is the temperature, B_ϕ is the strength of the toroidal field component, ρ is the mass density, $m_{\rm p}^*(m_{\rm p})$ is the effective (bare) mass of protons, $x_{\rm p}$ is the proton fraction, and R is the radius of the location of the toroidal field region.
- As a pulsar ages relaxation timescale (2) becomes longer and the glitches resemble step-like changes which are supported by observations [2,3].

With entrainment in the crustal superfluid taken into account, the angular momentum balance gives [23]

$$\frac{\Delta\Omega_{\rm c}}{\delta\Omega_{\rm s}} \leq \frac{m_{\rm n}}{m_{\rm n}^*}\frac{I_{\rm cs}}{I-I_{\rm cs}-I_{\rm tor}}, \tag{3}$$

where $\delta\Omega_{\rm s}$ and $I_{\rm cs}$ denote change in the superfluid rotation rate and the crustal superfluid moment of inertia, respectively. $m_{\rm n}^*/m_{\rm n} > 1$ characterizes the mass entrainment factor [20]. In the NS core, achieving critical threshold for vortex unpinning from the potential sustained by flux tubes is more likely than the case for NS crust if relevant superfluid instabilities occur [24]. Then condition (3) becomes

$$\frac{\Delta\Omega_{\rm c}}{\delta\Omega_{\rm s}} \leq \frac{m_{\rm n}}{m_{\rm n}^*}\frac{I_{\rm cs}+\alpha I_{\rm tor}}{I-I_{\rm cs}-I_{\rm tor}}, \tag{4}$$

where α is the fraction of the toroidal field region in which vortex lines unpinned from the flux tubes participated in the glitch. Thus, glitch magnitude observations yield constraints for the non-dissipative crustal entrainment effect.

4. Glitch relaxation as neutron star probe

Canonical radio pulsars. Temporal evolution of the change in the spin-down rate at the time of a glitch is well described by the fit function [2,3]

$$\Delta\dot{\Omega}(t) = \Delta\dot{\Omega}_{\rm d}{\rm e}^{-t/\tau_{\rm d}} + \Delta\dot{\Omega}_{\rm p} = -Q\,\Delta\Omega\,\tau_{\rm d}^{-1}{\rm e}^{-t/\tau_{\rm d}} + \Delta\dot{\Omega}_{\rm p}. \tag{5}$$

Here $\Delta\dot{\Omega}_{\rm d} = -\Delta\Omega_{\rm d}/\tau_{\rm d}$ and $Q = \Delta\Omega_{\rm d}/\Delta\Omega$ is the ratio of the exponentially decaying fraction to the total glitch magnitude $\Delta\Omega = \Delta\Omega_{\rm d} + \Delta\Omega_{\rm p}$. Upon comparing the fit function (5) with vortex creep across flux tubes model prediction, equations (1) and (2), one arrives at three possibilities [25]:

(i) If $\tau_{\rm tor} \approx \tau_{\rm d}$, then $I_{\rm tor}/I \sim Q$.

(ii) 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 has only an upper bound $I_{\rm tor}/I \leq 1 - Q$.

(iii) If $\tau_{\rm tor} \ll \tau_{\rm d}$, then the prompt response of the toroidal field region is missed from the observations.

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

In the inner crust, a linear regime of creep of vortices against nuclei also results in an exponential post-glitch response with a decay timescale

$$\tau_1 = \frac{kT}{E_{\rm p}} \frac{R\omega_{\rm cr}}{4\Omega_{\rm s} v_0} \exp\left(\frac{E_{\rm p}}{kT}\right), \tag{6}$$

where $v_0 \approx 10^7$ cm/s is microscopic vortex velocity around the nuclei [8,24]. From crustal response one can deduce pinning strength and lattice properties, for which there exist early analytical estimates [26] and recent numerical computations [27].

Magnetars. Magnetar glitches differ from radio pulsar glitches in many respects. Magnetars, through displaying unstable spin-down and burst like activities following their glitches [4], provide strong evidence that both magnetospheric processes and internal superfluid play an important role in their glitch events as reflected by anomalous Q values [28]. Magnetars' different behavior from radio pulsars in general may be related to their unusual properties. Due to magnetic field decay, magnetar spin-down rates are somewhat lower than those of canonical radio pulsars [29]. As a result of the magnetic field decay, magnetars also have higher surface temperatures [30]. In strong and twisted magnetic field configurations, the toroidal field component transfers some of its magnetic energy to the poloidal field so that in magnetars $B_\phi \leq 0.01 B_{\rm p}$ [31]. In order to fit the relaxation timescale (2) to post-glitch observations it is argued that magnetars should have a cooler core [25]. If the density of the core exceeds a critical threshold, the powerful direct Urca process operates. Magnetar surface thermal emission behavior can be explained by a cooler core and a heater in the crust [32]. Therefore, magnetars may have a massive core allowing enhanced cooling processes. This, in turn, implies that magnetars may be originated from massive progenitors in which dynamo processes endowed them with stronger magnetic fields than those of canonical pulsars.

Glitches with external torque variation. High magnetic field pulsars exhibit glitches which have much in common with magnetars. PSR J1119–6127 is observed to have additional pulse components emergent with glitch [33]. PSR J1846–0258 showed violent emission changes and burst activity right after the glitch [34]. These peculiar glitches have some implications for NS structure [35]. Gügercinoğlu and Alpar [28] developed the vortex creep model [8] by taking time varying external torques into account in order to answer these issues. Variable external torque and superfluid coupling results in extra terms in the Q values [28]. An exponentially decaying torque on timescale $\tau_{\rm d}$ added to the pre-glitch level $N_0 = I\dot{\Omega}_\infty$, with $\dot{\Omega}_\infty$ being long-term spin-down rate, yields $N_{\rm ext}(t) = N_0 + \delta N \exp(-t/\tau)$. For this particular choice of time varying external torque post-glitch spin-down rate the evolution is [28]

$$\Delta\dot{\Omega}_{\rm c}(t) = \frac{\delta N}{I_{\rm c}}\,{\rm e}^{-t/\tau}\left(1-\frac{I_{\rm s}}{I}\,\frac{\tau}{\tau-\tau_{\rm d}}\right)+{\rm e}^{-t/\tau_{\rm d}}\,\frac{I_{\rm s}}{I}\left(\frac{\omega(0)}{\tau_{\rm d}}+\frac{I}{I_{\rm c}}\,\dot{\Omega}_\infty+\frac{\delta N}{I_{\rm c}}\,\frac{\tau}{\tau-\tau_{\rm d}}\right). \qquad (7)$$

The same formalism can be applied to sources showing precession like oscillations [36] and anomalous braking indices [37] as well.

5. Conclusions

Pulsar glitch observations enable us to infer NS internal structure in many ways:

- Pulsar glitch observations can be used to place stringent constraints on the equation of state [17,22].
- Post-glitch exponential decay provide indirect measure for magnetic field configuration [25].
- Magnetar glitch observations are best explained by a core in which the direct Urca cooling operates [25].
- Glitches with external torque variation implies a strong coupling between the internal superfluid and spinning down or up magnetospheric or accretion torques [28].

References

[1] Hobbs G, Lyne A G and Kramer M 2010 *Mon. Not. Roy. Astron. Soc.* **402** 1027
[2] Espinoza C M, Lyne A G, Stappers B W and Kramer M 2011 *Mon. Not. Roy. Astron. Soc.* **414** 1679
[3] Yu M et al. 2013 *Mon. Not. Roy. Astron. Soc.* **429** 688
[4] Dib R and Kaspi V M 2014 *Astrophys. J.* **784** 37
[5] Baym G, Pethick C J, Pines D and Ruderman M 1969 *Nature* **224** 872
[6] Shternin P S et al. 2011 *Mon. Not. Roy. Astron. Soc.* **412** L108
[7] Anderson P W and Itoh N 1975 *Nature* **256** 25
[8] Alpar M A, Anderson P W, Pines D, and Shaham J 1984 *Astrophys. J.* **276** 325
[9] Dodson R G, McCulloch P M and Lewis D R 2002 *Astrophys. J. Lett.* **564** L85
[10] Lyne A G et al. 2015 *Mon. Not. Roy. Astron. Soc.* **446** 857
[11] Cheng K S, Alpar M A, Pines D, and Shaham J 1988 *Astrophys. J.* **330** 835
[12] Chugunov A I and Horowitz C J 2010 *Mon. Not. Roy. Astron. Soc.* **407** L54
[13] Warszawski L, Melatos A and Berloff N G 2012 *Phys. Rev. B.* **835** 104503
[14] Epstein R I and Baym G 1992 *Astrophys. J.* **387** 276
[15] Sedrakian A and Cordes J M 1999 *Mon. Not. Roy. Astron. Soc.* **307** 365
[16] Jones P B 2006 *Mon. Not. Roy. Astron. Soc.* **365** 339
[17] Link B, Epstein R I and Lattimer J M 1999 *Phys. Rev. Lett.* **83** 3362
[18] Antonelli M and Pizzochero P M 2017 *Mon. Not. Roy. Astron. Soc.* **464** 721
[19] Chamel N and Carter B 2006 *Mon. Not. Roy. Astron. Soc.* **368** 796
[20] Chamel N 2013 *Phys. Rev. Lett.* **110** 011101
[21] Andersson N, Glampedakis K, Ho W C G and Espinoza C M 2012 *Phys. Rev. Lett.* **109** 241103
[22] Delsate T, Chamel N, Gürlebeck N, Fantina A F, Pearson J M and Ducoin C 2016 *Phys. Rev. D.* **94** 023008
[23] Gügercinoğlu E and Alpar M A 2014 *Astrophys. J. Lett.* **788** L11
[24] Gügercinoğlu E and Alpar M A 2016 *Mon. Not. Roy. Astron. Soc.* **462** 1453
[25] Gügercinoğlu E 2017 *Mon. Not. Roy. Astron. Soc.* **469** 2313
[26] Alpar M A 1977 *Astrophys. J.* **213** 527
[27] Seveso S, Pizzochero P M, Grill F and Haskell B 2016 *Mon. Not. Roy. Astron. Soc.* **455** 3952
[28] Gügercinoğlu E and Alpar M A 2017 *Mon. Not. Roy. Astron. Soc.* **471** 4827
[29] Dall'Osso S, Granot J and Piran T 2012 *Mon. Not. Roy. Astron. Soc.* **422** 2878
[30] Beloborodov A M and Li X 2016 *Astrophys. J.* **833** 261
[31] Fujisawa K and Kisaka S 2014 *Mon. Not. Roy. Astron. Soc.* **445** 2777
[32] Kaminker A D, Potekhin A Y, Yakovlev D G and Chabrier G 2009 *Mon. Not. Roy. Astron. Soc.* **395** 2257
[33] Weltevrede P, Johnston S and Espinoza C M 2011 *Mon. Not. Roy. Astron. Soc.* **411** 1917
[34] Livingstone M A, Kaspi V M and Gavriil F P 2010 *Astrophys. J.* **710** 1710
[35] Akbal O, Gügercinoğlu E, Şaşmaz Muş S and Alpar M A 2015 *Mon. Not. Roy. Astron. Soc.* **449** 933
[36] Ashton G, Jones D I and Prix R 2017 *Mon. Not. Roy. Astron. Soc.* **467** 164
[37] Ou Z W, Tong H, Kou F F and Ding G Q 2016 *Mon. Not. Roy. Astron. Soc.* **457** 3922