INVESTIGATING SUPERCONDUCTIVITY IN NEUTRON STAR INTERIORS WITH GLITCH MODELS

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ABSTRACT

The high-density interior of a neutron star is expected to contain superconducting protons and superfluid neutrons. Theoretical estimates suggest that the protons will form a type II superconductor in which the stellar magnetic field is carried by flux tubes. The strong interaction between the flux tubes and the neutron rotational vortices could lead to strong "pinning," i.e., vortex motion could be impeded. This has important implications especially for pulsar glitch models as it would lead to a large part of the vorticity of the star being decoupled from the "normal" component to which the electromagnetic emission is locked. In this Letter, we explore the consequences of strong pinning in the core on the "snowplow" model for pulsar glitches, making use of realistic equations of state and relativistic background models for the neutron star. We find that, in general, a large fraction of the pinned vorticity in the core is not compatible with observations of giant glitches in the Vela pulsar. Thus, the conclusion is that either most of the core is in a type I superconducting state or the interaction between vortices and flux tubes is weaker than previously assumed.

Key words: dense matter – pulsars: individual (PSR J0835−4510) – stars: neutron

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1. INTRODUCTION

Neutron stars (NSs) allow us to probe the state of matter in some of the most extreme conditions in the universe. Not only can the density in the interior of these very compact objects exceed nuclear saturation density, but NSs also host some of the strongest magnetic fields in nature, with intensities of up to $\approx 10^{15}$ G for magnetars. Not surprisingly, modeling such complex objects requires the use of some poorly understood physics.

In particular, the star will rapidly cool below the critical temperature for the neutrons to be superfluid and the protons to be superconducting. The protons of the outer core are predicted to form a type II superconductor (Migdal 1959; Baym et al. 1969), in which the magnetic flux is confined to flux tubes, inside which the magnetic field strength is of the order of the lower critical field for superconductivity, $B_c \approx 10^{15}$ G. However, above a critical density of approximately $\rho_c \approx 3 \times 10^{14}$ g cm^{-3}, one expects a transition to type I superconductivity in which the formation of flux tubes is no longer favorable but rather the magnetic field is contained in regions of normal protons (Sedrakian 2005). Given that the critical density for this transition is easily reached in NS interiors, it is possible that a sizeable portion of the star may in fact be in a type I superconducting state (Jones 2006).

The dynamics of the outer core play a crucial role in the interpretation of various astrophysical phenomena, such as pulsar glitches, timing noise, precession, and fluid oscillations. In particular, pulsar glitches are sudden increases in the otherwise steadily decreasing rotational frequency of a pulsar. Although their origin is still debated, it is generally thought that these phenomena are the direct manifestation of a superfluid component inside the star, which is only weakly coupled to the normal component due to the interaction between the quantized neutron vortex lines and the charged particles in the crust or core.

In particular, if vortices can "pin" (i.e., are strongly attracted) to the Coulomb lattice in the crust, they can decouple the neutron superfluid from the normal component (to which the electromagnetic emission is locked) and their sudden depinning will give rise to a rapid transfer of angular momentum, i.e., a glitch (Anderson & Itoh 1975; Alpar 1977; Pines et al. 1980; Alpar et al. 1981; Anderson et al. 1982). Recent work has shown that this scenario can successfully account for the distribution in glitch sizes and waiting times (Warszawski & Melatos 2008, 2011, 2012; Melatos & Warszawski 2009) and describe the size and relaxation timescales of giant glitches in the Vela pulsar (Pizzochero 2011; Haskell et al. 2012b).

An important issue to address, however, is whether or not vortices will only pin to the crustal lattice or if they are pinned to flux tubes when the outer core is in a type II superconducting state (Link 2003), thus effectively decoupling a large fraction of the stellar moment of inertia from the crust. Furthermore, if vortices are pinned in the core, this is likely to lead to the onset of turbulence and may play an important role in pulsar "timing noise" (Link 2012b). The interaction between flux tubes and vortices can also have a strong impact on the gravitational wave (GW) driven r-mode instability (Ho et al. 2011; Haskell et al. 2012a) and on NS precession (Link 2003).

In this Letter, we investigate the effect of vortex pinning in the core on the "snowplow" glitch model of Pizzochero (2011). We extend the model to realistic equations of state and relativistic stellar models, as in Seveso et al. (2012), and show that, in general, one cannot fit the size and post-glitch jumps in frequency derivatives of Vela giant glitches if a large portion of the core vortices is pinned. This is the same conclusion obtained by Haskell et al. (2012b) when fitting the post-glitch relaxation of Vela. This points to the fact that most of the core could in fact be in a type I superconducting state, or that the vortex/flux tube interaction is weaker than previously assumed, as some microphysical estimates suggest (Babaev 2009).

2. THE "SNOWPLOW" MODEL

The starting point of our investigation will be Pizzochero's (2011) "snowplow" model for glitches, which we briefly review here. We take the NS to be a two-component system, where one of the components, the so-called the "normal" component, is given by the crust and all the charged components tightly coupled to it by the magnetic field. The other, the "superfluid," is given by the superfluid neutrons in the core and crust. The superfluid rotates by forming an array of quantized vortices that carry the circulation and mediate an interaction between the two components known as mutual friction, which in the core can couple the two fluids on timescales of seconds (Andersson et al. 2006). Vortices can, however, also be *pinned* to ions in the crust or flux tubes in the core (Anderson & Itoh 1975; Alpar 1977; Pines et al. 1980; Alpar et al. 1981; Anderson et al. 1982; Ruderman et al. 1998; Link 2003). As a consequence, vortex motion is impeded and the superfluid component cannot spin down, effectively decoupling it from the normal component which is spinning down due to electromagnetic emission. If a lag builds up between the superfluid and the normal component, this will, however, give rise to a Magnus force acting on the vortices, which takes the form $\mathbf{f}_m = \kappa \rho_s \hat{\mathbf{\Omega}} \times (\mathbf{v}_v - \mathbf{v}_s)$, where $\mathbf{f}_m$ is the force *per unit length*, $\kappa = 1.99 \times 10^{-3}$ cm^2 s^{-1} is the quantum of circulation, ρ_s is the superfluid density, $\hat{\mathbf{\Omega}}$ is the unit vector pointing along the rotation axis, $\mathbf{v}_v$ is the velocity of the vortex lines, and $\mathbf{v}_s$ is the velocity of the superfluid. We assume that the neutrons are superfluid throughout the star and take $\rho_s = (1 - x_p)\rho$, with x_p the proton fraction calculated by Zuo et al. (2004) and ρ the density. Once the Magnus force integrated over a vortex exceeds the pinning force, the vortex will unpin and be free to move out.

We follow the procedure of Seveso et al. (2012) and integrate the relativistic equations of stellar structure for two realistic equations of state, SLy (Douchin & Haensel 2001) and GM1 (Glendenning & Moszokowski 1991). We assume straight vortices that cross through the core (Zhou et al. 2004) and for the pinning force per unit length $\mathbf{f}_p$ we use the realistic estimates of Grill & Pizzochero (2012) and F. Grill et al. 2013 (in preparation). Balancing the pinning force to the Magnus force and integrating over the vortex length allows us to calculate the lag at which the vortices will unpin in different regions. The normalization of $\mathbf{f}_p$ is chosen in such a way as to give an inter-glitch waiting time $T_g = \Delta\Omega_{max}/|\dot{\Omega}|$ of approximately 2.8 yr for the Vela pulsar, where $\Delta\Omega_{max}$ is the maximum of the critical unpinning lag.

If there is no pinning in the core, vortices will unpin and move out toward the crust where they encounter a steeply increasing pinning potential and repin. This leads to the creation of a thin vortex sheet that moves toward the peak of the potential, the so-called "snowplow" effect. Once the maximum of the critical lag has been reached the vortices can no longer be held in place and the excess vorticity is released catastrophically, exchanging angular momentum with the normal component and giving rise to a glitch (Pizzochero 2011). We assume that this is the mechanism that gives rise to giant glitches, i.e., glitches with steps in the spin rate $\Delta\Omega_{gl} \approx 10^{-4}$ rad that are observed in Vela and other pulsars (Espinoza et al. 2011). Smaller glitches are likely to be triggered by crust quakes or random vortex avalanches (Warszawski & Melatos 2008, 2011; Melatos & Warszawski 2009). Note that our model is only applicable to pulsars such as Vela that exhibit quasi-periodicity in their glitching behavior such that an average waiting time can be

extracted. Many pulsars, however, show no such periodicity (Melatos et al. 2008). This is likely due to the fact that we are not observing glitches that occur close to the maximum of the pinning force but rather the result of a self-organized critical process (Warszawski & Melatos 2008).

We can easily calculate the number of vortices in the vortex sheet once it has reached the peak of the potential as $N_v = (2\pi/\kappa)r_{max}^2\Delta\Omega_{max}$, where r_{max} is the cylindrical radius at which the maximum of the critical lag is located and $\Delta\Omega_{max}$ is the value of said maximum. The angular momentum exchanged as the vortices move out and annihilate is then given by:

$$\Delta L_{gl} = 2\kappa N_v \int_{r_{max}}^{R_c} x\,dx \int_0^{l(x)/2} \rho_s(\sqrt{x^2 + z^2})dz, \quad (1)$$

where R_c is the radius of the inner crust where the vortices annihilate (taken at neutron drip density) and $l(x)$ is the length of a vortex at a given cylindrical radius x. The glitch observables can then be derived as $\Delta\Omega_{gl} = \Delta L/I_{tot}[1 - Q(1 - Y_{gl})]$ and $\Delta\dot{\Omega}_{gl}/\dot{\Omega}_\infty = [Q(1 - Y_{gl})]/[1 - Q(1 - Y_{gl})]$, where $\Delta\Omega_{gl}$ is the step in angular velocity due to the glitch, $Q = I_s/I_{tot}$ is the superfluid fraction of the moment of inertia, and $\Delta\dot{\Omega}_{gl}/\dot{\Omega}_\infty$ is the *instantaneous* step in the spin-down rate immediately after the glitch, relative to the steady state pre-glitch spin-down rate $\dot{\Omega}_\infty$. We have also introduced the parameter Y_{gl} which represents the fraction of superfluid moment of inertia, and which is coupled to the crust during the glitch. Given that the rise time τ_r is very short (less than a minute; Dodson et al. 2002), it is likely that only a small fraction of the core will be coupled to the crust on this short timescale, with the rest of the star recoupling gradually on longer timescales and giving rise to the observed exponential post-glitch relaxation (see Haskell et al. 2012b for a detailed discussion of this issue). The best observational upper limits on the rise time are $\tau_r < 40$ s (Dodson et al. 2002) from the Vela 2000 glitch while a lower limit of $\tau > 10^{-4}$ ms can be derived from the non-detection of a GW signal from the Vela 2006 glitch (Warszawski & Melatos 2012). Theoretical estimates give $\tau_r \approx 1$–10 s (Haskell et al. 2012b), which easily allows for the angular momentum in Equation (1) to be exchanged during the short rise times that are observed.

Let us now consider the motion of a vortex if the NS core is a type II superconductor. As a vortex approaches a flux tube, its magnetic energy will increase if they are aligned or decrease if they are antialigned resulting in an energy per intersection of approximately $E_p \approx 5$ MeV (Ruderman et al. 1998). Note that we have neglected the contribution associated with the reduction of the condensation energy cost if a vortex and a flux tube overlap. This leads to an energy cost per intersection slightly smaller than that estimated above (Ruderman et al. 1998; Sidery & Alpar 2009). Vortex motion is thus impeded by the flux tubes unless the vortices have enough energy to cut through them. The corresponding pinning force per unit length of a vortex has been estimated to be $f_p \approx 3 \times 10^{15}B_{12}^{1/2}$ dyn cm^{-1} (Link 2003), and is balanced by the Magnus force for a critical relative velocity of $w_c \approx 5 \times 10^3 B_{12}^{1/2}$ cm s^{-1}. This leads to a critical lag (at a radius of 10 km) $\Delta\Omega_c \approx 5 \times 10^{-3}B_{12}^{1/2}$ rad, where we have assumed an average density for the core of $\rho = 3 \times 10^{14}$ g cm^{-3}. Given the large value of the critical lag, comparable to what could be built up between Vela glitches, a substantial part of the vorticity in the core could be pinned.

To account for this effect, we assume that a fraction of the vorticity in the core is pinned and does not contribute to the
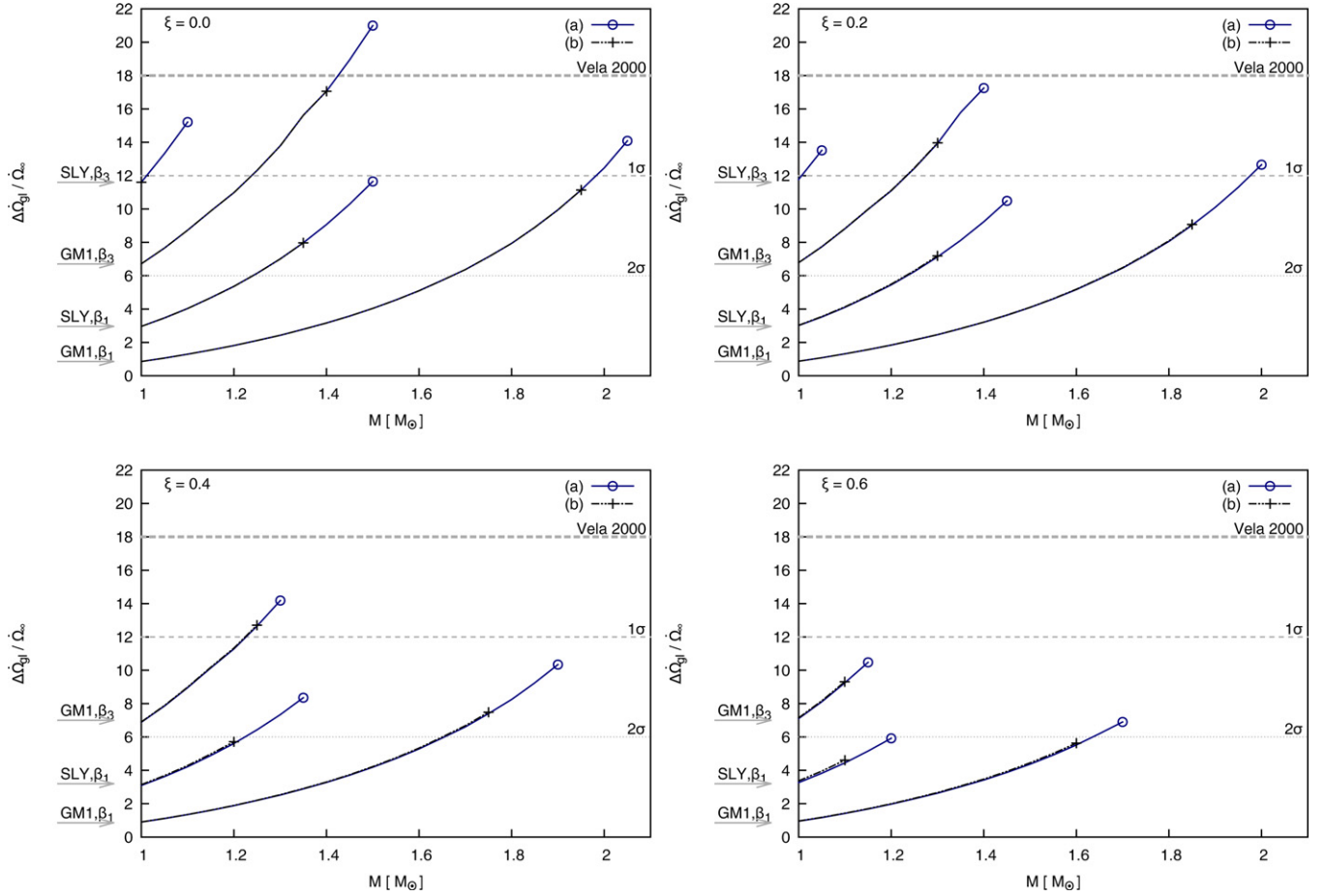
Figure 1. We plot the value of the fractional step in frequency derivative $\Delta\dot{\Omega}/\dot{\Omega}$ for varying values of the fraction of pinned vorticity in the core, ξ for SLy and GM1. The parameter β encodes in-medium polarization effects, as described in the text. For x_p we use the results of Zuo et al. (2004), both those obtained with two-body interactions (case a) and with three-body forces (case b). The end of the curves, indicated with crosses or circles in the two cases, corresponds to the point after which we can no longer find a reasonable physical solution. The horizontal line represents the measured value for the Vela 2000 glitch, and the thin lines are respectively 1σ and 2σ deviations. It is clear that, in general, both equations of state and models for the proton fraction are compatible with free vorticity in the core. As we increase the pinned fraction, however, it becomes increasingly difficult to fit the data, and for $\xi > 0.5$ no fit can be obtained at the 1σ level.

(A color version of this figure is available in the online journal.)

angular momentum stored in the vortex sheet. This is equivalent to assuming that all the vorticity within a radius $R_v = \eta R_b$ is frozen, with R_b the radius of the base of the crust and η a free parameter. We thus define a fraction of pinned vorticity in the core as $\xi = (R_v^2)/(r_{\max}^2)$. The total number of vortices in the vortex sheet before the glitch scales accordingly:

$$N_v = (1 - \xi)\frac{2\pi}{\kappa}\left(r_{\max}^2\right)\Delta\Omega_{\max}. \qquad (2)$$

By using Equation (2) in Equation (1) we can obtain the angular momentum exchanged during the glitch and by fitting the size of a glitch, $\Delta\Omega_{gl}$, we can derive the coupled fraction of superfluid:

$$Y_{gl} = \frac{1}{Q(1 - \xi)}\left[\frac{\Delta L}{\Delta\Omega_{gl}I_{tot}} + Q - 1\right]. \qquad (3)$$

The instantaneous step in the frequency derivative then follows from

$$\frac{\Delta\dot{\Omega}_{gl}}{\dot{\Omega}_\infty} = \frac{Q(1 - \xi)(1 - Y_{gl})}{1 - Q[1 - (1 - \xi)Y_{gl}]} \qquad (4)$$

3. RESULTS

In order to compare our results with observations, we consider the case of the Vela pulsar. The Vela (PSR B0833−45 or PSR

J0835−4510) has a spin frequency $\nu \approx 11.19$ Hz and spin-down rate $\dot{\nu} \approx -1.55 \times 10^{-11}$ Hz s^{-1}. Giant glitches are observed roughly every thousand days and have relative frequency jumps of the order $\Delta\Omega/\Omega \approx 10^{-6}$. The spin-up is instantaneous to the accuracy of the data, with upper limits of 40 s for the rise time obtained from the 2000 glitch (Dodson et al. 2002) and of 30 s for the 2004 glitch, although this limit was less significant (Dodson et al. 2007). The glitch is usually fitted to a model consisting of permanent steps in the frequency and frequency derivative and a series of transient terms. It is well known that to fit the data at least three are required, with decay timescales that range from months to hours (Flanagan 1996). Recent observations of the 2000 and 2004 glitch have shown that an additional term is required on short timescales, with a decay time of approximately a minute. Given that the Vela 2000 glitch provides the most robust observational results, we shall compare the expression in Equation (4) to the step in frequency derivative associated with the short timescale (1 minute) after the Vela 2000 glitch, which we assume is a reasonable approximation to the instantaneous post-glitch step in the spin-down rate. We thus obtain the normalization of the pinning force by fitting the glitch waiting time, and the parameter Y_{gl} is obtained from Equation (3) by fitting to the Vela 2000 glitch size of $\Delta\Omega/\Omega = 2.2 \times 10^{-6}$ (Dodson et al. 2002). This specifies all the parameters of the

model and allows us to calculate $\Delta\dot\Omega_{gl}/\dot\Omega_\infty$, to compare with observations, as described in detail in Seveso et al. (2012).

In Figure 1, we show the results for varying values of ξ, for both SLy and GM1. The parameter β encodes the reduction of the pairing gap due to polarization effects in the neutron medium. Recent calculations suggest that polarization reduces the gap and shifts the maximum to lower densities (Gandolfi et al. 2009), an effect that, in our setting, corresponds to the value $\beta \approx 3$, while $\beta = 1$ corresponds to a bare particle approximation. The horizontal lines show the region that is allowed by the measurements of $\Delta\dot\Omega_{gl}/\dot\Omega_\infty$ for the Vela 2000 glitch. Most equations of state and proton fractions can match this value if all vorticity in the core is free, as was also found by Seveso et al. (2012) and Haskell et al. (2012b), although, for the more realistic case of $\beta = 3$ and three-body interactions included in the calculation of x_p, a stiffer equation of state is favored. We now compare this to the case in which part of the core is in a type II superconducting state and part of the vorticity is pinned. As we can see from Figure 1, as the parameter ξ increases, it becomes increasingly harder to fit the observed values of $\Delta\dot\Omega$ and in most cases this is only possible for a restricted interval of masses. In general, one cannot fit the step in frequency derivative at the 1σ level if more than half of the vorticity in the core is pinned. This points to the conclusion that the vortex/flux tube interaction is weaker than previously assumed and that most of the vorticity in the core is free.

4. CONCLUSIONS

In this Letter we have extended the "snowplow" model of Pizzochero (2011) to account for the possibility that part of the vorticity in the core may be pinned due to the interaction between vortices and flux tubes. We fit the step in frequency and in frequency derivative of the Vela 2000 glitch to obtain constraints on the pinned fraction of vortices in the core and find that both quantities cannot be fitted for reasonable physical parameters if the pinned fraction is larger than 50%. Although we do not deal with the microphysical details of the vortex dynamics in the core, our conclusions are quite general. The only quantity that is needed to evaluate the angular momentum that is exchanged during a glitch is the number of vortices that are stored close to the peak of the pinning potential in the crust. As long as the excess vorticity of the core can be transferred to the equatorial strong pinning region in-between glitches, the details of the vortex motion are not influential.

The general conclusion is that either most of the core is in a type I superconducting state (and the vortex pinning is negligible; Sedrakian 2005) or the vortex/flux tube interaction is weaker than previously thought. This conclusion is compatible with that of Haskell et al. (2012b), who found that a weak coupling between the superfluid and normal component in the core (as would be the case if most of the vortices in the core are pinned) does not allow to fit the shorter post-glitch relaxation timescales of the Vela. The conclusions of this Letter and those of Haskell et al. (2012b) are derived with different methods (in this case by calculating the exchange of angular momentum in a static model and in the case of Haskell et al. 2012b by fitting the post-glitch relaxation with a dynamical multifluid model) and are thus independent, save for the use of the pinning forces calculated in Grill & Pizzochero (2012) and F. Grill et al. 2013, in preparation. Note, however, that the model of Haskell et al. (2012b) neglects the effect of Ekmann pumping at the crust/core

interface, which could play a role in the recovery (van Eysden & Melatos 2010). If such a conclusion is confirmed, it would also have serious implications for NS precession (Link 2003) and for GW emission (Haskell et al. 2008, 2012a; Lander et al. 2012; Ho et al. 2011). On a microphysical level, it is very likely that the interaction between vortices and flux tubes is weaker than the current estimates. Such estimates are, in fact, upper limits on the strength of the pinning force, as they do not account for the finite rigidity of vortices, which could lead to a reduction of a factor 100–1000 (Link 2012b; Grill & Pizzochero 2012; F. Grill et al. 2013, in preparation), as recent theoretical estimates also confirm (S. Seveso et al. 2013, in preparation). Furthermore, recent calculations (Babaev 2009) suggest that in the presence of strong entrainment or gapped Σ^- hyperons, the interaction between flux tubes and vortices will be significantly weaker, and even in the presence of pinning the superfluid may be coupled to the crust on short timescales (Sidery & Alpar 2009). It should also be pointed out that if flux tubes are able to move out with the neutron vortices on the inter-glitch timescale, this could lead to a potential barrier at the crust core interface and a glitch (Sedrakian & Cordes 1999). However, recent quantitative estimates by Glampedakis & Andersson (2011) indicate that in the pinning regime, vortices and flux tubes can be considered essentially immobile on the inter-glitch timescale, as we assume in the present model.

Note that we have assumed straight vortices that cross the core. Superfluid turbulence is, however, a well-known phenomenon in laboratory superfluids and is expected to also occur in NSs (see, e.g., Andersson et al. 2007), especially in the presence of strong pinning (Link 2012a, 2012b). In this case, the vortices will form a turbulent tangle, leading to longer coupling timescales in the outer core and crust (Peralta et al. 2006; Peralta & Melatos 2009). The different components will, however, couple on long inter-glitch timescales. The transition between a laminar and turbulent flow could, however, have a large impact on the glitch mechanism (Peralta et al. 2006; Melatos & Peralta 2007; Peralta & Melatos 2009) and the definition of a pinning force per unit length is significantly more complex in a vortex tangle.

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