The so-called “creeping” motion of the pinned vortices in a rotating superfluid involves “random unpinning” and “vortex motion” as two physically separate processes. We argue that such a creeping motion of the vortices need not be (biased) in the direction of an existing radial Magnus force, nor should a constant microscopic radial velocity be assigned to the vortex motion, in contradiction with the basic assumptions of the “vortex creep” model. We point out internal inconsistencies in the predictions of this model which arise due to this unjustified foundation that ignores the role of the actual torque on the superfluid. The proper spin-down rate of a pinned superfluid is then calculated and turns out to be much less than that suggested in the vortex creep model, hence being of even less observational significance for its possible application in explaining the post-glitch relaxations of the radio pulsars.

I. INTRODUCTION

Spinning down (up) of a superfluid at a given rate is associated with a corresponding rate of outward (inward) radial motion of its vortices. If the vortices are subject to pinning, as it is assumed for the superfluid in the crust of a neutron star, a spin-down would require unpinning of the vortices (from the lattice nuclei). The model of “vortex creep” [1] envisages such a spinning down to occur through quantum tunnelling between adjacent pinning sites. Here, we aim to show that the model is internally inconsistent, and also contradicts the well-known general requirements for a superfluid spin-down process. We argue that, while tunnelling and/or thermal activation could only help the vortices to overcome the pinning barriers, however any possible (radial) motion of the vortices (before repinning) is a separate dynamical process, subject to their equation of motion. The vortex radial motion is, as in the absence of any pinning, determined by the external torque on the superfluid (as a whole including its vortices). The same torque might as well be termed internal with respect to the superfluid and its container, but should be distinguished from the external torque on the container, as well as the internal torque between the superfluid and its vortices. As is well-known, the external torque on a superfluid is primarily exerted on the vortex cores, and may be realized only when the vortices (tend to) have an instantaneous azimuthal velocity relative to the “container” (ie. the crust of the star in this case, consisting of the solid lattice, phonons, and the permeating electron gas). Thus, in the presence of pinning, the vortices may or may not tend to undergo a radial displacement upon unpinning (as for the free vortices in the absence of any pinning); an unpinned vortex might as well repin at the same site. In contrast, the vortex creep model implies the following equivalence:

\[ \text{vortex unpinning} \equiv \text{vortex radial motion}. \] (1)

in the sense that both are related to a single cause, in that model. It should be however apparent that the two are physically distinct processes which in principle may or may not occur simultaneously. In fact, the misconception and mixing of the two processes is inherent in the adopted terminology, ie. “creeping vortices”, which may be replaced by a “random unpinning” followed by a “vortex motion” before repinning. “Creeping” may be indeed saved for the case of vortices (fluxoids) in a superconductor where their (radial) displacements bear no dynamical significance, as such. Clearly, a quantum tunnelling of the vortices between pinning sites at different radial positions (when realized) would involve both the processes simultaneously. Nevertheless, the combined processes would amount to a transition between states with different angular momenta, hence different energies. To invoke such a quantum description of the phenomenon, however, one needs to work out the problem of superfluid spin-down (-up) self-consistently in quantum mechanics, at least qualitatively. The relevant transition rules have to be taken into account, while allowing for a transfer of angular momentum (which is associated with a radial motion of the vortices) between the superfluid and the container/normal fluid. The analogy with the tunnelling of a particle out of a potential well is not straightforward in the case of “hopping” of a vortex if a radial displacement is also involved. A proper consideration for the \( r \)-dependence of the angular momentum carried by a vortex should be made, in order to describe a vortex radial motion in terms of a quantum tunnelling (transition). In contrast, the unpinning event by itself, without any implicitly assumed radial
displacement of the unpinned vortex, might provide a straightforward analogy with the case of particle in a potential well. A quantum mechanical treatment of the spin-down process has not been, so far, addressed in the context of the vortex creep model, and we would likewise adhere to the classical hydrodynamical description of the vortex motion as is commonly adopted [2].

It should be also emphasized that the original prescription of the vortex creep model for the spin-down rate of a pinned superfluid [1] has remained the same throughout all the subsequent applications and modifications of the model [3]. The feature which has been changing is the assumed detailed and complicated picture of the numerous superfluid layers within the crust of a neutron star, having different pinning and unpinning properties. We will be however concerned only with the basic relation suggested in that model for the spin-down rate of a pinned superfluid. More sophisticated treatments of the vortex creep process have also appeared [4,5] discussing the physics of pinning/unpinning in great depths and details. Nevertheless the dynamical significance of the vortex radial motion does not seem to have been emphasized and treated properly, in this context. Moreover, the spin-down (-up) process discussed here is a general phenomenon of the pinned superfluidity, applicable to the laboratory experiments on superfluid Helium [6–9], as well, in addition to its common application in the case of neutron stars. The predicted rate may be indeed tested experimentally, at least in principle. Even though the process has not been so far invoked in this context, however there exist no fundamental reasons against its potential application in future experiments.

In section 2 the well-known physics of superfluid spin-down (up) is stated briefly, highlighting the prime role played by the vortices in communicating the external torque to the bulk superfluid. It is then pointed out that the vortex creep formulation does not incorporate this fundamental role played by the vortices. Section 3 contains our reasoning against the model, in further details. Two misleading assumptions in the model are discussed in the two subsections separately. In section 4 a revised form of the superfluid spin-down rate, in the presence of pinning, is suggested, depending on the two possibilities discussed for the relative azimuthal motion of the unpinned vortices.

II. SPIN-DOWN AND VORTEX CREEP

Superfluid vortices move with the local superfluid velocity except when there is an external force acting on them (see Eqs 3 & 6 below). A torque on the superfluid, acting primarily on the vortices, results in a vortex radial velocity $v_r$ corresponding to a given rate $\dot{\Omega}_s$ of change of the rotation frequency $\Omega_s$ of the superfluid:

$$v_r = -\frac{r}{2\Omega_s} \dot{\Omega}_s,$$

where $r$ is the distance from rotation axis, and $v_r > 0$ is in the outward direction. In the case of pinned vortices the superfluid spin-down, or equivalently the vortex radial motion, is subject to unpinning of the vortices (at least temporarily). The required unpinning of the vortices might be achieved under the influence of a Magnus force $\vec{F}_M$ acting on the vortices, which is given, per unit length, as [2]

$$\vec{F}_M = -\rho_s \vec{\kappa} \times (\vec{v}_s - \vec{v}_L),$$

where $\rho_s$ is the superfluid density, $\vec{\kappa}$ is the vorticity of the vortex line directed along the rotation axis, $\vec{v}_s$ is the local velocity of the superfluid, and $\vec{v}_L$ is the velocity of a vortex-line. Accordingly, if a lag $\omega \equiv \Omega_s - \Omega_c$ exists between the rotation frequency of the superfluid and that of the vortices (pinned and co-rotating with the crust at $\Omega_c$) a radially directed Magnus force $(F_M)_r = \rho_s \kappa \vec{v}_r \omega$ would act on the vortices, where $\omega > 0$ corresponds to an outward directed $(F_M)_r$, vice-versa. A pinned superfluid may therefore follow the steady-state spinning down of its container provided that $\omega > \omega_{\text{crit}}$, where $\omega_{\text{crit}}$ is the critical lag value required for the Magnus force $(F_M)_r$ to overcome the pinning forces. Likewise, any other mechanism for an unpinning of the vortices (say, their random unpinning through quantum tunnelling) would have a role similar (and added) to that of the Magnus force above. The important point to note is that, whatever the unpinning mechanism might be, the basic role played by the vortices in transferring a torque to the superfluid could not be different from that in the absence of any pinning, which is well established [2,10].

In contrast, the existing formulation of the vortex creep model is such that if a superfluid spin-down were to be “driven” by the process of unpinning itself. The evidence is that the suggested spin-down rate is independent of the instantaneous value of the external torque on the superfluid. The fundamental relation in that model for the vortex radial velocity is (Eq. 17 in Ref. [1]):

$$v_r = v_0 \exp \left[ -\frac{E_p}{kT} \frac{\omega_{\text{crit}} - \omega}{\omega_{\text{crit}}}, \right]$$

(4)
where $E_p$ is the pinning energy, $k$ is the Boltzmann constant, $T$ is the temperature, and $v_0$ is a constant referred to as the “typical microscopic velocity” of the unpinned vortices. The relation (Eq. 4) consists of two terms. The exponential term (arising from terms $e^{-\Delta E/kT}$, where $\Delta E$ is the relevant energy barrier; see Eqs 14–16 in Ref. [1]) represents the rate coefficient for the unpinning events. That is, the probability of a vortex being free, in close analogy with the case of unpinning of fluxoids in a hard superconductor [11]. The other term, ie. $v_0$, is an assumed constant velocity for the radial motion of the vortices. Thus, the averaged radial velocity of the vortices as given by Eq. 4, hence the corresponding superfluid spin-down rate (Eq. 2), are obviously independent of the presence or absence of an external torque on the superfluid. We caution again that the fundamental quantity missing in this formula, ie. the actual external torque on the superfluid, should not be confused with the external torque on the container which is further introduced in the formulation of the creep model.

However, Eq. 4 is further transformed, in the creep model, into the following form which artificially introduces the missing role of the actual torque. This is achieved by simultaneously solving the above equation together with the one governing the rotational dynamics of the whole system of the superfluid plus the container, which results in (Eq. 28 in Ref. [1])

$$v_r = v_\infty \exp \left[ -\frac{E_p v_{\infty}}{kT} \frac{\omega_{\infty} - \omega}{\omega_{ext}} \right],$$ (5)

where $v_\infty$ is the average radial velocity corresponding to the steady state spin-down rate $\dot{\Omega}_\infty = \frac{N_{ext}v}{I}$ of the superfluid along with the crust in response to the external torque $N_{ext}$ acting on the crust (the superfluid container), $I$ is the total moment of inertia of the system, and $\omega_{\infty}$ is the steady-state value of the lag defined as the value of $\omega$ in Eq. 4 for which $v_r = v_\infty$. Note that the sign of $v_r$ in Eq. 4 is to be decided by the sign of $\omega$, however in Eq. 5 it is not clear how the sign should be determined since $v_\infty$ might impose a sign for $v_r$, opposite to that required by $\omega$; see item two below. The illusive role of the external torque (even) on the container, represented by $N_{ext}$, hence the inward bias of creeping motions) and $\dot{\Omega}_s$ < 0 (due to the sign of $N_{ext}$, hence the sign of $v_r$), respectively. The artificial appearance of $N_{ext}$ (through $v_\infty$ in Eq. 5) in the model may be best observed from the fact that in the presence of an external torque, $\dot{\Omega}_s > 0$ has been favored in the vortex creep for this case [12]. We note that the above contradictions persist even for the more general form of Eq. 4 (ie. Eq. 16 in Ref. [1]), with a sigmoid dependence instead of the exponential term in Eq. 4; the exponential or the sigmoid terms have no influence on the sign of $v_r$. The above contradictory predictions of the vortex creep model is rather due to the fact that their original relation for the spin-down rate of a pinned superfluid (Eq. 4) makes by itself a definite prediction; there exist no free parameter to be further fixed when it is solved together with the equation governing the dynamics of the whole system. Hence Eq. 5 which is supposed to incorporate also the effect of the external torque is inconsistent with Eq. 4.

III. MAIN OBJECTIONS

The missing role of a torque, between the superfluid and its container, is imitated in the model by virtue of the following two unjustified assumptions, which artificially compensate for the sign and the magnitude of the torque, respectively. Firstly, Eq. 4 is derived assuming that a radial Magnus force causes a radial bias in the (creeping) motion of vortices. Moreover, a constant radial velocity $v_0$ (Eq. 4) has been assigned to the unpinned moving vortices, irrespective of the actual instantaneous torque that may or may not be realized. A detailed discussion of the two points will follow.

A. Radial Bias

The derivation of Eq. 4 in the vortex creep model is based on the assumption that random creeping motion of pinned vortices would be biased in the, say, outward radial direction if there exists a Magnus force acting in the same radial
direction. This has been further argued to be a consequence of the presence of a slope (a bias) in the radial profile of free energy of the vortices (see Fig. 3 in Ref. [1], and also Eq. 5 in Ref. [5]). It is however noted that the slope in the potential energy is realized only if vortices are already moving radially [13]. The slope, arising from the $r$-dependence of the Magnus force (Eq. 3), does not have the usual dynamical interpretation implying a “down-the-hill” motion. In other words, the slope is a consequence of, not a cause for, the motion. This unusual dynamical behavior is of course another aspect of the basic property of the vortices that move in a direction perpendicular to an applied force. It might be instructive to note that the original formulation of the flux creep in hard superconductors had also been criticized on the same footing even though vortices do not play any dynamical role in that context [14]. In short, the derivation of Eq. 4 is unjustified for the obvious reason that a radial Magnus force should not be associated with a radial vortex motion.

Furthermore, the (radial) Magnus force could not be the primary cause of the radial motion of the vortices also because it is an internal force exerted by the superfluid on the vortices and thus could not be the source of a torque on the fluid itself. The role of the Magnus force is rather to assist vortices to overcome the pinning barriers, independent of its direction. That is, it drives the system towards a state similar to the absence of any pinning, by increasing the instantaneous number of free vortices. The subsequent motion of the unpinned vortices until their repinning is decided by the vortex equation of motion [2]:

$$\vec{F}_{\text{ext}} + \vec{F}_M = 0$$  \hspace{1cm} (6)$$

where $\vec{F}_{\text{ext}}$ is the external force on a vortex, per unit length, exerted by the environment of the superfluid (i.e. by the crust). Any radial motion of the vortices, requires (Eqs 3 & 6) a corresponding azimuthal external force $F_{\text{ext}}$ acting on the moving vortices, instantaneously.

B. Constant $v_0$

The vortex creep model also introduces a constant “microscopic” velocity $v_0$, for the vortex radial motion (Eq. 4). Firstly, the term “microscopic” might be misleading, because here one may not think in terms of a microscopic velocity as opposed to a (macroscopic) drift velocity observed in, say, statistical mechanics of gas particles. Superfluid vortices do not obey Newtonian dynamics (or its equivalent formulations) upon which the common notions of the statistical mechanics lie. Thus, unlike ordinary gas particles which have constant microscopic thermal velocities at a given temperature, even in the absence of external forces, a vortex may move with a constant velocity, be it called microscopic or macroscopic, only as long as an external force acts on it, as required by Eq. 6. The above notion of “microscopic velocity” should be interpreted accordingly. Thence, equation 4 may be readily disqualified, given that the other exponential (or $\sinh$) term therein accounts only for the vortex unpinning probability. The obvious reason is that, it assigns a constant radial velocity to the unpinned vortices, irrespective of the presence and the magnitude of the external azimuthal forces which should act on the vortex cores for a spin-down to be achieved. The required torque for a change in the spin frequency of the superfluid is determined by the existing forces, which would equivalently determine (Eqs 3 & 6) the magnitude of the (microscopic) radial velocity of instantaneously moving vortices. The radial motion of vortices during a change in the spin frequency of a superfluid has to be accompanied by a corresponding azimuthal one (in their instantaneous rotating frame). This may be seen directly from a solution of the equation of motion of vortices during a superfluid rotational relaxation (Eq. 9 in Ref. [17], and Eq. 4 in Ref. [18]). A torque may be transmitted to a superfluid only by virtue of the simultaneous and corresponding azimuthal-radial motions of the vortices. The radial motion is initiated by the azimuthal force on vortices, which in turn relies on the vortex azimuthal motion relative to the environment of the superfluid. The constant $v_0$, as in Eq. 4, does not comply to these well-known requirements of the vortex dynamics.

Curiously, no explicit derivation for the constant velocity, and its magnitude $v_0 = 10^7 \text{cm s}^{-1}$, may be found in the related published literature, in spite of its prime significance in determining the rate of spinning down of a superfluid. There exists only a short comment indicating that it is associated with the so-called “Bernoulli forces” [1]. Such a force is defined [13] to be a generalization of the Magnus force in presence of superfluid density variations (between the interior and exterior of the nuclei). The same force, acting as a repulsive central force field between a vortex and the nuclei (i.e. pinning centers), is in fact invoked as part of the pinning forces which prevent a superfluid to respond to an otherwise active torque! The definition [13] is, nevertheless, for an assumed cylindrical geometry of a nucleus, and its generalization to the real spherical case of pinning sites (the nuclei) must be unknown, as is the case with the configuration of vortex lattice inside a spherical container [10]. Hence, the way to a quantitative estimate of the force,
thus \( v_0 \), must be obscured. Notwithstanding, whatever the magnitude of the assumed force might be, the resulting radial velocity could not be a constant.

In the absence of any definite supporting argument, a discussion of the irrelevance of the Bernoulli force to the torque on superfluid would be naturally ambiguous and superficial. Some general remarks might be made, however. A vortex will be subject to the similar central force fields, around its successive unpinning and repinning sites, which would act in azimuthal opposite directions; the two effects might as well cancel out with no net torque being imparted. Moreover, one may ask how the same force could be simultaneously responsible for a stationary pinning condition as well as the torque. Notice that the vortex is assumed to escape the pinning barrier through a quantum tunnelling, thus the pinning potential does not do any work on the vortex, by definition. Finally, since the assumed force arises from a Magnus effect one might doubt whether it is imparted by the nuclei, or by the superfluid itself in which case it could not be the source of a torque on the superfluid.

The external forces on vortices could, in general, be of a viscous drag or a “static” frictional nature \([15,16]\). The latter type, associated with the “pinning” forces should not be however confused with the role of pinning forces on the pinned vortices co-rotating with the pinning centers. In order for the pinning forces to act as frictional forces and impart a net torque on the superfluid the vortices should remain unpinned due to the effect of Magnus force \([15]\). This requires \(|\omega| > \omega_{\text{crit}}\) which means there should be no stationary pinning, hence no “creeping,” to start with. Therefore, the static frictional forces are not relevant to the cases of interest here, given \(|\omega| < \omega_{\text{crit}}\).

**IV. ESTIMATING THE SPIN-DOWN RATE**

A proper formulation of the superfluid spin-down rate in presence of the random unpinning is however straightforward. The corresponding averaged radial velocity \( v_r \) of the vortices is determined by the unpinning probability for each vortex times the radial velocity \( v_t \) of an unpinned vortex during its motion until repinning. That is,

\[
v_r = P_u \ v_t \tag{7}\]

where \( P_u \) is the unpinning probability, that is the weight function for the instantaneous number of (unpinned) moving vortices. The unpinning probability, corresponding to the energy barrier \( \Delta E = E_p (1 - \omega/\omega_{\text{cr}}) \), is given as \([11,1]\)

\[
P_u = \exp(-\Delta E/kT) = \exp[-E_p \frac{\omega_{\text{cr}} - \omega}{kT \omega_{\text{cr}}}] \tag{8}\]

Substituting in Eq. 7, the revised spin-down rate of a pinned superfluid is derived as

\[
v_r = v_t \exp[-E_p \frac{\omega_{\text{cr}} - \omega}{kT \omega_{\text{cr}}}]. \tag{9}\]

In contrast to the constant \( v_0 \) in the earlier rate given by Eq. 4, both the magnitude and the (inward or outward radial) direction of \( v_t \), in Eq. 9, are to be determined by the instantaneous azimuthal external force \( F_{\text{ext}} \) (Eq. 6) acting on the moving vortices. The external force, being the viscous drag of the permeating electron (and phonon) gas co-rotating with the crust, depends on the relative azimuthal velocity \( v_{\text{rel}} \) between the crust and the unpinned vortices, and on the associated velocity-relaxation timescale \( \tau_v \) of the vortices. The drag force, per unit length, is given as \([17,18]\)

\[
n_v F_{\text{ext}} = \rho_c \frac{v_{\text{rel}}}{\tau_v}. \tag{10}\]

where \( n_v \) is the number density of the vortices per unit area, and \( \rho_c \) is the effective density of the “crust”. For a given force on the vortices, Eq. 10 might be interpreted as the defining relation for \( \tau_v \), which is the velocity-relaxation timescale of the microscopic constituents of the system (as for, say, particles in a normal gas).

In order to determine \( v_{\text{rel}} \) one might distinguish between two distinct possibilities, which has not been addressed previously. When a vortex becomes unpinned it might be expected to either

1) maintain its overall co-rotation with the pinned vortex lattice; hence

\[
v_{\text{rel}} \sim r \frac{I}{I_s - I_s} \tau_\text{D} \dot{\Omega}_\infty, \tag{11}\]

due to the spinning down of the crust, at a rate \( \dot{\Omega}_\infty \), under the influence of an external torque, where \( \tau_\text{D} \) is the superfluid dynamical coupling timescale (see below), \( I_s \) is the moment of inertia of the superfluid, and \( I \) is that of the superfluid plus its container (ie. the whole star). Else, the unpinned vortex may
ii) jump instantaneously to a rotation frequency $\Omega_L = \Omega_s$; hence

$$v_{\text{rel}} \sim r \omega. \quad (12)$$

Case (i) could arise due to the general requirement for a locally uniform vortex distribution imposed by the minimization of the free energy. Case (ii), on the other hand, might be realized because of (Eq. 6) the presence of an otherwise unbalanced radial force $(F_{\text{M}})$ on an unpinning vortex, also considering the usual approximation of zero inertial mass for a vortex $[2,19]$. Either of the two possibilities might provide a better approximation depending on whether a vortex unpin as a whole along its length (Case ii), or only small segments of it are unpinning randomly. Case (i) is probably more favorable for the superfluid in the crust of neutron stars, given the huge number of the pinning centers along each vortex which prevent a complete unpinning of the whole vortex. In contrast, for laboratory experiments where only the end point(s) of a vortex is pinned the latter case might be more relevant.

In spite of the above uncertainties, a tentative estimate of the magnitude of $v_1$, for each of the two cases, might be instructive. For this purpose, we consider the limiting situation with an unpinning probability $P_u \lesssim 1$. Thus $v_1 = v_r$, and from Eq. 2

$$v_1 = -\frac{r \dot{\Omega}_u}{2 \Omega_s}. \quad (13)$$

On the other hand, for an assumed two-component model of the superfluid plus the “crust”, the superfluid spin-down rate may be given as [20]

$$\dot{\Omega}_s \sim \frac{I - I_s}{I} \frac{v_{\text{rel}}}{r \tau_D}, \quad (14)$$

in accord with the estimate given in Eq. 11.

The relation between $\tau_D$ and the vortex velocity relaxation timescale, $\tau_v$, may be determined from a solution of the vortex equation of motion (Eq. 6). This will indeed secure the crucial dependence of the microscopic velocity $v_1$ of the unpinned vortices on the instantaneous external forces $(F_{\text{ext}})$ acting on them; the vital dependence that is missing in the creep model. The quantity $\tau_D$ is the macroscopic timescale for the dynamical coupling of the assumed two-component model of the superfluid and its container (ie. the rest of a neutron star apart from the superfluid). In other words, $\tau_D$ is the time needed for the simultaneous readjustment of the vorticities as a whole, in both the radial and azimuthal directions, in response to a given torque on the superfluid. The calculated general relation between $\tau_D$ and $\tau_v$ [15,18] gives the following approximate relation:

$$\tau_D \sim \frac{I_s}{I} \tau_v. \quad (15)$$

Substituting for $\tau_D$ (Eq. 15) and $\dot{\Omega}_s$ (Eq. 14) back in Eq. 13 one derives

$$v_1 \sim \frac{(I - I_s)}{I_s} \frac{v_{\text{rel}}}{2 \Omega_s \tau_v}. \quad (16)$$

Finally, either of the two estimates given for $v_{\text{rel}}$ (Eq. 11 or 12), may be substituted for to derive

$$v_1 \sim \frac{2 \Omega_\infty}{2 I_s} \frac{\dot{\Omega}_\infty}{r \omega} \frac{\omega}{\tau_v} \quad \text{case (i)}$$

$$v_1 \sim \frac{2 I_s}{2 I_s} \frac{\omega}{\tau_v} \quad \text{case (ii)}, \quad (17)$$

A comparison of the corresponding spin-down rate of the pinned superfluid in the crust of a neutron star with that predicted in the creep model would be instructive. Using typical values of the parameters such as $r \sim 10^6$ cm, $\Omega_s \sim 10^2$grad s$^{-1}$, $I_s/I \sim 0.02$, $\Omega_\infty \sim 10^{-10}$grad s$^{-2}$, $\omega \sim 10^{-2}$rad s$^{-1}$, $\tau_v \sim 10^{-1}$s, one obtains $v_1 \sim 10^{-3}$, or $10^3$ cm s$^{-1}$, for the two cases, respectively, in contrast with $v_0 = 10^6$ cm s$^{-1}$. Therefore, the rate of spinning down of a superfluid by virtue of random unpinning of its vortices (from Eqs 2, 9, and 17) may as well be much less, up to 12 orders of magnitudes, than that predicted in the vortex creep model. Consequently, the spinning down of the superfluid in the crust of a neutron star, through random unpinning of its pinned vortices, would have no significant effects on the observable post-glitch spin-down behavior of the star.

Further studies should indicate which of the two cases, (i) or (ii), is relevant (if at all) and thus determine the radial creep rate appropriately. It has to be verified that a torque may be imparted on a superfluid while a large fraction
of its vortices and/or a large part of each creeping vortex is pinned. Microscopic description of the vortex motion should indicate the extent to which any single vortex may deviate from Eq. 6 and behave independently (if at all). Otherwise a generalization of the idea of creeping of the fluxoids, in random directions, to the vortices of a stationary rotating superfluid would be moot. While Magnus force and/or thermal activation (quantum tunnelling) could cause unpinning however the subsequent radial motion of the released vortices might as well be “truncated”, except in the presence of an external torque on the superfluid.

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