Peculiar Glitch of PSR J1119-6127 and Extension of the Vortex Creep Model

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ABSTRACT

Glitches are sudden changes in rotation frequency and spin-down rate, observed from pulsars of all ages. Standard glitches are characterized by a positive step in angular velocity ($\Delta \Omega > 0$) and a negative step in the spin-down rate ($\Delta \dot{\Omega} < 0$) of the pulsar. There are no glitch-associated changes in the electromagnetic signature of rotation-powered pulsars in all cases so far. For the first time, in the last glitch of PSR J1119-6127, there is clear evidence for changing emission properties coincident with the glitch. This glitch is also unusual in its signature. Further, the absolute value of the spin-down rate actually decreases in the long term. This is in contrast to usual glitch behaviour. In this paper we extend the vortex creep model in order to take into account these peculiarities. We propose that a starquake with crustal plate movement towards the rotational poles of the star induces inward vortex motion which causes the unusual glitch signature. The component of the magnetic field perpendicular to the rotation axis will decrease, giving rise to a permanent change in the pulsar external torque.

1 INTRODUCTION

The 2007 glitch of PSR J1119-6127 is unusual and interesting as the first case with clear indications of changing pulsar emission properties coincident with the glitch. The event is also unusual in its long term signature of decreased spin-down rate. These signatures require an extension of the vortex creep model which has become the standard model for evaluating glitches and post-glitch response. The extension of the model must also make allowance for changes in the pulsar torque suggested by the glitch related changes in emission properties.

Glitches are sudden increases in the rotation rate of pulsars followed by relaxation towards the pre-glitch state. The fractional change of the angular velocity, $\Delta \Omega/\Omega$, in a glitch is in the range $\sim 10^{-10} - 10^{-5}$. Glitches are usually accompanied by jumps in the spin-down rate, $\Delta \dot{\Omega}/\dot{\Omega}$, in the range $\sim 10^{-4} - 10^{-2}$. To date, about 400 glitches have been observed in more than a hundred pulsars (Espinosa et al. 2011, Yu et al. 2013). Since the earliest glitch observations, the sudden changes in rotation frequency and spin-down rate were seen to relax back towards the pre-glitch values on timescales of days to years. This is interpreted as a signature of superfluid interior components of the neutron star (Baym, Pethick & Pines 1969), as a star composed of normal matter would relax much faster.

Several models have been proposed to explain glitches and post-glitch relaxation. In the early starquake model (Ruderman 1969), the solid crust of the neutron star occasionally cracks under stresses induced by the ongoing spin-down of the star, thereby readjusting to a less oblate shape closer to the equilibrium shape that a fluid star would follow while spinning down. By conservation of angular momentum, the reduction in moment of inertia of the crust is accompanied by an increase in its angular velocity. Glitches in the Crab pulsar (Wong, Backer & Lyne 2001) and PSR J0537-6910 (Middleditch et al. 2006) can be explained by this model. However, starquakes cannot explain large glitches that repeat every few years, as exhibited by the Vela pulsar (Baym & Pines 1971). The required rate of dissipation of elastic energy stored in the solid crust would produce an X-ray luminosity enhancement which is not observed (Gürkan et al. 2000).

The standard model for the pulsar glitches is the vortex pinning–unpinning (vortex creep) model based on the dynamics of the neutron star’s superfluid interior (Anderson & Itoh 1973, Alpar et al. 1984). This model invokes the minimal storage and dissipation of energy for a star with angular momentum. The expected energy dissipation in a large glitch, at the expense of the rotational kinetic energies of the two components, does not violate any observational upper bounds. Models based on pinned superfluid components can explain the various modes of glitch and post-glitch behaviour (Haskell, Pizzochero & Sidery 2012, Haskell & Antonopoulos 2014). Radio pulsar glitches observed up to the 2007 glitch of PSR J1119-6127 (Weltevrede, Johnston & Espinoza 2011) showed no glitch correlated changes in the electromagnetic signatures, like pulse shape, emission pattern, spectrum and polarization. Previous applications of the vortex creep and starquake models assumed that there were no changes in the pulsar torque at the time of the glitch. Glitches and post-glitch response were explained entirely in terms of the
internal structure and dynamics of the neutron star. The 2007 glitch of PSR J1119-6127 shows clear evidence for changing emission properties induced by the glitch, switching on intermittent pulses (see, e.g., Kramer et al. 2006) and also showing rotating radio transient (RRAT) behaviour (see, e.g., Keane & McLaughlin 2011). Interestingly, this glitch also displayed $\Delta \Omega > 0$ after transients have decayed, in contrast to the signatures of “standard” glitches which are characterized by a negative step in spin-down rate ($\Delta \Omega < 0$). The high magnetic field radio pulsar PSR J1846-0258 had comparable glitch-induced emission changes (Livingstone, Kaspi & Gavriil 2010). The radio pulsar PSR J0742-2822 showed a suggestive connection between glitch activity and radio emission and pulse shape features and glitch activity, however there is currently little direct evidence to establish a robust link between them due to absence of enough data following the glitch date (Keith, Shannon & Johnston 2013). The RRAT J1819-1458 was also reported to have an increase in its activity associated with a glitch (Lyne et al. 2009).

In this paper we analyze the 2007 glitch of PSR J1119-6127 and extend the vortex creep model to include the possibility of a sudden change in the pulsar torque associated with the glitch, as suggested by the changing emission properties, and to address the atypical glitch signature. In §2 we summarize the unique properties of the 2007 glitch of PSR J1119-6127. In §3 we review the vortex creep model, while in §4 we develop the model to include the unusual signatures in the spin frequency and spin-down rate, and allow for glitch associated changes in the pulsed torque. We apply our extended model to the peculiar glitch of PSR J1119-6127 in §5. We discuss our results in §6.

2 THE PECULIAR GLITCH OF PSR J1119-6127

PSR J1119-6127 is a young pulsar with a period $P = 0.41$ s and a period derivative $\dot{P} = 4 \times 10^{-12}$ Hz s$^{-1}$ discovered by Camilo et al. (2000). It has a characteristic age $\tau_c \equiv P/(2P) \sim 1625$ years, and a high surface dipole magnetic field $B \sim 8.2 \times 10^{13}$ G (at the poles). This pulsar has exhibited three glitches (Camilo et al. 2000; Weltevrede, Johnston & Espinoza 2011). The third glitch, which occurred in 2007, was quite unusual in a number of ways (Weltevrede, Johnston & Espinoza 2011):

(i) For a while after the initial exponential relaxation is completed, the pulsar is found to be rotating with a smaller angular velocity as compared to the pre-glitch value, $\Delta \Omega(t) < 0$. In the latest data $\Delta \Omega(t) > 0$, and may be settling at a positive value (Antonopoulou et al. 2014).

(ii) In the long term, the pulsar slows down at a lower rate; the absolute value of the spin-down rate is less (the frequency derivative is greater) than its pre-glitch value, $\Delta \dot{\Omega} > 0$.

(iii) While the fractional changes in angular velocity are small, of the order of $10^{-3}$, for the glitches of the Crab pulsar, Vela and older pulsars undergo large glitches of size $\Delta \Omega/\Omega \sim 10^{-6}$ as well as smaller “Crab-like” events. The 2007 glitch of PSR J1119-6127 is a “Vela-like” giant glitch from a young pulsar comparable to the Crab pulsar in characteristic age.

(iv) The radio emission properties of PSR J1119-6127 displayed changes associated with the glitch. The pulsar switched on intermittent pulses and also showed RRAT behaviour which seems to have emerged with the glitch. This anomalous emission behaviour of PSR J1119-6127 was observed for about three months following the 2007 glitch.

The much smaller second glitch which occurred in 2004 may have had similar signatures in the long term post-glitch frequency and frequency derivative remnants (Antonopoulou et al. 2014). The data is sparse, and post-glitch evolution may have been interrupted by the arrival of the 2007 glitch. Furthermore, no glitch associated changes in emission properties were observed for the 2004 glitch. Here we address only the 2007 glitch.

3 OVERVIEW OF THE VORTEX CREEP MODEL

The vortex creep model (Alpar et al. 1984; Alpar, Cheng & Pines 1983) attempts to explain the processes which cause both the glitches and the post-glitch relaxation in terms of a number of distinct superfluid regions in the inner crust. The superfluid core of the neutron star is coupled to the external torque on very short timescales, via electron scattering off magnetized vortices (Alpar 1977; Alpar, Langer & Sauls 1984). The core superfluid therefore behaves as part of the effective normal matter crust. Hence the superfluid component relevant for glitch and postglitch dynamics is the crust superfluid. A description of the core superfluid blue as well as the crustal superfluid in terms of mutual friction forces acting upon vortex lines is given by Andersson, Sidery & Comer (2006).

The dynamics of the crust superfluid is constrained by the pinning of the quantized vortex lines to nuclei, interstitial positions and possibly other structures in the crust lattice (Alpar 1977; Link & Epstein 1991; Mochizuki et al. 1993; Avogadro et al. 2008; Pizzochero 2011; Haskell, Pizzochero & Sidery 2012; Seveso et al. 2014). When vortices pin to nuclei, they move with the crust’s velocity. A lag $\omega = \Omega_c - \Omega$, builds up between the superfluid and the crustal angular velocities $\Omega_c$ and $\Omega$, as the crust spins down under the external pulsar torque. This lag is sustained by the pinning forces acting upon the vortex line. In the case of rotational (cylindrical) symmetry, the magnitude of the required pinning force (per unit length) is $f = r \rho_s \kappa \omega = r \rho_s \kappa (\Omega_c - \Omega)$, where $r$ is the distance from rotation axis, $\rho_s$ is superfluid density, $\kappa$ is the quantum of vorticity. The critical (maximum) lag $\omega_{cr}$, determined by the maximum available pinning force, is given by $\omega_{cr} = E_p/(\rho_bp_s\kappa \xi)$. Here $E_p$ is pinning energy, $\xi$ is the vortex core radius and $b$ is the distance between successive pinning sites along the vortex line. If local fluctuations in vortex density and superfluid velocity raise $\omega_{cr}$, there will be sudden unpinning and outward motion which can lead to an avalanche of vortex discharge (Anderson & Toh 1973). By conservation of angular momentum this leads to speeding up of the crust, $\Delta \Omega_c > 0$, observed as a glitch. The possibility of such vortex unpinning avalanches taking place spontaneously was confirmed by computer simulations (Melatos & Warszawski 2009; Warszawski & Melatos 2011; Warszawski, Melatos & Berloff 2012).
Extension of the Vortex Creep Model

Apart from the discontinuous angular momentum imparted to the crust by sudden vortex unpinning at glitches, the superfluid also spins down continuously between glitches by outward flow of vortices. The crustal neutron superfluid follows the spin-down of the crust by means of thermally activated outward creep of vortex lines against the pinning energy barriers \cite{Alpar1984, Alpar1989a}.

In terms of a simple two component model, involving the crust and the superfluid component, the observed spin-down of a neutron star’s crust satisfies the equation,

\begin{equation}
I_c \ddot{\Omega}_c = N_{ext} + N_{int} = N_{ext} - I_s \dot{\Omega}_s,
\end{equation}

where \(N_{ext} = R \dot{\Omega}_\infty\) is the external torque on the neutron star which tries to slow down the crust, and \(N_{int}\) is the internal torque arising from the coupling of the superfluid to the crust by vortex creep and tends to speed up the crust. \(I_c\) is the moment of inertia of the effective crust (including the superfluid core of the neutron star), \(I_s\) is the moment of inertia of the pinned superfluid, while their spin-down rates are \(\dot{\Omega}_c\) and \(\dot{\Omega}_s\), respectively. The spin-down rate \(\dot{\Omega}_c\) of the superfluid is determined by vortex creep \cite{Alpar1984}. The system reaches a steady state when both the superfluid and the crust spin-down at the same rate \(\dot{\Omega}_\infty \equiv N_{ext}/(I_s + I_c)\), sustained at the steady state lag \(\omega_\infty\).

Glitches set the system off from steady state. Post-glitch relaxation is due to the recovery of vortex creep, as the lag \(\omega\) inevitably builds back towards steady state due to the ongoing spin-down of the crust under the external pulsar torque. The internal torque is so sensitively dependent on the pinning energy \(E_p\) and the crustal temperature \(T\) that we expect vortex lines in the different regions of the superfluid to respond differently. Depending on the temperature and the local pinning parameters in relation to the external torque, vortex creep can have a linear or nonlinear dependence on the lag \cite{Alpar1989a}.

In the linear regime, the response is linear in the glitch-induced perturbation to the lag \(\omega\) and gives simple exponential relaxation. The relaxation time \(\tau\) is very sensitively dependent on \(E_p/kT\), with \(\tau \propto \exp(E_p/kT)\). The steady state lag \(\omega_\infty = |\dot{\Omega}|_\infty\) is always much less than \(\omega_\infty\) in this regime. From glitch observations, up to four exponential relaxation terms are seen from a particular pulsar \cite{Dodson2007}.

In the opposite regime we have a very nonlinear response to perturbations. The response of a nonlinear creep region \(k\) to the glitch will be \cite{Alpar1984},

\begin{equation}
\Delta \dot{\Omega}_c,k = -\frac{I_s}{T} \ddot{\Omega}_\infty \left[ 1 - \frac{1}{1 + \left(e^{(t_0/kT \tau_n)}/(1 + (e^{(t_0/kT \tau_n)}/(1 + (e^{(t_0/kT \tau_n)}/(1 + (e^{(t_0/kT \tau_n)})^n}\right] \right].
\end{equation}

At the time of glitch, creep in those regions which show nonlinear response can stop temporarily. These regions decouple from rest of the star, so that external torque acts on less moment of inertia. Creep restarts after a waiting time of \(t_0 = \delta \omega / |\dot{\Omega}|_\infty\), since the external torque restores the glitch induced decrease in angular velocity lag. The relaxation time is

\[\tau_{nl} = \frac{kT}{E_p |\dot{\Omega}|_\infty}.\]

In those superfluid regions through which the avalanche of vortices unpinned at the glitch pass, moving rapidly in the radially outward direction, the ensuing reduction \(\delta \omega\) in the superfluid rotation rate determines the offset \(\delta \omega = \delta \Omega_p + \Delta \Omega_c\) in the lag, as \(\delta \Omega_p \gg \Delta \Omega_c\). This results in the response given in Eq. (2), characterized by the waiting time \(t_0 \equiv |\dot{\Omega}|_s / |\dot{\Omega}|_\infty > \tau_{nl}\). There can also be nonlinear creep regions through which no unpinned vortices pass at the glitch, so that \(\delta \omega = \Delta \Omega_c\). In this case \(t_0 = |\dot{\Omega}|_s / |\dot{\Omega}|_\infty\) can be much shorter than \(\tau_{nl}\), and the contribution of such a nonlinear creep region reduces to simple exponential relaxation \cite{Gugercinoglu2014},

\[\Delta \dot{\Omega}_{c,k} = I_s |\dot{\Omega}|_s |\dot{\Omega}|_\infty e^{-t/\tau_{nl}}\]

like in the case of linear creep regions, but with the nonlinear creep relaxation time \(\tau_{nl}\).

If we integrate Eq. (2) with the assumption that the post-glitch superfluid angular velocity decreases linearly in \(r\) over the region, corresponding to uniform density of unpinning vortices, one obtains \cite{Alpar1984},

\[\frac{\Delta \dot{\Omega}_c(t)}{\dot{\Omega}_c} = \frac{I_s}{T} \left(1 - \frac{1 - (t_0/t_0)}{1 + (t_0/t_0)} \ln \left[1 + \frac{1}{1 + \left(e^{(t_0/kT \tau_n)}/(1 + (e^{(t_0/kT \tau_n)})^n\right] \right) \right].
\]

In the limit \(t_0 \gg \tau_{nl}\) this reduces to recovery with a constant \(\dot{\Omega}_c\),

\[\frac{\Delta \dot{\Omega}_c(t)}{\dot{\Omega}_c} = \frac{I_s}{T} \left(1 - \frac{1}{t_0}\right),\]

as observed in the Vela pulsar \cite{Alpar1993} and in most Vela-like giant glitches in older pulsars \cite{Yu2013}. In the above equations \(t_0\) is the maximum waiting time, \(I_s\) is the moment of inertia of the vortex creep region \(A\) where unpinning of the vortices has taken place during the glitch. Vortices unpinning in regions \(A\) pass through regions \(B\) with moment of inertia \(I_B\) before repinning in another creep region \(A\). Regions \(B\) do not participate in spin-down by creep, as they do not sustain pinned vortices. Regions \(B\) contribute to the angular momentum transfer only at glitches, when an avalanche of unpinned vortices moves through them. These regions \(A\) and \(B\) determine the glitch, interglitch and long term behaviour of pulsars \cite{Alpar1993, Alpar1996}.

After the exponential transients are removed, observable variables associated with glitches are related to the model parameters by the following simple three equations \cite{Alpar2006}:

\[I_c \Delta \dot{\Omega}_c = (I_A/2 + I_B) \delta \Omega_c.\]

\[\frac{\Delta \dot{\Omega}_c}{\dot{\Omega}_c} = \frac{I_A}{T} \delta \Omega_c,\]

\[\tilde{\delta} \dot{\Omega}_c = \frac{I_A \dot{\Omega}_c}{I_B \delta \Omega_c}.\]
Eq. (6) simply states angular momentum conservation and gives the glitch magnitude. This is proportional to the number of vortices which participated in the glitch event. For a uniform array of vortices the number of unpinned vortices moving outward through radius \( r \) is related to the change in angular velocity of the superfluid at \( r \),

\[
\delta N = 2\pi r^2 \delta \Omega_t / \kappa \cong 2\pi R^2 \delta \Omega_t / \kappa, \tag{9}
\]

since \( r \cong R \), the radius of the star, in the crust superfluid. The angular momentum transfer depends on \( \delta \Omega_t \) and the moment of inertia of the region that vortices pass through, \( I_A \) and \( I_B \). Eq. (7) is about the torques acting on the pulsar. Before the glitch, in steady state, the crust superfluid and the rest of the star spin down at the same rate. When a glitch occurs, some part of the crustal superfluid decouples from the external torque leading to a jump in spin-down rate. Solving these equations for the three unknowns, \( I_A, I_B, \) and \( \delta \Omega_t \), one can obtain model parameters uniquely without making any further assumptions.

\section{Extension of the Vortex Creep Model}

In the standard vortex unpinning-creep model only the outward motion of vortices is considered. This gives a negative post-glitch offset (an increase in the absolute value) of the spin-down rate from its pre-glitch value, \( \Delta \Omega < 0 \). The spin-down rate relaxes back to the pre-glitch value \( (\Delta \Omega \rightarrow 0) \) for all modes of vortex creep which supply the internal torques from the superfluid acting on the normal matter crust. Thus, (i) glitches with the “wrong” sign in frequency and spin-down rate require inward vortex motion at the glitch; and (ii) long term (persistent) shifts in the spin-down rate require either a structural change in the neutron star crust, as proposed for the Crab pulsar \( \{\text{Alpar et al. 1996}\} \), or a glitch associated shift in the external torque \( \{\text{Link, Epstein \\& Bavil 1992}\} \).

Occasional inward fluctuations of vortices, facing an extra potential barrier, is a low probability component of the creep process. Therefore, bulk spontaneous inward motion of an avalanche of unpinning vortices is thermodynamically impossible in an isolated superfluid. Large numbers of vortices could be transported inward only if the glitch were induced by an agent external to the superfluid, like a starquake.

Inward vortex motion will increase the superfluid velocity by some \( \delta \Omega_t' \) in regions of superfluid through which vortices have moved inward. Its effect can be investigated by changing \( t_0 \) with \(-t_0\), where \( t_0' \equiv \delta \Omega'_t / |\Omega_t|_{\infty} \). With this we obtain:

\[
\frac{\Delta \Omega_t}{\Omega_t} = -\frac{I_A'}{I} \left[ \frac{1}{1 + (e^{\tau_{nl} - t_0'}/\tau_{nl})} \right], \tag{10}
\]

where the primes indicate parameters associated with inward vortex motion. This equation describes the response to inward motion of unpinned vortices. When vortices travel inward, superfluid rotates faster. The lag \( \omega \) thereby increases from its steady state value, and creep will be more efficient than in steady state, with an enhanced vortex current in the radially outward direction. If we integrate Eq. (10) over a nonlinear creep region throughout which a uniform average density of vortex lines unpinned, or re pinned, we obtain:

\[
\frac{\Delta \Omega_t}{\Omega_t} = \frac{I_A'}{I} \left[ 1 + \frac{1}{1 + (e^{\tau_{nl} - t_0'}/\tau_{nl})} \right] - \frac{1 - e^{-t_0' / \tau_{nl}}}{1 - e^{-\tau_{nl} / \tau_{nl}}}, \tag{11}
\]

The internal torque contribution given in Eqs. (10) and (11) leads to an initial positive contribution to \( \Delta \Omega_t \), which asymptotically decays to zero. Unlike the nonlinear creep response to glitch associated outward vortex motion, as given in Eq. (2), the nonlinear creep response to inward vortex motion, \textit{does not have a waiting time}. Instead Eqs. (10) and (11) display quasi-exponential relaxation. A constant second derivative \( \Omega_t \) is not obtained from Eq. (11) when \( t_0' \gg \tau_{nl} \) or in any other limit. As the integrated response in Eq. (11) is very similar, Eq. (10) is adequate to describe the spindown rate when vortices have moved inward.

Allowing for the starquake induced inward vortex motion at the glitch, in addition to the natural outward motion of many unpinned vortices, we get the following equation instead of Eq. (6),

\[
I_c \Delta \Omega_t(0) = (I_A f + I_B) \delta \Omega_t - (I_A' f + I_B') \delta \Omega_t', \tag{12}
\]

where \( f = 1/2 \) is for the integrated response, Eqs. (4), (5) and (11), and \( f = 1 \) for the simpler response, Eqs. (2) and (10). The first term on the right hand side is the angular momentum transfer due to outward moving vortices, while the second term is the contribution of inward moving vortices.

The physical meanings of \( I_A' \) and \( I_B' \) are similar to their non-primed counterparts. A plate of the crustal solid that moves inward in a quake could carry vortices with it, in the inward, \(-r\), direction. Nonlinear creep regions with moment of inertia \( I_{A'} \), and vortex free regions with moment of inertia \( I_{B'} \) are at radial positions between the original and the new positions of the plate, and therefore experience a sudden increase in \( \delta \Omega_t' > 0 \). As creep relaxes back to steady state, the net angular momentum transfer from the regions \( A \) and \( A' \) is zero, while the regions \( B \) and \( B' \) transport angular momentum only at glitches and will contribute a remnant frequency offset \( \Delta \Omega_p \).

\[
I_c \Delta \Omega_p = I_B \delta \Omega_t - I_B' \delta \Omega_t'. \tag{13}
\]

Extending Eq. (7) to describe the net glitch in the spin-down rate with the terms of opposite signs describing the response of creep to outward and inward vortex motion, we obtain

\[
\frac{\Delta \Omega_t}{\Omega_t} = \frac{I_A}{I} - \frac{I_A'}{I}. \tag{14}
\]

For PSR J1119-6127 the post-glitch \( \Delta \Omega > 0 \) persists for \( \sim 2500 \) days, as far as the pulsar has been observed since the glitch \( \{\text{Antonopoulou et al. 2014}\} \). Here we pursue the assumption that \( \Delta \Omega_t > 0 \) is permanent; that it will not decay on long timescales in the future. This is a viable assumption with the present data, as discussed in the next section. With this assumption the permanent shift \( \Delta \Omega_p \) could be due to a structural change in the star, as postulated for the persistent shifts in spin-down rate observed to accompany the Crab pulsar glitches \( \{\text{Alpar et al. 1996}\} \), or, alternatively, due to a glitch associated permanent change in the external torque. Unlike the Crab pulsar, the 2007 glitch of PSR...
J1119-6127 has strong indications that actually the external torque has changed, since the pulsar has switched to intermittent and RRAT behaviour with the glitch. It is likely that structural changes experienced by PSR J1119-6127 lead to a permanent change in the external torque.

5 MODEL FITS

We apply a model which is an extension of earlier applications of the vortex creep model to the Vela (Alpar et al. 1993) and Crab (Alpar et al. 1996) pulsars’ glitches. We take one nonlinear creep region with relaxation time $\tau_2$ corresponding to the outward motion of the glitches. The new component in the extended model is the inclusion of inward moving vortices in the glitch, which move through a nonlinear creep region with relaxation time $\tau_1$ (cf. Eq. (10)). We also employ a region in which relaxation occurs exponentially with a timescale $\tau_3$, discussed below. Finally, we include a possible external torque change as a constant offset to the spin-down. We tried model fits with the integrated response, Eqs. (4) and (11) and with the simple response Eq. (2) and (10). As the residuals are comparable, we choose to employ the simple model.

The expression used for the fit including our extended formula is:

$$
\Delta \Omega_c(t) = -a_1 \left[ \frac{1}{1 + \alpha_1 e^{-(t+\Delta)/\tau_1}} - \frac{1}{1 + \alpha_2 e^{-(t+\Delta)/\tau_2}} - a_3 e^{-(t+\Delta)/\tau_3} + b, \right.
$$

(15)

The various parameters are defined by: $a_1 = \frac{\Delta \Omega_{\text{ext}}}{I_{\text{ext}}}$, $a_2 = \frac{\Delta \Omega_{\text{in}}}{I_{\text{in}}}$, $\alpha_1 = (e^{-\tau_1/\tau_1} - 1)$, $\alpha_2 = (e^{-\tau_2/\tau_2} - 1)$, $a_3 = \frac{\Delta \Omega_{\text{int}}}{I_{\text{int}}}$, and $b = (\Delta N_{\text{ext}}/N)\Omega_{\text{in}}$, and $t$ is the time since the first post-glitch observation, with the time lag $\Delta$ between the actual glitch date and the first post-glitch observation. We have 9 free parameters. Parameters with the subscript “1” denote the contribution from the response of vortex creep to glitch associated inward vortex motion, while those with subscript “2” and “3” are associated with creep response to glitch associated outward vortex motion.

The exponential relaxation term with amplitude $a_3$ might describe the response of either an intrinsically linear creep region, or a nonlinear creep region where there was no vortex motion at the glitch, so that the angular velocity of the superfluid remains unchanged and the glitch induced perturbation to the angular velocity lag is simply $\delta \omega = \Delta \Omega_c$ (Gügerich and Alpar 2014). We adopt the latter interpretation. This assumption is consistent with the results obtained from the fits.

The moments of inertia of nonlinear creep regions contributing to the long term response are obtained from the fit parameters $a_1$ and $a_2$. The terms $\alpha_1$ and $\alpha_2$ yield the numbers of vortices moving inwards and outwards, respectively, during the glitch. $b$ is the long term offset of $\Delta \Omega_c$ after all the contributions from creep regions relax back to zero. We interpret this as the contribution of the change in the external torque. The terms with subscripts “2” and “3” contribute $\Delta \Omega_c(t) < 0$ while the parameter $b$ (external torque change) and the term with subscript “1” (inward motion of vortices) contribute $\Delta \Omega_c(t) > 0$ (see Figure 1).

This term has the longest time constant, $\tau_1 \gg \tau_2 > \tau_3$. The data could also be fitted by assuming no change in the external torque, $b = 0$ and choosing long enough $\tau_1$ so that in the long run $\Delta \Omega_c$ relaxes back to zero while accommodating the $\Delta \Omega_c(t) > 0$ values for the latest present observations. We have explored models with $0 \leq b \leq 1.1 \times 10^{-13}$ rad s$^{-2}$, corresponding to $-7.2 \times 10^{-4} \leq N_{\text{ext}}/N \leq 0$. The values of $b$ between $0.8 \times 10^{-13}$ rad s$^{-2}$ and $1.1 \times 10^{-13}$ rad s$^{-2}$ yield reasonable fit results. Here we choose to explore the possibility of a permanent change in the external torque as reflected by $b = 1 \times 10^{-13}$ rad s$^{-2}$. However, at present we cannot rule out $b = 0$, a full decay. Parameters of the best fits with $b = 0$ and $b = 1 \times 10^{-13}$ rad s$^{-2}$ are shown in Table 1. The long term data display quasi-periodic residuals with a period of $\sim 400$ days (Antonopoulou et al. 2014); we find a best fitting sinusoidal period $P = 394$ d by fitting the data from the last $\sim 1500$ days with a model involving only the terms that are dominant in the long term: the contributions from inward moving vortices, the long-term offset with $b = 1 \times 10^{-13}$ rad s$^{-2}$ and the sinusoidal term. In our further investigations comprising all the data we fixed this period for the sinusoid. The residuals of the $b = 1 \times 10^{-13}$ rad s$^{-2}$ model also show initial fluctuations, which may be due to transient emission patterns in the magnetosphere. Future timing data will distinguish between these alternatives.

To apply our extended creep model to the peculiar glitch of PSR J1119-6127, we use the spin-down rate data for the 2007 glitch, a total of 85 data points. The arrival time data from MJD 54268 indicate that a glitch has taken place since the previous data set on MJD 54220. The first post-glitch data fit to produce frequency derivative values is dated MJD 54300 (Weltevrede, Johnston & Espinoza 2011). The presently available spin-down rate and frequency data extending to MJD 56751 was kindly shared with us by Patrick Weltevrede (P. Weltevrede private communication, Antonopoulou et al. 2014). The time interval $\Delta$ between the actual glitch date and the first post-glitch frequency derivative values thus lies between $\Delta = 32$ days and $\Delta = 80$ days. The coefficient $I_2/\Omega$ of the exponentially relaxing term is sensitive to the choice of $\Delta$. We arbitrarily take $\Delta = 60$ days, which gives $I_2/\Omega \approx 1.74 \times 10^{-1}$.

We use the Levendberg-Marquardt method to find the best fit values of the parameters, starting from initial guesses with MPFITFUN procedure (Markwardt 2009). The best fit is displayed in Figure 1 and its parameters are listed in Table 1. Inferred model parameter values corresponding to Eq. (15) are shown in Table 2.

The long term remnant $\Delta \Omega_p$ of the glitch in frequency can be found by comparing the indefinite integral of the model for spin-down rate with the observed frequency residual at the latest available data points. Using the frequency residual data on MJD 56688, $\Delta \Omega_p \approx 9.4 \times 10^{-5}$ rad s$^{-1}$ is obtained. We find $\Delta \Omega_p > 0$, unlike the earlier result of Weltevrede et al. (2011), who found a negative long term frequency residual based on the latest post-glitch data then available, but in agreement with their current estimate (Model A in Antonopoulou et al. 2014).

Table 1. The long term data display quasi-periodic residuals with a period of $\sim 400$ days (Antonopoulou et al. 2014); we find a best fitting sinusoidal period $P = 394$ d by fitting the data from the last $\sim 1500$ days with a model involving only the terms that are dominant in the long term: the contributions from inward moving vortices, the long-term offset with $b = 1 \times 10^{-13}$ rad s$^{-2}$ and the sinusoidal term. In our further investigations comprising all the data we fixed this period for the sinusoid. The residuals of the $b = 1 \times 10^{-13}$ rad s$^{-2}$ model also show initial fluctuations, which may be due to transient emission patterns in the magnetosphere. Future timing data will distinguish between these alternatives.

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Figure 1. Top panel: Fit to the post-glitch spin-down rate data with the model of Eq. (15), with $\Delta = 60$ days and $b = 1.0 \times 10^{-13} \text{rad s}^{-2}$. Middle panel: Zoomed version of top panel with model components representing contribution of exponential relaxation term (purple solid line), inward moving vortices (gray dashed line) and outward moving vortices (blue dash dotted line) are shown separately. Sinusoidal component and long-term offset $b$ are not shown in the figure for clarity. Bottom panel: Difference between data and model.

6 DISCUSSION AND CONCLUSIONS

We have examined the peculiar 2007 glitch of PSR J1119-6127 by extending the vortex creep model to take into account (i) the possibility of a glitch associated change in the pulsar external torque, and (ii) inward motion of vortices. Both of these effects can be induced by a starquake that triggered the glitch. We model the peculiar glitch of PSR J1119-6127 as follows: a crustquake occurs, causing the crustal plates to move towards the rotation axis, together with some pinned vortices. At the same time, some vortices affected by the crustquake are un-pin- ned and move outward. The glitch is due to the angular momentum transfer associated with the sudden outward and inward vortex motions. Magnetic field lines, which move with the conducting crustal plate, change the external torque and give rise to the abnormal emission properties.

In contrast to the changes in other pulsars’ glitches, the long-term change in spin-down rate, after transients are over, is (possibly) positive for PSR J1119-6127. In the creep process under the action of an external *spin-down* torque, the inward motion of vortices is thermodynamically unlikely, unless induced by a driving force such as arising from crustquake induced motion of crustal plates that carrying pinned vortices inwards. Inward vortex motion increases the lag between local superfluid and normal matter rotation rates from the steady state value, thereby accelerating rather than cutting off the creep process. This in turn increases the rate of angular momentum transfer to the crust and thereby decreases the spin-down rate of the crust, producing a positive change in the observed crust spin-down rate. By contrast, in standard glitches vortices move outward, decreasing the lag and turning off or suppressing the creep process which transfers angular momentum from superfluid to the crust; this leads to a negative step in the spin-down rate of the crust. Glitch induced steps of either sign arising from the offset in the vortex creep process always relax back to the pre-glitch spin-down rate as the creep process heals back to the steady state. The model we have fitted to the spin-down rate data after the 2007 glitch of PSR J1119-6127 includes the creep response to outward and inward vortex motion as well as a glitch associated change in the external (pulsar) torque.

Table 2. Inferred Parameters with $b = 1.0 \times 10^{-13} \text{rad s}^{-2}$.

| Parameter          | Value (Error) | Value (Error) |
|--------------------|---------------|---------------|
| $(\Omega_{\nu})_{-3}$ | 1.11          |               |
| $(\Omega_{\nu})_{-3}$ | 6.70          |               |
| $(\Omega_{\nu})_{-1}$ | 1.74          |               |
| $\Omega_{0}(\text{days})$ | 2046          |               |
| $\Omega_{0}(\text{days})$ | 317           |               |
| $(\delta \Omega_{\nu})_{-2} \text{ (rad s}^{-1})$ | 2.69          |               |
| $(\delta \Omega_{\nu})_{-3} \text{ (rad s}^{-1})$ | 4.16          |               |
| $(\Delta \Omega_{\nu})_{-4}$ | -6.58         |               |

[Antonopoulou et al. (2014)] fit their data set with two models, model A with a long term exponential relaxation, and model B with a negative frequency second derivative ($\Delta \Omega_{\nu} < 0$ in their notation). The positive $\Delta \Omega_{\nu}$ decays towards zero in both models, asymptotically in the case of Model A. The two models leave comparable residuals. Our investigation of crust breaking, giving a permanent change in the external torque and spin-down rate and causing inward vortex motion, is complementary to their work. Future timing observations will decide if the offset in the spin-down rate is really permanent or relaxing; and searches for thermal signals accompanying future glitches of PSR J1119-6127 will distinguish between the different models.
We must use the long term remnant of the frequency glitch in Eq. (13) to constrain $I_B$ and $I_B^r$, the moments of inertia of superfluid regions which transfer angular momentum only at glitches, due to the outward and inward motion of unpinned vortices, respectively. Using the values of $\delta \Omega$ and $\delta \Omega^r$ from Table 2 leads to the constraint $9.4 \times 10^{-5} I = 4.2 \times 10^{-3} I_B - 2.7 \times 10^{-2} I_B^r$. This gives $I_B/I > 2.2 \times 10^{-2}$. Then the superfluid creep regions with a total moment of inertia $I_3 > I_A + I_B + I_A^r + I_B^r + I_3 > I_A + I_B + I_A^r + I_3 \geq 20.4 \times 10^{-2} I$ is affected by the glitch event. The region with moment of inertia $I_3 = 1.74 \times 10^{-1} I$ comprises most of the moment of inertia in pinned superfluid.

Recent calculations (Chamel 2013, Andersson et al. 2012) show that Bragg scattering of conduction neutrons from nuclei in the neutron star crust induces a neutron effective mass that is larger than the bare mass. This “entrainment” of superfluid neutrons in the crust by the crystal lattice requires that the actual moment of inertia associated with the superfluid response is larger by a factor $m^*_s/m_\alpha > 1$ where $m^*_s$ and $m_\alpha$ are effective and bare neutron masses in the lattice. The moment of inertia $I_s \gtrsim (m^*_s/m_\alpha) \times 20.4 \times 10^{-2} I$ associated with creep cannot be accommodated by the crust superfluid alone for most neutron star models, even without the effective mass correction. In addition to the crust superfluid, other locations are required to sustain vortex creep. Contribution from vortex line-toroidal flux line pinning and creep at the outer-core of the neutron star (Sidery & Alpar 2009), which has a comparable or larger moment of inertia than that of the crust superfluid, could provide the required extra moment of inertia (Gügercinoglu & Alpar 2014). The moment of inertia of the creep region where vortex motion is controlled by the toroidal arrangement of flux lines can amount to $I_{\text{cir}}/I \sim 2 \times 10^{-1}$ depending on the radial extension of the toroidal field in the outer core. Creep here is in the non-linear regime. As no glitch associated vortex motion is expected, the response to a glitch is exponential relaxation (Gügercinoglu & Alpar 2014). The relaxation time $\tau_{\text{cir}} \simeq 50$ days for PSR J1119-6117 parameters is in line with our estimate of $\tau_{\text{cir}} \simeq 48$ days (and with $\tau_{\text{cir}} \simeq 33$ days for the application to the Vela pulsar, which has parameters similar to those of PSR J1119-6117; Gügercinoglu & Alpar 2014).

So, we argue that $I_3/I = 1.74 \times 10^{-1}$ reflects the moment of inertia associated with the toroidal flux line region of the outer core. The moment of inertia of the crustal superfluid participating in the glitch, when the crustal entrainment correction is included, is $I_{s,\text{crust}} > (m^*_s/m_\alpha)(I_A + I_B + I_A^r) \gtrsim (m^*_s/m_\alpha) \times 2.98 \times 10^{-2} I$. This total moment of inertia fraction can be accommodated in the crust in neutron star models with hard equations of state, if the mean value of $m^*_s/m_\alpha$ to represent the crust superfluid is not much larger than 1. The recent work of Piekarewicz, Fattoyev & Horowitz (2014) shows that the neutron star crust may maintain larger moment of inertia so that the above constraint is easier to be satisfied.

The total numbers of vortices displaced in this glitch are determined by the superfluid angular velocity changes $\delta \Omega$ and $\delta \Omega_r$ using Eq. (9). The number of vortices that have moved outward is found to be $\delta N_{\text{out}} \sim 1.3 \times 10^{13}$, while the corresponding number for inward moving vortices is $\delta N_{\text{in}} \sim 8.4 \times 10^{13}$. These numbers are typical of all small or large glitches, from Crab, Vela and other pulsars analyzed so far in terms of vortex unpinning, indicating a particular scale of the glitch trigger.

The glitch associated change in the external torque contributes a constant offset from the pre-glitch behaviour that remains in the spin-down rate after all post-glitch relaxation is over. This term, denoted $b$ in Eq. (15), indicates a change in the external torque, which leads to a change in the spin-down rate through $\Delta N_{\text{ext}}/N_{\text{ext}} = \delta \Omega/\dot{\Omega} + \Delta I/I$. The actual fractional change in the moment of inertia associated with a possible quake must be less than the observed glitch magnitude, so $|\Delta I/I| < \Delta \Omega/\dot{\Omega} \sim 10^{-5} << |\Delta \Omega/\dot{\Omega}| \sim 10^{-4}$.

The measured permanent term $b$ in $\Delta \Omega/\dot{\Omega}$ therefore gives the fractional change in the external torque. Taking the external torque to be essentially the dipole radiation torque, we have:

$$\Delta N_{\text{ext}}/N_{\text{ext}} = \frac{3}{2} \frac{\Delta \Omega}{\Omega} + \frac{\Delta B_{\perp}}{B_{\perp}} \simeq \frac{2}{3} \frac{\Delta B_{\perp}}{B_{\perp}},$$

(16)

as the term $3\Delta \Omega/\Omega \sim 10^{-5}$ is again negligible. We assume that the magnetic field change is associated with crust breaking, involving broken plates of size $D$ distributed in a ring of the crust of width $D$ and radius $R \cos \alpha$ from the rotation axis, with each plate moving a distance $D$ at the quake. The field moves with each broken piece of the conducting crust, without any change in the local field magnitude and orientation, which we take to be normal to the crust plate. The local field strength varies azimuthally in the broken ring.

The assumption that magnetic stresses play a role in crust breaking (Franco, Link & Epstein 2000, Lander et al. 2014). A schematic view of our model for external torque variation via change of magnetic field’s perpendicular component is depicted in Figure 2. The external torque variation is related to the change $\Delta \alpha$ in the angle between the rotation and magnetic axes:

$$\frac{\Delta B_{\perp}}{B_{\perp}} = \frac{\Delta \alpha}{\tan \alpha},$$

(17)

From our estimate of the change in external torque, $\Delta N_{\text{ext}}/N_{\text{ext}} \simeq -6.58 \times 10^{-4}$ given in Table 2, we obtain:

$$\alpha = \frac{1}{2} \frac{\Delta N_{\text{ext}}}{N_{\text{ext}}} \tan \alpha \simeq (-3.3 \times 10^{-4}) \tan \alpha$$

(18)

which is between $(-1.0 \times 10^{-4})$ and $(-2.8 \times 10^{-4})$. To obtain this, we have used the range of $\alpha$ considered by Weltevrede, Johnston & Espinoza (2011), $\alpha \sim 17^\circ - 30^\circ$ corresponding to an emission height $\sim 500$ km and $\alpha \sim 30^\circ - 45^\circ$ corresponding to an emission height $\sim 1800$ km.

The tiny change $\Delta \alpha$ in inclination angle cannot be resolved as an observable glitch associated pulse shape change in the present radio timing data. Motion of crustal plates towards the pole ($\Delta \alpha < 0$) results in a reduction in the moment of inertia of the solid, and therefore an increase in the spin-down rate. This is the signature of a crust quake in a spinning down pulsar, tending to make the shape more spherical.

The reason for the external torque change is likely to be a starquake, inducing motion of crustal plates, and reducing $B_{\perp}$, as the surface magnetic field moves with the conducting plates towards the rotation axis.

The fractional change in moment of inertia due to the
motion of the crustal plates is \( \Delta J / I \sim (m/M) \Delta \alpha \ll \Delta \alpha \sim 10^{-4} \), where \( m \) is the total mass of the moving plates and \( M \) is the mass of the entire star. Observing the direct effect of this actual change in the crustal moment of inertia as a glitch is impossible. The glitch magnitude \( \Delta \Omega \) is due to amplification by the vortex motion triggered by crust-breaking and the resulting angular momentum transfer from superfluid to normal matter. We have assumed that some of the vortices pinned to the moving plates are initially carried inward with the plates. This is possible when the increase \( \delta \Omega \) in superfluid rotation rate, due to the inward motion of the pinned vortices on the time scale of crust breaking is not sufficient for the local lag to increase from the steady state value to the critical value, \( \delta \Omega < \omega_{\alpha} - \omega_{\infty} \), for typical values of \( \omega_{\infty} \) (Alpar, Cheng & Pines 1989). These vortices will bend and are likely to be strongly perturbed by the sudden inward motion and become unpin. The unpinned vortices will then move downstream azimuthally with the superfluid flow, causing more vortices to unpin and scatter outward until they reach a new radial position where they join the background vortex flow and creep. The avalanche of unpinning takes place rapidly on the glitch “rise” timescale. Some number \( \delta N_{\text{in}} \) of vortices associated with the moving plates end up in radial positions inward of their original position while a number \( \delta N_{\text{out}} \) of vortices end up in radial positions further out compared to their original position. The moment of inertia of the superfluid creep regions affected by the inward motion of the plates and net inward vortex motion is of order

\[
I_{\alpha} / I \equiv \frac{4 \pi \rho_c R^4 \sin \alpha \cos^2 \alpha}{(2/5) M R^2} \approx 15/2 \sin \alpha \cos^2 \alpha (D/R) \sim (2D/R),
\]

(19)

assuming a uniform density neutron star, and adopting \( \sin \alpha \cos^2 \alpha \sim 0.3 \) for the range of \( \alpha \sim 17^\circ \sim 40^\circ \) indicated by Weltevrede, Johnston & Espinoza (2011). Using the value of \( I_{\alpha} / I \) from fits, we obtain the ring width \( D \sim 6 R_0 \), where \( R_0 \) is the neutron star radius in units of \( 10^6 \) cm. The number of vortices pinned to each plate is

\[
\delta N_{\text{plate}} \sim D^2 \frac{2 \Omega}{K} \sim 3 \times 10^6 \Omega R_0^2 \sim 5.5 R_0^2 \times 10^9.
\]

(20)

The total number of vortices associated with broken plates with a net inward motion during the glitch, is \( \delta N_{\text{in}} \sim 8.4 \times 10^{13} \) vortices, as we estimated above from the results of our fits for \( t_g \), a parameter independent from \( I_{\alpha} / I \) which we used to estimate the plate size \( D \). The number of plates involved should be \( \sim \delta N_{\text{in}} / \delta N_{\text{plate}} \sim 10^8 \), in agreement with the number of plates in the broken ring, \( \sim 2 \pi R_0 / D \sim 10^4 \). A comparable number of vortices \( \delta N_{\text{out}} \sim 1.3 \times 10^{13} \) end up moving outward through a superfluid region of comparable moment of inertia, \( I_{\alpha} \). We find here an indication that the common scale, \( \sim 10^{13} \), of the number of vortices unpinned in all pulsar glitches may be associated with the number of vortices in the typical plate size \( D \) involved in a triggering crust quake, multiplied by the number of plates involved, \( \sim 2 \pi R_0 / D \sim 10^4 \). These scales rest on the single parameter, the plate size \( D \) which must be related to the physics of the crustal solid. This plate size \( D \) is of the same order of magnitude as the ‘mountain’ height \( \sim 1 \) estimated for the Crab pulsar (Chamel & Haensel 2008). Note that the critical strain angle \( \theta_{cr} \) at which the crust lattice breaks is \( \theta_{cr} \sim D / h \) where \( h \) is the radial thickness of the broken crustal plates. Thus,

\[
\theta_{cr} \sim 10^{-2} \left( \frac{D}{1 \text{ m}} \right) \left( \frac{h}{100 \text{ m}} \right)^{-1},
\]

compatible with the results of Horowitz & Kadau (2009) for the critical strain angle.

It is interesting to compare the moment of inertia fractions in crust superfluid regions through which the unpinned vortices moved during the peculiar glitch of PSR J1119-6127, given in Table 2, with the corresponding Crab (Alpar et al. 1996) and Vela (Alpar et al. 1993) values, \((0.01-1.87) \times 10^{-3}\) and \((2.3-3.4) \times 10^{-2}\) respectively, as this gives a lower limit on the moment of inertia fraction in the crust, leading to constraints on the neutron star equation of state (Datta & Alpar 1993; Link, Epstein & Lattimer 1994). With its characteristic age of \( \sim 1625 \) years, PSR J1119-6127 is between the Crab and Vela pulsars in age, but its implied crustal superfluid moment of inertia fraction \( 2.98 \times 10^{-2} \) is comparable to the values inferred for the Vela pulsar. The qualitative evolution of glitching behaviour from Crab-like to Vela-like was proposed to be due to the development of connections in a network of vortex creep regions, so that the moment of inertia involved increases with age (Pines & Alpar 1983). PSR J1119-6127 should already have a sufficiently well connected vortex creep network. Presumably the high magnetic field and associated stresses in the crust of this pulsar lead to high crust breaking activity. While similar moments of inertia in vortex creep regions \( I_{\alpha} \) are inferred, and the long term fractional offsets in the spin-down rate are similar in absolute value, for the Crab case no change in electromagnetic signature is observed.

Magnetic stresses will play a role comparable to that of rotation induced stresses in conventional starquake models if, roughly,

\[
\frac{B_0^2 - B^2}{8 \pi} \sim 1 \left( \frac{1}{2} \frac{R^2}{\Omega_0^2 - \Omega^2} \right) \sim 1 \left( \frac{1}{2} \right) R^2 \Omega | \dot{\Omega} | t_g,
\]

where \( B_0 \) and \( \Omega_0 \) denote reference values of \( B \) and \( \Omega \) frozen into the crust. Using the glitch interval \( t_g \sim 3 \) yrs, typical for young pulsars, we find that magnetic stresses can play a role when \( B \gtrsim 10^{13} \) G in the crust. The magnetic field can have poloidal and toroidal components whose geometry will determine where in the crust the local stresses reach the critical values for crust breaking (Lander et al. 2014). The higher multiple components of the magnetic field and the geometry of the stress tensor when both magnetic and rotational effects are included further complicate the situation. In addition, the changes in electromagnetic signature, as seen only in PSR J1119-6127, are likely to occur if the broken plate extends to the surface and leads to reconfiguration of the magnetosphere. This may explain why the behaviour exhibited by PSR J1119-6127 is rare. As a rough guideline, such behaviour may be exhibited by young pulsars with high magnetic field in young pulsars with high magnetic field.

We should note the different responses of the crust and the superfluid to a starquake. After the crust breaks and plates move towards the rotation axis in order to relieve their stresses, those broken pieces of the crust are stuck to new metastable positions, and do not come back to their pre-glitch sites. Thus, crust breaking and crustal motion are irreversible. Starquake induced inward motion of vor-
The starquake is a large, sudden change in the rotation of a neutron star, often triggered by a magnetic field reconfiguration due to internal stresses or external factors like collisions or supernova explosions. These changes can cause a temporary slowdown in the rotation rate, followed by a rebound to a new steady state.

A starquake can be represented as a change in the star's rotation rate, ∆Ω, which can lead to a temporary change in the star's pulse pattern. The magnitude of this change is typically on the order of $2.8 \times 10^{-4}$ for the Crab pulsar.

**Figure 2.** Starquake Model in cross section. The dotted area represents the new position of crustal plates (broken ring) after the starquake.

The main reason for the switch in emission patterns to intermittent and RRAT behaviour lasting for about a hundred days after the event is likely the effect of the quake on magnetic field lines which are anchored to the crust. If the magnetospheric field pattern could move rigidly, without distortion, together with the motion of the crust. If the magnetospheric field pattern could move rigidly, without distortion, together with the motion of the crust, the changes in the emission pattern would be no significant change in the emission pattern. However, when a crustal plate moves in a quake, the vortex current, as described by the vortex creep response to the pre-glitch dynamical steady state, and all the parts of the starquake.

The distorted magnetospheric geometry will subsequently relax towards a quasi-stable configuration for the new position of the plate. The changes in the emission pattern are observed for about a hundred days following the glitch, after which the pulsar returns to its pre-glitch pulse shape and emission pattern. Twisting of field lines and their subsequent relaxation will also introduce temporary fluctuations in arrival times. Our timing model fits indeed leave relatively large residuals for about a hundred days in the post-glitch data given in the bottom panel of Figure 1.

Although the recently discovered magnetar anti-glich from 1E 2259+586 has also shown a negative spin jump and changing emission features, the situation is very different from that of PSR J1119-6127. In the case of 1E 2259+586, the magnitude of the change in spin-down rate, $|\Delta \dot{\Omega}| \sim 2.8|\dot{\Omega}|$ is too large to be associated with the superfluid regions in the star. It is likely that only a large change in the external torque is involved, as suggested by the violent change in emission, so that this magnetar ‘antiglich’ must be external/magnetospheric in origin (Lyutikov 2013; Tong 2014).

In summary, the peculiar glitch of PSR J1119-6127 offers an invaluable opportunity for the reexamination and extension of glitch models to account for anomalous glitch signatures and transient emission phenomena initiated by a quake leading to a change in the external torque and triggering the response of the superfluid regions of the neutron star. Our model predicts that the change in the external torque is permanent. The coincidence of the numbers of vortices involved in the glitch with the numbers inferred in Crab and Vela pulsar glitches is highly suggestive, supporting the explanation in terms of a crust breaking event with a typical plate size, which may be a common, even universal, trigger for glitches. If future timing observations rule out a permanent change in the external torque, this coincidence would turn out to be spurious. The explanation of the post-glitch evolution of $\Delta \dot{\Omega}_e(t)$ in terms of internal torques responding to glitch associated inward and outward vortex motion, and relaxing to $\Delta \dot{\Omega}_e = 0$ is viable when there are no observed changes in the external torque.

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