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Starquakes in Neutron Stars

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Abstract. The Crab and other pulsars suffer sudden and permanent increases in their spin-down rates in association with glitches, suggesting that the external torque on these objects grows in steps. Here, we describe how torque changes may arise from *starquakes*, occurring as the star spins down and its rigid crust becomes less oblate. We study the evolution of strain in the crust, the initiation of starquakes, the effects on the magnetic field geometry, and possible observable consequences for neutron star spin down. We find that the stellar crust begins breaking at the rotational equator, forming a fault inclined at an angle to the equator and directed toward the magnetic poles. The resulting asymmetric matter redistribution produces a misalignment of the angular momentum and spin axes. Subsequently, damped precession to a new rotational state increases the angle between rotation and magnetic axes. The change in this angle could increase the external torque, producing a permanent increase in the spin-down rate.

Sudden jumps in rotation rate, *glitches*, are a common phenomenon in isolated pulsars. Less common but equally dramatic are the persistent increases (*offsets*) in spin-down rate that accompany glitches in the Crab pulsar, PSR 0355+54 and PSR 1830 (Shemar & Lyne 1996) In the Crab pulsar, these permanent offsets involve fractional changes in the spin-down rate of $\sim 10^{-6}$–10^{-4} (Figure 1, left). Remarkably, all observed offsets are of the same sign and appear to correspond to *increases* in the external torque acting on the star. Here, we describe how violent crust motions, associated with breaking of the rigid crust as the star slows down, could change the orientation of the magnetic moment with respect to the spin axis and lead to an increase in the external torque.

To study starquakes in a spinning-down neutron star, we modeled a brittle crust of uniform density afloat on an incompressible liquid core. In equilibrium, the star is a spheroid with an equatorial bulge. As the star spins down, the fluid

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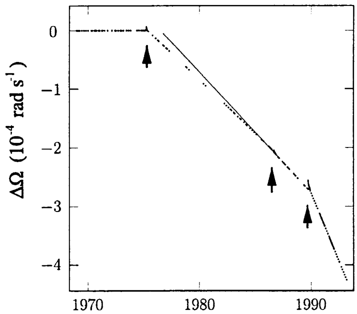

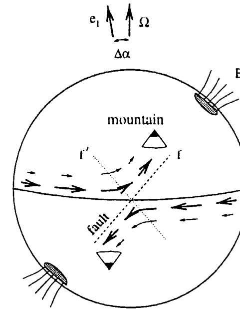

Figure 1. **Left:** Crab pulsar spin-rate residuals (Lyne, Pritchard, & Smith 1993). At each glitch, there is a permanent increase in spin-down rate. **Right:** In a strong magnetic field, fault propagation occurs preferentially along f, creating "mountains" and shifting the principal axis of inertia to e_1.

interior becomes more spherical, while strain develops in the rigid crust. The crust breaks once the strain reaches the elastic limit for the crustal material. The distribution of strain determines the geometry of the starquake. A calculation of the strain field shows that, for realistic crust thicknesses, the strain is largest at the equator, where an element of matter receives compressive stress until it shears (Franco, Link, & Epstein 2000) along fault f or f' as in Figure 1 (right).

For the azimuthally-symmetric situation just described, there is no preferred location on the equator for the break to begin. A magnetic field, however, introduces stresses that break the azimuthal symmetry if the field is not symmetric about the rotation axis. In Figure 1 (right), we show the effects of a dipole field inclined at an angle α with respect to the rotation axis. The magnetic field inhibits strain close to the magnetic poles, making starquakes most likely to originate at the two points on the equator farthest from the magnetic poles. The magnetic field inhibits motion across field lines, favoring fault f over f'. As material moves along f, "mountains" (< 10 μm high) form at higher latitudes, decreasing the star's equatorial circumference and breaking the axial symmetry of the star's mass distribution. As a result, the principal axis of inertia e_1 shifts by an angle $\Delta\alpha$ *away* from the angular momentum vector. This misalignment causes the star to precess. Damping of the precession eventually restores alignment of the principal axis of inertia and the angular momentum vector, increasing the angle α between the rotation and magnetic axes to $\alpha + \Delta\alpha$. In some models of pulsar spin down (e.g., the vacuum dipole model), an increase in α produces an increase in the spin-down torque. We estimate that the release of the spin-down strain that develops between glitches in the Crab is adequate to give $\Delta\dot{\Omega}/|\dot{\Omega}| \sim 10^{-6}$–$10^{-4}$ (Link, Franco, & Epstein 1998), as observed.

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