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Thermally-Driven Glitches

Abstract

During a neutron star's evolution, starquakes and other heating processes increase the frictional coupling between the crust and the neutron superfluid the star is expected to contain. We examine the thermal and dynamical response of an isolated neutron star to a sudden perturbation of the inner crust temperature, and show that internal heating can trigger sudden spin jumps resembling pulsar glitches.

I Introduction

Glitches have now been observed in more than 20 pulsars. Typical glitches in mature pulsars, e.g., the Vela pulsar, involve fractional jumps in the rotation rate of $\sim 10^{-6}$. Glitches in the relatively young Crab pulsar, on the other hand, are typically a factor of 10 to 100 smaller. The Crab glitch of 1989 was the first such spin-up to be partially time-resolved; following a jump in the spin rate (occurring in < 2 hours), the pulsar completed the remainder of the spin-up over ~ 1 d (Lyne, Smith, & Pritchard 1992; see Figure 2). By contrast, the Vela pulsar has shown very different behavior in at least one case. The giant "Christmas glitch" of December 24, 1989 (1.8×10^{-6} fractional spin-up), which occurred during an observing session, could not be time-resolved; most, or possibly all, of the spin-up took place in less than two minutes (McCulloch et al. 1990; see Fig. 2). Giant glitches seem to be typical behavior among mature pulsars, while the Crab appears to be unique in the smallness of its glitches.

Glitches might represent variable coupling between the neutron star crust, whose spin rate we observe, and the more rapidly rotating neutron superfluid the star is expected to contain. The coupling is related to the dynamics of the array of *vortices* that thread a rotating superfluid. The rotational state of the superfluid is determined by the distribution of vortices with respect to the rotation axis; hence, for the superfluid to change its angular momentum, vortices must move radially. In the inner crust, however, interactions between nuclei and vortex cores tend to *pin* the vortices to the lattice, nearly fixing the angular velocity of the superfluid there (see, e.g., Anderson & Itoh 1975). The inner crust superfluid is coupled to the crust to the extent that vortices can move through the lattice by thermally-activated *vortex creep* (see, e.g., Alpar et al. 1984; Link, Epstein, & Baym 1993). As the crust slows under the magnetic torque, the inner crust superfluid, because it is pinned, rotates more rapidly than the crust by as much as ~ 1 rad s^{-1}. The excess angular momentum residing in the inner crust superfluid is more than enough to drive glitches (Anderson & Itoh 1975; Ruderman 1976). Here we show that sudden internal heating, perhaps from a modest starquake, can trigger angular momentum transfer to the crust, producing spin-up events that resemble pulsar glitches.

II The model

As a neutron star spins down, sudden structural relaxations, *starquakes*, are expected to occur which heat the crust (Ruderman 1969; Baym & Pines 1971). Owing to the enormous rigidity of the crust, these events should produce significant heating; the elastic energy released in a starquake could exceed 10^{42} ergs (see, e.g., Baym & Pines 1971). The seismic modes excited in the inner crust are efficiently damped by electron shear viscosity over time scales of ~ 1 minute, indicating that a large fraction of the energy released in a starquake goes quickly into heat. Starquakes could occur in accreting systems as well—matter accumulates on the surface until gravitational forces on the accreted matter exceed the yield strength of the neutron star crust.

The inner crust superfluid is very sensitive to starquake-generated temperature perturbations. The frictional coupling of the superfluid to the crust is a sensitive function of temperature (Link, Epstein, & Baym 1993), and so even small heating events, when processed by the superfluid-crust system, can noticeably affect the star's spin behavior. In particular, *sudden* inner crust heating from a moderate starquake would dramatically increase the frictional coupling between the superfluid and the crust, bringing the two components closer to corotation (see, e.g., Greenstein 1979); the superfluid spins down, while the crust spins up. We conjecture that glitches originate from the sudden deposition of thermal energy in the inner crust. Preliminary work on this question has been presented by Link & Epstein (1996).

III Dynamical description

Following a starquake, a thermal wave propagates through the crust over a thermal diffusion time scale. The resulting angular momentum transfer from the superfluid to the crust is controlled by the extent to which the pinned vortices can unpin through thermal activation and move through the inhomogeneous environment of the inner crust lattice (Link & Epstein 1991; Link, Epstein, & Baym 1993; Chau & Cheng 1993). The vortex mobility depends on the vortex-nucleus interaction potential (itself a function of density), the temperature, and the velocity difference between the superfluid and the crust. A description of the response of a star to internal heating would require solving for the superfluid hydrodynamics coupled to the propagation of the thermal wave and the motion of the crust. In general, this problem is three-dimensional and highly nonlinear.

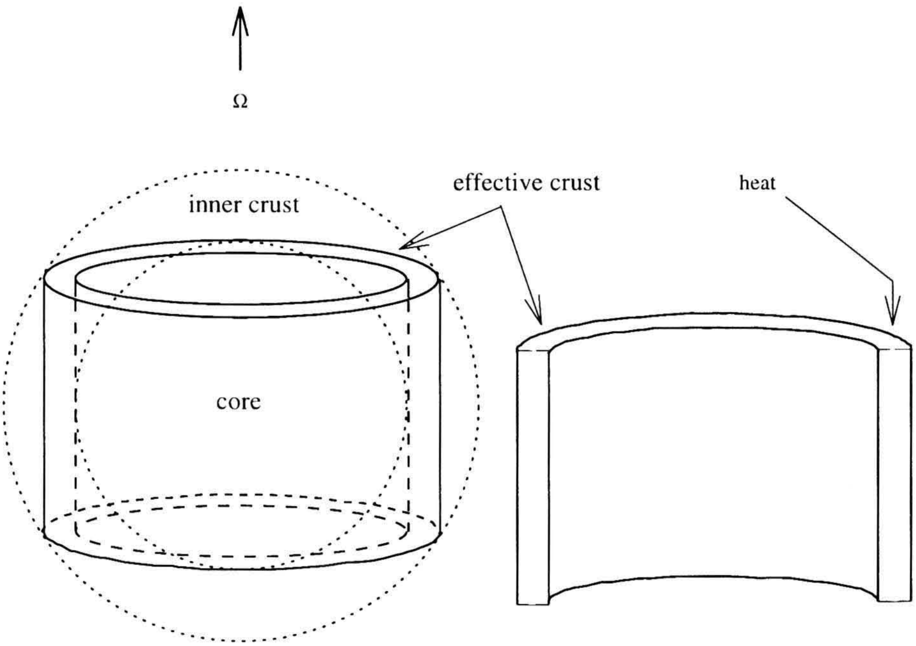

Figure 1. Model geometry. The inner crust superfluid is modeled as a cylindrical shell. Heat is deposited in a thinner cylindrical shell.

As a first step in addressing this problem, we have modeled the superfluid-crust system making several simplifying approximations (see Link & Epstein 1996 for details). First, we model the inner crust superfluid as a cylindrical shell of constant density (see Figure 1). We choose this geometry because the greatest contribution to the moment of inertia of the inner crust superfluid is in a band about the equator of the star. Second, we consider heating of a thin region within the cylindrical crust. Third, we neglect the generation of additional heat through friction between the superfluid and crust. We also assume that the core superfluid is rigidly coupled to the crust over short time scales ($\lesssim$ 10 s), as recently argued by Abney, Epstein, & Olinto (1996) in their analysis of Vela's Christmas glitch; the effects of a more weakly-coupled core are straightforward to include.

For a given nuclear matter equation of state, the only important free parameters of the model are: 1) the initial energy deposition, 2) a coupling parameter that measures the frictional interaction between the superfluid and the normal matter (related to the vortex pinning energy per nucleus), and 3) the unperturbed inner crust temperature.

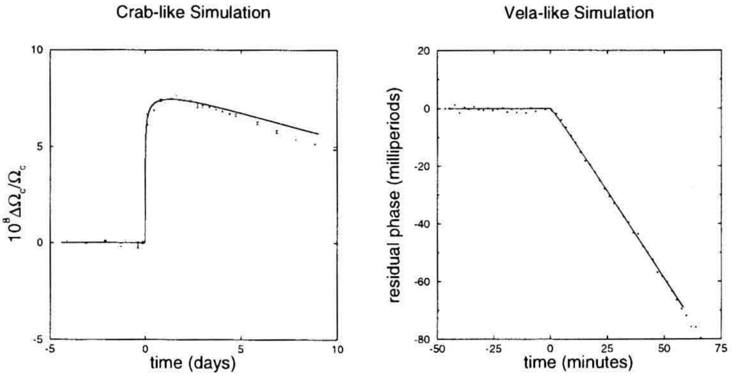

Figure 2. *Left panel:* simulation of the response of the Crab pulsar following the deposition of 2.2×10^{42} ergs in the inner crust. Shown is the excess spin rate relative to the pre-glitch extrapolated spin rate. Data from the large 1989 glitch are shown. *Right panel:* simulation of the response of the Vela pulsar following the deposition of 1.5×10^{42} ergs in the inner crust. Shown are the pulse arrival times minus the values extrapolated from a pre-glitch fit. Data from the Christmas glitch are shown.

IV Results

To illustrate the consequences of sudden inner crust heating, we show the results of two numerical simulations intended to represent the Crab and Vela pulsars. The models of the two stars differ only in the unperturbed spin rate, spin-down rate and inner crust temperature. Internal temperatures were calculated from surface emission data; we take 18 keV and 5 keV for the Crab and Vela, respectively. The value of the coupling parameter for the effective crust is the same for both simulations and was selected to give good fits to the Crab and Vela glitch data; its value is consistent with first-principles calculations (see, e.g., Epstein & Baym 1988) and observational constraints from surface emission measurements (see, e.g., Shibazaki & Lamb 1989; Van Riper, Link & Epstein 1995).

A deposition of $\sim 2 \times 10^{42}$ ergs in our simulation of the Crab pulsar triggers a small spin-up, taking place over $\sim$ 1 day, remarkably similar to that seen during the partially time-resolved Crab glitch of 1989 (see Fig. 2). A slightly smaller energy deposition (1.5×10^{42}) ergs in the simulation of Vela produces a much larger and faster glitch, taking place over minutes, similar to the Christmas glitch (see Fig. 2). The differences in glitch magnitude and time scale between these two simulations are due mainly to the strong temperature dependence of the vortex mobility. For a star with a lower temperature, e.g., Vela, a given energy deposition produces a much larger relative temperature change than in a hotter star. As a result, more vortices move, and they do so at a higher average velocity. The resulting spin jump is larger and faster than for a hotter star. Moreover, the higher thermal diffusivity of a cooler star causes the glitch to end sooner.

V Concluding remarks

The key result of this preliminary work is that *energy depositions of comparable magnitude to those expected from starquakes produce sudden spin jumps resembling pulsar glitches.* Moreover, the simple, one-dimensional model we have presented accounts naturally for the observed differences in glitch behavior between the Crab and Vela pulsars as being related to internal temperature alone. One prediction of this model is that the spin-up time scale for a given star should decrease with glitch magnitude. In the simulation of the Vela pulsar, for example, a glitch of $\Delta\Omega/\Omega = 10^{-6}$ occurs over minutes, while a glitch of 10^{-8} takes place over ~ 1 d. Data on the spin-up time scales for Vela's smaller glitches would be valuable in establishing the viability of this model.

If glitches are indeed triggered by internal heating, each spin-up is followed by the emergence of a thermal wave from the star's surface. Frictional heating between the superfluid and crust as the glitch proceeds augments the initial energy deposition. The magnitude and time scale of enhanced surface emission are sensitive to the nuclear matter equation of state and the depth of energy deposition. If the equation of state is fairly soft, and the star's surface temperature is 10^6 K, an energy deposition of 5×10^{42} ergs at an inner crust density of 3×10^{13} g-cm^{-3} would produce a 9% surface temperature enhancement peaking ~ 8 days after the glitch (Van Riper, Epstein & Miller 1991). Surface emission enhancements of this magnitude should be detectable with the ROSAT HRI, AXAF and possibly ASCA. A Target of Opportunity program led by F. Seward is already in place utilizing the ROSAT HRI.

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