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POSTGLITCH BEHAVIOR OF THE CRAB PULSAR: EVIDENCE FOR EXTERNAL TORQUE VARIATIONS

BENNETT LINK, RICHARD I. EPSTEIN, AND GORDON BAYM[1]
Los Alamos National Laboratory, MS-D436, Los Alamos, NM 87545
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ABSTRACT

We show that the persistent offset in the spin-down rate of the Crab pulsar following the 1975 glitch is difficult to explain by the usually assumed dynamic coupling between the crust and the superfluid interior. One explanation of the observed behavior is an increase in the external torque caused by a rearrangement of the stellar magnetic field.

Subject headings: dense matter — hydrodynamics — pulsars: individual: Crab — stars: neutron

In 1975 February the spin rate Ω_c of the Crab pulsar suddenly increased by an amount $\Delta\Omega_c/\Omega_c \simeq 3.8 \times 10^{-8}$. Following this event, the pulsar continued to spin down at a rate faster than before the glitch (Gullahorn et al. 1977; Lohsen 1981; Demiański & Prószyński 1983). The offset in the spin rate, $\Delta\dot{\Omega}_c/\dot{\Omega}_c = (2.15 \pm 0.16) \times 10^{-4}$, persisted until at least 1979 April, when the timing observations were discontinued (Lohsen 1981; Demiański & Prószyński 1983). Owing to the increased spin-down rate, by 50^d after the glitch the pulsar was spinning *slower* than the expected rate had the glitch not occurred (Fig. 1). By 1979 April the magnitude of the *relative frequency deficit*, $|\Omega_c(t) - \Omega_{c0}(t)|/\Omega_{c0}(t)$, had grown to more than 3×10^{-7}, 8 times the size of the glitch itself. Here $\Omega_c(t)$ is the observed pulsar spin rate and $\Omega_{c0}(t)$ is the extrapolation of the preglitch pulse frequency to postglich times. In early studies, the frequency deficit was taken as evidence for a change in the external torque acting on the star (Gullahorn et al. 1977; Demiański & Prószyński 1983). In more recent work, however, the deficit has been interpreted as due to a long-term decoupling of part of the interior neutron superfluid from the stellar crust (Alpar et al. 1984a; Alpar et al. 1985; Pines & Alpar 1991). In this *Letter* we show that the observed frequency deficit in the Crab spin rate cannot be accommodated within existing explanations of postglitch behavior based solely on superfluidity.

Pulsar glitches and postglitch behavior are commonly attributed to dynamic coupling between the superfluid and normal components in neutron stars. In this picture glitches originate as a sudden transfer of angular momentum from the superfluid to the crust (Anderson & Itoh 1975), and postglitch response is ascribed to the gradual recoupling of the two components (Baym et al. 1969). Glitches in these models are driven by the buildup, as the star slows, of the difference between the local superfluid angular velocity $\Omega_s(\boldsymbol{r}, t)$ and that of the crust $\Omega_c(t)$. In a sudden spin-up, the local lag frequency, $\omega(\boldsymbol{r}, t) \equiv \Omega_s(\boldsymbol{r}, t) - \Omega_c(t)$, decreases everywhere. In frictional coupling models, such as the simple two-component model (Baym et al. 1969) or the more sophisticated vortex creep models (Alpar et al. 1984a; Link, Epstein, & Baym 1992), the postglitch behavior of the local lag frequency usually takes the form

$$\frac{\partial}{\partial t}\,\omega(\boldsymbol{r}, t) = f(\omega, \boldsymbol{r})\,, \tag{1}$$

where the specific torque $f(\omega, \boldsymbol{r})$ has no explicit time dependence and is unchanged by the glitch. The mechanism driving the glitch is not included in f. We now show that equation (1), independent of the detailed form of f, cannot lead to the observed frequency deficit.

The total angular momentum of the star $J(t)$ is given by

$$J(t) = I_c\,\Omega_c(t) + \int dI_s(\boldsymbol{r})\Omega_s(\boldsymbol{r}, t) \equiv I\Omega_c(t) + I_s\,\bar{\omega}(t)\,, \tag{2}$$

where $dI_s(\boldsymbol{r})$ is the moment of inertia of an element of superfluid at a position $\boldsymbol{r}$; $I_s = \int dI_s$ is the total moment of inertia of the superfluid; $\bar{\omega}(t) \equiv I_s^{-1} \int \omega(\boldsymbol{r}, t)dI_s(\boldsymbol{r})$ is the average lag; and I_c is the moment of inertia of the crust and all components strongly coupled to it. The core couples to the crust on time scales of minutes (Alpar et al. 1984b), so I_c includes the core moment of inertia. The total moment of inertia, I, equals $I_s + I_c$.

Let us assume for the moment that the glitch does not change the structure of the magnetosphere. Then to a very good approximation $J(t)$ is unaffected by the glitch. The only change in the external torque on the star caused by the glitch arises from the frequency dependence of the torque; the relative change produced in $J(t)$ is of order $(\Delta t/t_{\rm age})^2\Delta\dot{\Omega}_c/\dot{\Omega}_c \lesssim 10^{-9}$, where Δt is the time since the glitch and $t_{\rm age}$ is the pulsar age. Hence, to a very good approximation,

$$J(t) = I\Omega_{c0}(t) + I_s\,\bar{\omega}_0(t)\,, \tag{3}$$

where $\bar{\omega}_0(t)$ is the average lag that the superfluid would have had if the glitch had not occurred. The quantity $\bar{\omega}_0(t)$ is the average of the solution $\omega_0(\boldsymbol{r}, t)$ of equation (1) that agrees with ω prior to the glitch. From equations (2) and (3), we see that

$$\Omega_c(t) - \Omega_{c0}(t) = \frac{I_s}{I}\,[\bar{\omega}_0(t) - \bar{\omega}(t)]\,. \tag{4}$$

Immediately after the glitch, the lag $\omega(\boldsymbol{r}, t)$ is below the extrapolated lag $\omega_0(\boldsymbol{r}, t)$ throughout the crust. Both lags are solutions of equation (1). Two solutions of this equation can never cross; if they approach each other, their trajectories in the ω-t plane become nearly tangential. Thus for all times after the glitch, $\omega(\boldsymbol{r}, t) < \omega_0(\boldsymbol{r}, t)$. It follows from equation (4) that

$$\Omega_c(t) > \Omega_{c0}(t)\,; \tag{5}$$

i.e., the postglitch frequency never falls below the extrapolated frequency. We conclude that any models of postglitch relax-

[1] Also Loomis Laboratory of Physics, University of Illinois, Urbana, IL 61801.

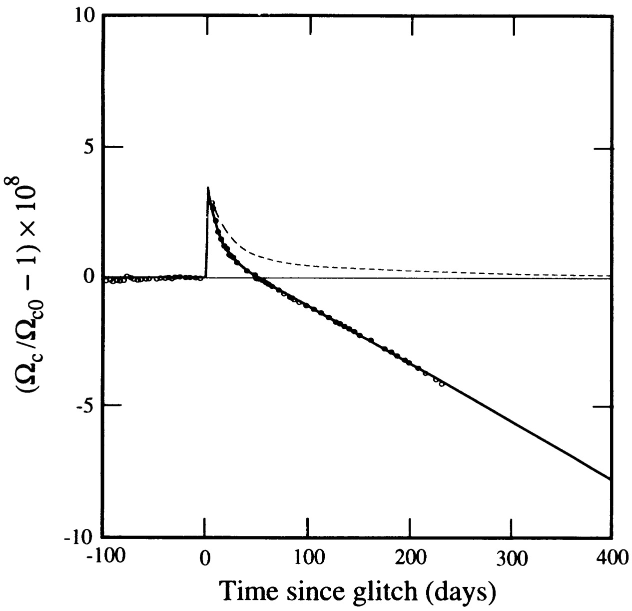

FIG. 1.—Spin evolution of the Crab pulsar following the 1975 February 4 glitch. The circles show the observed frequency residuals ($\Omega_c/\Omega_{c0} - 1$) reported by Lohsen (1981), and the solid line is Lohsen's fit to these residuals. The dashed line illustrates the response of the crust in the vortex creep model assuming constant external torque and moments of inertia of the crust and superfluid; this model cannot exhibit a frequency deficit.

ation based on an equation of the form (1) cannot, in the absence of significant changes in the external torque or moments of inertia, explain the observed frequency deficit.

A frequency deficit indicates that the angular momentum of the crust is less than it would have been had the glitch not occurred. If the external torque is not changed by the glitch, the angular momentum in the superfluid would have to be greater than in the absence of the glitch; such a relative increase of the superfluid angular momentum is not accommodated in the vortex creep models that lead to equation (1).

What mechanisms might allow a frequency deficit? Three possibilities present themselves: an increase in the external torque; a change in the specific torque f caused by the glitch; or an increase in the stellar moment of inertia (the reverse of the behavior of starquake models). The latter possibility is in fact ruled out. While an increase in the moment of inertia for a given angular momentum would slow the crust, it would also lead to a *smaller* slow-down rate, $|\dot{\Omega}_c|$, contrary to observations.

An explanation of the frequency deficit of the Crab pulsar within the superfluid-crust coupling model requires new physics. Coupling due to vortex creep depends not only on the lag, but on other factors not included so far, such as temperature, local crystal orientation in the crust, and the local density of vortex lines. Any of these quantities may change during a glitch, effectively changing $f(\omega, \boldsymbol{r})$. For example, glitches could significantly heat the star (Van Riper, Epstein, & Miller 1991) and change the nature of the coupling. In the vortex creep model, however, a temperature increase leads to a smaller lag, exacerbating the problem. Accumulations of vortex lines in some regions of the crust change $f(\omega, \boldsymbol{r})$; however, contrary to the suggestion of Alpar et al. (1985), enhancements in the local vortex line density $n_v(\boldsymbol{r}, t)$ cannot produce a frequency deficit. These enhancements *increase* the local superfluid spin-down rate $[\dot{\Omega}_s(\boldsymbol{r}, t) \propto -n_v(\boldsymbol{r}, t)]$, and, by angular momentum conservation, produce a corresponding *decrease* in the spin-down rate of the crust.[2]

A promising possibility for explaining the relative frequency deficit is an increase in the external torque caused by the glitch. Such a change could occur via "plate tectonic" activity (Ruderman 1991). In this model, forces exerted by pinned vortices on the crust move crustal plates toward the equator. The surface magnetic field moves with the plates to which it is frozen. The dipole moment of the star thus becomes more misaligned with respect to the rotation axis, increasing the external torque. If glitches in the Crab pulsar are associated with crust cracking, each glitch may produce a sudden increase, $\delta\alpha$, in the alignment angle α between the magnetic moment and angular momentum axes of the star. In the magnetic dipole model, a change $\delta\alpha \sim 10^{-4} \tan\alpha$ would produce the observed offset in $\dot{\Omega}_c$. Since the interval between glitches in the Crab pulsar is ~ 3 yr, the implied growth time for α would be $\sim 3 \times 10^4$ yr, consistent with the pulsar age of $\sim 10^3$ yr.

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[2] When vortex accumulations occur, they are not long-lived. Because of the variations of the radial creep velocity produced by vorticity gradients, vortex accumulations disperse. A solution of the linearized equations of motion for the superfluid velocity shows that the dispersion time scale is comparable to the characteristic post-glitch relaxation time scale, a few days for the Crab pulsar.

REFERENCES

Alpar, M. A., Anderson, P. W., Pines, D., & Shaham, J. 1984a, ApJ, 276, 325
Alpar, M. A., Langer, S. A., & Sauls, J. A. 1984b, ApJ, 282, 533
Alpar, M. A., Nandkumar, R., & Pines, D. 1985, ApJ, 288, 191
Anderson, P. W., & Itoh, N. 1975, Nature, 256, 25
Baym, G., Pethick, C., Pines, D., & Ruderman, M. 1969, Nature, 224, 872
Demiański, M., & Prószyński, M. 1983, MNRAS, 202, 437
Gullahorn, G. E., Issacman, R., Rankin, J. M., & Payne, R. R. 1977, AJ, 82, 309
Link, B., Epstein, R. I., & Baym, G. 1992, in preparation
Lohsen, E. H. G. 1981, A&AS, 44, 1
Pines, D., & Alpar, M. A. 1991, in Structure and Evolution of Neutron Stars, ed. D. Pines, R. Tamagaki, & S. Tsuruta (New York: Addison-Wesley), in press
Ruderman, M. 1991, ApJ, 366, 261
Van Riper, K. A., Epstein, R. I., & Miller, G. S. 1991, ApJ, 381, L47

Note added in proof.—A relative frequency deficit similar to that associated with the 1975 Crab glitch was observed following the 1989 Crab glitch as given in presentations by D. Nice and A. G. Lyne (Proc. Los Alamos Workshop on The Physics of Isolated Pulsars, ed. K. A. Van Riper, R. I. Epstein, & C. Ho [Cambridge: Cambridge Univ. Press], in press [1992]).