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# POSTGLITCH RELAXATION OF THE CRAB PULSAR: EVIDENCE FOR CRUST CRACKING

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## ABSTRACT

The pattern of glitches and postglitch behavior observed for the Crab pulsar (Boynton et al. 1972; Demiański & Prószyński 1983; Lyne & Pritchard 1987; Lyne, Graham-Smith, & Pritchard 1992) is strikingly different from that observed for the Vela pulsar (Alpar et al. 1993). A key question is whether the differences can be understood on evolutionary grounds. An analysis of the Crab pulsar suggests that this is indeed the case. Thus, we propose that the comparatively modest ($\Delta\Omega/\Omega \sim 10^{-8}$) and somewhat infrequent ($\sim$6 yr interglitch intervals) Crab pulsar glitches are caused by starquakes induced by pulsar spin-down (Ruderman 1976; Baym & Pines 1971); we attribute its anomalous postglitch behavior (an occasional extended spin-up and a long-term response opposite in sign to that seen in the Vela pulsar (Lyne et al. 1992) to vortices transported inward during a quake, while the observed unexpected persistent change in angular acceleration, $\dot{\Omega}_e$, following a glitch represents the creation of a new vortex depletion region, as suggested by Alpar & Pines (1993).


*Subject headings:* dense matter — pulsars: individual (Crab Pulsar) — stars: neutron

Six glitches have been observed in the Crab pulsar (PSR 0531+21) since its discovery. The fractional increase in angular velocity at the time of glitch ($\Delta\Omega_c/\Omega_c$) ranges from $9 \times 10^{-9}$ to $6 \times 10^{-8}$, while the fractional change in angular acceleration ($\Delta\dot{\Omega}_c/\dot{\Omega}_c$) is of the order of $10^{-3}$. The exact times of the first two events (Boynton et al. 1972; Demiański & Prószyński 1983), which happened in 1969 and 1975, respectively, are uncertain, while the fourth and the fifth events (Lyne & Pritchard 1987; Lyne, Graham-Smith, & Pritchard 1992), which happened in 1986 and 1989, respectively, were caught during regular observation sessions at Jodrell Bank. There is not enough data for us to analyze the third and the sixth events.

Following the "minimalist" phenomenological approach used to analyze the postglitch relaxation of the Vela pulsar (Alpar et al. 1993), we construct a model to describe the observed events, with a minimum number of free parameters and with the response timescales fixed for every glitch. We interpret the model fits in terms of vortex creep and crust cracking. The simplest good fit to the four Crab pulsar glitches is obtained by the empirical equation

$$\Delta\dot{\Omega}_c(t) = -\sum_{i=1}^{2} a_i e^{-t/\tau_i} - a_3\left[1 - \frac{1}{1 + \alpha e^{-(t+\Delta)/\tau_3}}\right] - b\,, \quad (1)$$

where $t$ is the time since the first postglitch observation, with $\tau_1 = 0.8$ ($\pm 0.1$) day, $\tau_2 = 12$ ($\pm 1$) days, and $\tau_3 = 200$ ($\pm 20$) days as fixed response times which do not vary appreciably from glitch to glitch. The consistent fitting parameters for each glitch are tabulated in Table 1, and the corresponding consistent fitting curve for the 1989 postglitch response is shown in Figure 1. In the fits, we have assumed that the average amplitude of the timing residuals represents the overall error bars. The small $\chi^2$ per degree of freedom for the 1975 and the 1989 glitches, therefore, suggests a relatively low noise level during the period. Our fit resembles that proposed by Lyne et al. (1992), who used three exponentials, with response times 0.8 day, 18 days, and 265 days, to fit the 1989 glitch. We obtain shorter response times $\tau_2$ and $\tau_3$ in conjunction with our nonlinear response term, proportional to $a_3$, which is not a simple exponential.

The first two simple exponentials are the usual linear response of internal torques that are linear in the angular velocity lag between the observed crust and some component of the star's interior. In vortex creep theory (Alpar et al. 1993), these terms describe the postglitch recoupling of pinned crustal superfluid to the rest of the star with $a_i = (I_i/I)[\delta\omega_i(0)/\tau_i]$ exp $(-\Delta/\tau_i)$, where $I_i/I$ is the fractional inertial moment of the region involved, $-\delta\omega_i(0)$ is the initial change in angular velocity lag between superfluid and the crust, and $\Delta$ is the time gap between actual time of glitch and the first post-glitch observation; $\delta\omega > 0$ whenever there is a sudden spin-up in the star or a sudden outward motion of superfluid vortices (Alpar et al. 1993). The 12 day response must correspond to a region through which vortices pass at the time of glitch, so that $\delta\omega_2(0)$ is essentially the superfluid velocity change due to the passage of these vortices. Otherwise, $\delta\omega_2(0)$ would equal the initial spin up of the star, $\Delta\Omega_c(0)$, and the inertial moment $I_2/I$ deduced from Table 1 would be unrealistically high.

Unlike the 12 day response, the amplitude of the 0.8 day response ($a_1$) [and hence $\delta\omega_1(0)$] is negative in the 1989 event. This is possible only if a net inward motion of vortices accompanies the glitch. It is thus a signature of a glitch induced by a star quake (Ruderman 1976; Baym & Pines 1971), in which pinned vortices carried by a breaking crustal plate move inward, causing the 0.8 day "extended" spin-up.

The third term in equation (1) represents a nonlinear region where the steady state spindown of the superfluid requires a large equilibrium lag and responds very nonlinearly to glitch-associated perturbations (Alpar, Cheng, & Pines 1989). Here $a_3 = I_3/I\,|\dot{\Omega}_\infty|$, and $\alpha = e^{t_g/\tau_3} - 1$, where $t_g \equiv \delta\omega_3(0)/|\dot{\Omega}_\infty|$. In the event that $|\alpha| \ll 1$, the third term in equation 1 can be approximated by (Alpar et al. 1993) $-a_3\alpha e^{(t+\Delta)/\tau_3}$. In fact, except for the 1989 glitch, we cannot determine the values of $a_3$ and $\alpha$ unambiguously; only the $a_3\alpha e^{-\Delta/\tau_3}$ term is known in the other events. The 1989 Crab pulsar glitch is unusual in that its

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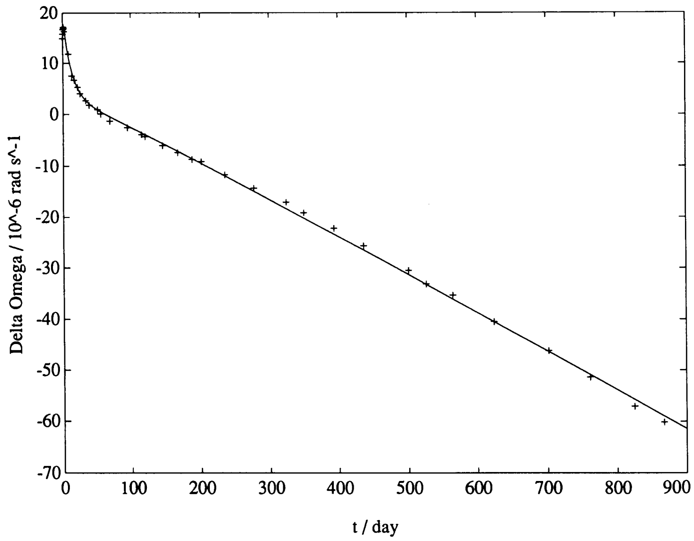


FIG. 1.—Consistent fit for the 1989 Crab pulsar glitch; $t$, the number of days after the glitch, is plotted against $\Delta\Omega_c$, the change in angular velocity in units of $10^{-6}$ rad s$^{-1}$. The observed $\Delta\Omega_c$ are marked by crosses.

nonlinear response indicates a negative $\delta\omega$ [as does the linear response with negative $\delta\omega_2(0)$], hence inward vortex motion through the nonlinear creep region is indicated. This is the first example of postglitch response involving inward vortex flow through nonlinear and linear creep regions, naturally suggesting the association of inward crust breaking and vortex motion with the inward moving parts of the crust, while simultaneous outward vortex release and transfer of angular momentum leads to the glitch.

Angular momentum is conserved in the glitch. The angular momentum balance equation takes the form

$$\Delta(I_c\,\Omega_c) = I_c\,\Delta\Omega_c + \Omega_c\,\Delta I_c = \sum_{i=1}^{3} I_i\,\delta\omega_i + I_B\,\delta\omega_B\,, \qquad (2)$$

where $\Delta I_c$ is the change in crustal inertial moment brought about by the starquake, and $I_B$ is the inertial moment of a vortex depletion or capacitor region of the kind proposed for the Vela pulsar (Alpar et al. 1993). Such a region does not allow vortices to pass through it except at the time of a glitch and does not show up in the postglitch response. Alpar and Pines call it a capacitor region because it acts as a vortex trap and releases vortices only at the time of a glitch (Alpar & Pines 1993).

Both the reduction of oblateness (and hence the crustal inertial moment) and the creation of a new capacitor region can lead to a permanent offset in $\dot{\Omega}_c$ (Baym & Pines 1971; Alpar & Pines 1993). To explore the first alternative, we note that if the permanent offset observed from the Crab pulsar is due to a reduction in stellar oblateness, then there should also be a remnant change in frequency, such that

$$\left(\frac{\Delta\Omega_c}{\Omega_c}\right)_{\rm res} = \left(\frac{\Delta\dot{\Omega}_c}{\dot{\Omega}_c}\right)_{\rm res} = \left|\frac{\Delta I}{I}\right|. \qquad (3)$$

As there is no such large remnant $\Delta\Omega/\Omega$, the permanent offset $\Delta\dot{\Omega}$ must have some other cause than an oblateness change. We propose that the permanent change in $\dot{\Omega}_c$ reflects the formation of new capacitor regions at the time of the glitch, and only a small portion of the permanent offset is contributed by the oblateness change; we may therefore neglect the $\Omega_c\,\Delta I_c$ term in the angular momentum balance equation (eq. [2]). An alternative way to explain the permanent offset in $\dot{\Omega}_c$ by a glitch-induced change in external torque has been discussed elsewhere (Ruderman 1991; Link, Epstein, & Baym 1992).

The inertial moment of a newly formed capacitor region, $I_b$, is given by $(I_b/I)\,|\dot{\Omega}|_\infty = b$. As Alpar & Pines (1993) have noted, if a capacitor region is formed after every glitch for pulsars with the same age as the Crab pulsar, a percolating capacitor network will be fully developed when these pulsars evolve to the age of the Vela pulsar. From the present rate of formation of capacitor regions, together with the estimate that some 2.6% of the inertial moment of a pulsar at the age of the Vela pulsar represents the pinned crustal superfluid (Chau et al. 1993), about 200 more glitches and, hence, some 2000 more years may be required for the Crab pulsar to reach the fully connected state hypothesized for the Vela pulsar.

We tabulate in Table 2 the various glitch parameters which can be deduced from our interpretation of the postglitch behavior of the Crab pulsar. If we assume that only the newly formed capacitor region is involved in the angular momentum balance in a glitch and that the values of $\delta\omega(0)$ for all the inward moving (and similarly for the outward moving) vortex regions are the same, the pinned crustal inertial moment of the Crab pulsar ($I_p$) must be at least 0.19% of that of the whole star.

As the Crab pulsar reaches the age of an "adolescent" pulsar, the epoch of capacitor region formation will have come to an end, while the connection of these capacitor regions can account for the more frequent and much larger glitches. To the extent that the value of $E_p/kT$ of a region is constant, where $E_p$

TABLE 1

OBSERVED PARAMETERS

| PARAMETER | GLITCH YEAR 1969 | 1975 | 1986 | 1989 |
|---|---|---|---|---|
| $a_1(\times 10^{-12}$ rad s$^{-2})$ | 0.49 | 4.01 | 25.7 | −79.6 |
| $a_2(\times 10^{-12}$ rad s$^{-2})$ | 0.45 | 3.15 | 0.68 | 17.0 |
| $a_3(\times 10^{-12}$ rad s$^{-2})$ | ... | ... | ... | 1.1 |
| $\alpha$ | ... | ... | ... | −0.321 |
| $a_3\,\alpha e^{-\Delta/\tau_3}(\times 10^{-14}$ rad s$^{-2})$ | 8.5 | 2.7 | 0.5 | ... |
| $b(\times 10^{-13}$ rad s$^{-2})$ | 0.08 | 5.7 | 0.44 | 9.2 |
| $[\Delta\Omega_c(0)/\Omega_c](\times 10^{-9})$ | 4.0 | 44.0 | 23.7 | 77.1 |
| $\chi^2$ | 10.2 | 7.9 | 43.6 | 11.4 |
| $n$ | 9 | 32 | 36 | 31 |

NOTES.—Observed parameters of the consistent fit of the Crab glitches; $n$ is the degree of freedom of the fits.

TABLE 2

DEDUCED PARAMETERS

| PARAMETER | GLITCH YEAR 1969 | 1975 | 1986 | 1989 |
|---|---|---|---|---|
| $(I_1/I)\delta\omega_1(\times 10^{-7}$ rad s$^{-1})$ | ≥0.34 | ≥2.77 | 17.8 | −55 |
| $(I_2/I)\delta\omega_2(\times 10^{-7}$ rad s$^{-1})$ | ≥4.7 | ≥32.7 | 7.1 | 177 |
| $I_3/I(\times 10^{-4})$ | ... | ... | ... | 4.4 |
| $\delta\omega_3(0)(\times 10^{-2}$ rad s$^{-1})$ | ... | ... | ... | −1.62 |
| $I_b/I(\times 10^{-4})$ | 0.03 | 2.2 | 0.18 | 3.8 |
| $(I_B/I)\delta\omega_B(0)(\times 10^{-7}$ rad s$^{-1})$ | ≤2.46 | ≤47.4 | 2.0 | 94.7 |
| $\delta\omega_B(0)(\times 10^{-2}$ rad s$^{-1})$ | ≤8.2 | ≤2.2 | ≤1.1 | ≤2.5 |
| $I_p/I(\times 10^{-3})$ | ≥0.01 | ≥1.74 | ≥0.25 | ≥1.87 |

NOTES.—Deduced parameters of the four Crab glitches from the consistent fit.

is a characteristic pinning energy of a vortex line in the region, the corresponding linear response timescales are proportional to the period of the pulsar (Alpar et al. 1993). With this assumption in mind, the 0.8 day and 12 day response of the Crab pulsar can be roughly scaled to the 3.2 day and 33 day response of the Vela pulsar, a result consistent with an evolutionary process in which the response timescales of the pulsar lengthen gradually as the star spins and cools down. (Further details concerning our fitting procedure and vortex motion during and after a glitch can be found in our manuscript in preparation.)

Our reaffirmation of the proposal that glitches in young pulsars are caused by starquakes is consistent with the recent report by Kaspi et al. (1994) on the spin-down of the young pulsar PSR B1509−58, who find it has not glitched during an 11 yr span. The frequency of starquakes induced by pulsar spin-down is directly proportional to the spin-down rate, $\dot{\Omega}$. Since the Crab pulsar has glitched 6 times in 25 yr, we would estimate that the likelihood of a PSR B1509−58 glitch is $(6/25)(\dot{\Omega}_{B1509}/\dot{\Omega}_{Crab}) \times 11 = 0.46$. Thus, it may will take another decade or so of timing observation of PSR B1509−58 before a glitch is observed.

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