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Glitches and the Vela Slowdown

I The basic model

In the superfluid component of a pulsar the angular momentum is represented by the area density of vortices. Slowing down therefore means that the vortices are moving outwards. If vortices in a component of the superfluid are pinned to the crystal lattice of the crust, that component does not participate in the slowdown.

The crust and the core are tightly linked: only the superfluid within the inner part of the crust can rotate independently.

II Glitches in all pulsars except the youngest

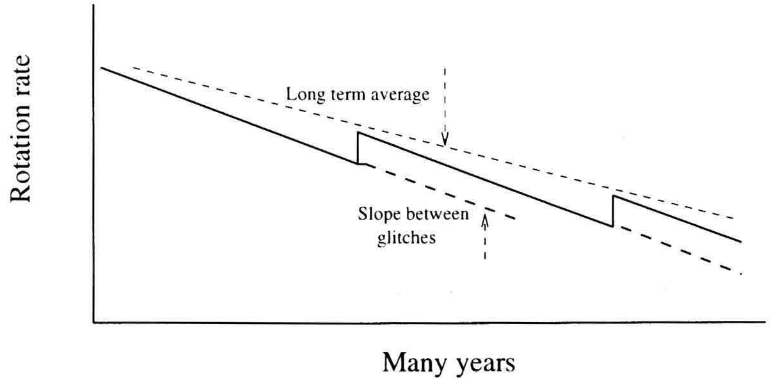

Figure 1. Sketch of the rotation rate of old glitching pulsars as a function of time.

There are three basic components of glitches in the older pulsars. The observations and interpretations can be summarized as follows:

Observation 1: The glitches are simply a step increase in rotation rate ν, reversing the predominant steady slowdown. The reversals, averaged over a long time, reduce the mean slowdown rate by about 1.7%. This fraction is independent of age and slowdown rate.

Interpretation: A region of superfluid with 1.7% of the total moment of inertia is fully pinned between glitches, and unpins completely at each glitch.

Observation 2: Part of the initial step recovers immediately following the glitch. This transient increase in ν amounts to around 1% of the glitch amplitude at most glitches. It decays in 10–100 days (see Figure 2).

Interpretation: A different region of superfluid is responding to the step in crustal rotation rate. In this region the vortices are not completely pinned, but their outward flow is impeded by the crustal lattice; they are 'creeping' outwards, and the rotation rate of this component is higher than in the crust. At the glitch the steady-state differential is disturbed and slowly re-established. In this model the moment of inertia of this component is around 1% of the total. Observations show that this proportion, which is of order 1% of the total, decreases with age.

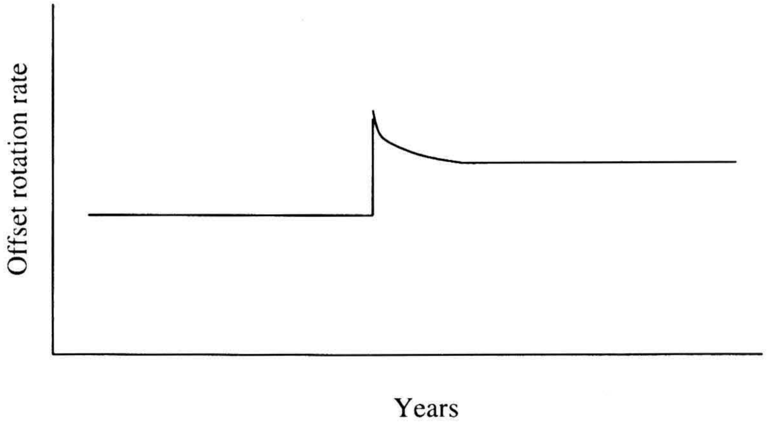

Figure 2. Transient increase in ν following a glitch (schematic). After a rapid decay following the glitch, an on average linear decay continues (see Figure 3).

Observation 3: Most pulsars show an approximately linear decrease of slowdown rate between glitches. This shows in a plot of slowdown rate, in which the mean slowdown rate has been removed (see Fig. 3).

Interpretation: Extending between the fully pinned region and the continuously creeping region is an intermediate region, all of which is fully pinned immediately after a glitch but which becomes progressively unpinned between glitches, like a zip fastener. The effective moment of inertia of this region increases as the unpinning spreads across it, giving a steady increase in slowdown rate. This component again represents about 1% of the total moment of inertia.

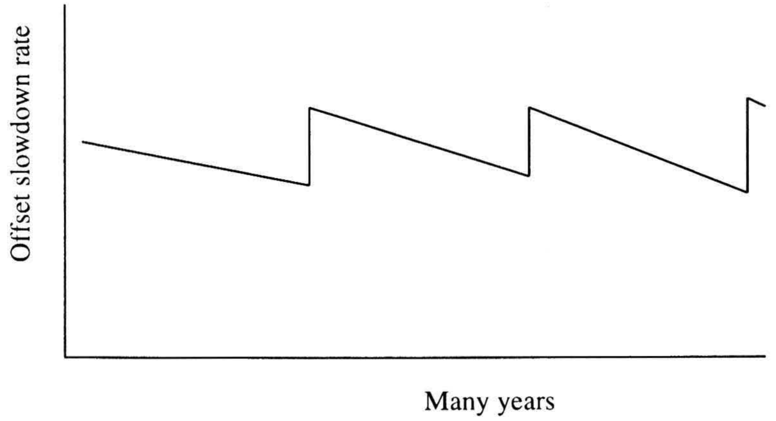

Figure 3. Mean trend of the slowdown rate between glitches (after subtraction of the mean slowdown rate).

III The young pulsars Crab and Vela

Glitches in the Vela pulsar show all three of the components described above, and in addition the slowdown rate shows an anomalous braking index. The short-term recovery has been resolved into several exponential components. Figure 4 shows the slowdown rate over 25 years (without any offset); the rate of change of slowdown rate is obtained from the long-term slope over the whole plot.

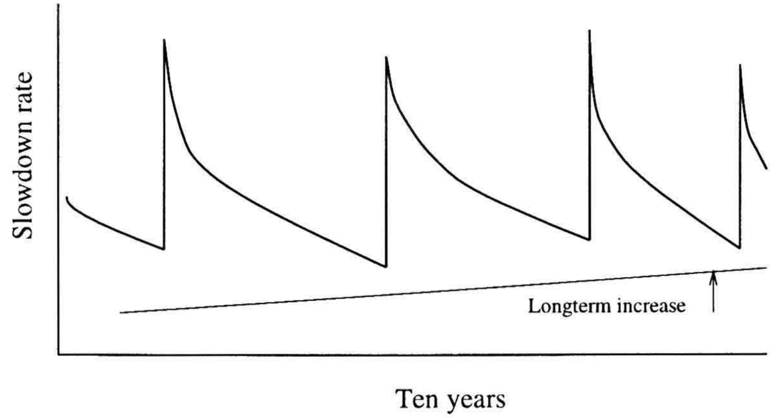

Figure 4. Slowdown rate of the Vela pulsar over a ten year period.

Crab glitches are completely different; as shown in Figure 5 they show primarily a step increase in slowdown rate which does not recover between glitches.

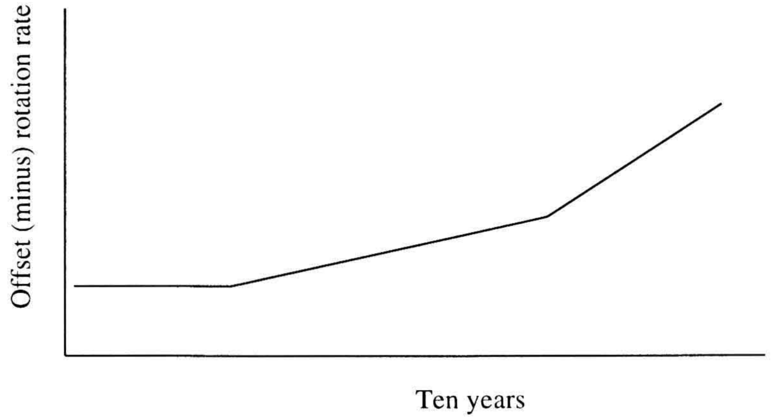

Figure 5. Offset slowdown rate of the Crab pulsar increases after each glitch.

Interpretation: The changes in slowdown rate in the Crab show a cumulative change in either moment of inertia or magnetic dipole moment. A decrease in moment of inertia would be due to a step decrease in pinning at each glitch, while an increase in dipole moment would be due to a rearrangement of the internal field.

IV The braking index of Vela

Why is the braking index of Vela 1.4 and not 3.0 as expected? The two possibilities are that either the magnetic moment M or the moment of inertia I changes in the slowdown process, averaged over many glitches. The slowdown law for magnetic dipole radiation gives

$$\frac{\mathrm{d}\dot{\nu}}{\dot{\nu}} = 3\frac{\mathrm{d}\nu}{\nu} + 2\frac{\mathrm{d}M}{M} - \frac{\mathrm{d}I}{I} \tag{1}$$

so that the braking index is

$$n = \frac{\nu\ddot{\nu}}{\dot{\nu}^2} = 3 - 2\tau_c M^{-1}\frac{\mathrm{d}M}{\mathrm{d}t} + \tau_c I^{-1}\frac{\mathrm{d}I}{\mathrm{d}t}, \tag{2}$$

where τ_c is the characteristic age,

$$\tau_c = -\frac{1}{2}\frac{\nu}{\dot{\nu}} \tag{3}$$

The low value of braking index $n = 1.4$ instead of the expected 3.0 might then be accounted for by a time-averaged change in either I or M; the required rates of change are

$$M^{-1}\frac{\mathrm{d}M}{\mathrm{d}t} = +0.8\tau_c^{-1} \tag{4}$$

and

$$I^{-1}\frac{\mathrm{d}I}{\mathrm{d}t} = -1.6\tau_c^{-1}, \tag{5}$$

i.e., either the effective moment of inertia is increasing on a time scale of 14 000 years or the total effective moment of inertia is decreasing on a time scale of 7 000 years. If this is to be explained in terms of incremental changes of I at the glitches, it must be related to the 2–3% of the total I that is involved in pinning. This rate of change could then only be sustained for less than 200 years. More reasonably, M might be increasing on a time scale comparable with the lifetime of the pulsar, either through a changing alignment angle or an internal organisation.

We suggest that this might occur at the glitches rather than as a continuous process. The step increase in the effective magnetic moment would then be one part in 5000 at each glitch.

This may also be occurring at Crab glitches, where the slowdown rate is observed to increase by about 1 in 5000 every 10 years.

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