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Timing Noise and Glitches

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Abstract. One of the most remarkable properties of radio pulsars is their rotational stability which allows many uses as clocks, For instance they enable us to determine the shapes and sizes of binary orbits, to study general relativistic effects in strong gravitational fields, to demonstrate the existance of gravitational radiation from binary systems, to permit the detection of extra solar planets, and also to put limits on the long period gravitational wave background. However, some display timing imperfections which tell us about the insides of neutron stars. This review describes the basic physics of slowdown and how period instabilities seem to be related to the rate of slowdown and the presence of internal superfluid liquid. Careful studies of glitches and the subsequent rotational behaviour of the pulsars can provide valuable information on the internal structure of neutron stars.

1. Regular Slowdown

Pulsars slow down through the loss of kinetic energy in the form of low frequency electromagnetic waves or high energy particles and radiation. We first of all discuss the process of the regular slowdown and its observation, before discussion departures from this monotonic behaviour.

In a general slowdown, the braking torque is proportional to the rotational frequency Ω to some power n, the braking index, which depends upon the physics of the braking mechanism:

$$\dot{\Omega} = -k\Omega^n. \tag{1}$$

For magnetic braking by a dipolar field, the rate of spin-down is determined by the component of magnetic dipole moment M normal to the rotation axis and moment of inertia I of the neutron star according to the equation:

$$Torque = -2 \times M^2\Omega^3/3c^3 = I\dot{\Omega} \tag{2}$$

Comparing this with equation (1), we see that n=3. For particle loss from a completely aligned rotator, n also has an expected value of 3 (Goldreich & Julian 1969). We can express M in terms of the magnetic field $B_0 = M / R^3$ at the surface of the star of radius R and obtain B_0 in terms of the period, $P = 2\pi / \Omega$:

$$B_0 = \sqrt{3Ic^3P\dot{P}/8\pi^2R^6} = 3.3 \times 10^{19}(P\dot{P})^{1/2} \; gauss \tag{3}$$

where we have taken the neutron star to have ε radius R = 10 km and moment of inertia I = 10^{45} gm cm^2. Integration of the general spindown equation (1) gives a time interval since the spin rate had an initial value Ω_i:

$$t = -\frac{\Omega}{(n-1)\dot{\Omega}}\left[1 - \left(\frac{\Omega}{\Omega_i}\right)^{n-1}\right] \tag{4}$$

In the case where the initial rotation rate was very high, i e. $\Omega_i \gg \Omega$, then

$$t = -\frac{\Omega}{(n-1)\dot{\Omega}} = +\frac{P}{(n-1)\dot{P}} = +\frac{P}{2\dot{P}}, \text{ for magnetic dipole braking } (\mathrm{n} = 3). \tag{5}$$

The latter estimate is commonly known as the characteristic age of the pulsar. For the Crab pulsar the characteristic age is 1250 years, in reasonable agreement with the known age of 940 years. Since the initial period must have been finite, the characteristic age is usually regarded as an upper limit to the true age. Any decay in the magnetic field will also serve to make it an overestimate of the true age.

In principal we can check on the value of n by differentiation of the spindown equation (1), giving

$$n = \Omega\ddot{\Omega}/\dot{\Omega}^2. \tag{6}$$

A stable value of η has been measured in this way for only 3 pulsars as shown in Table 1.

These values are all somewhat less than 3 and probably result from the non-dipolar nature of the magnetic field or the presence of particles in the magnetosphere. For older pulsars, timing noise dominates the measured value of $\ddot{\Omega}$ (see section 3) and the value of n is variable and is not related to the braking mechanism. Conversely, note also that the youngest pulsars such as the Crab may show significant higher-order derivatives due to the slow-down process which may be mistaken for timing noise.

Table 1: The breking indices of pulsars

Pulsar	Braking Index, n	Reference
0531+21	2.509±0.001	Lyne,Pritchard & Smith (1988)
0540-69	2.01 ±0.02	Manchester & Peterson (1989)
1509-58	2.838±0.001	Kaspi et al. (1994)

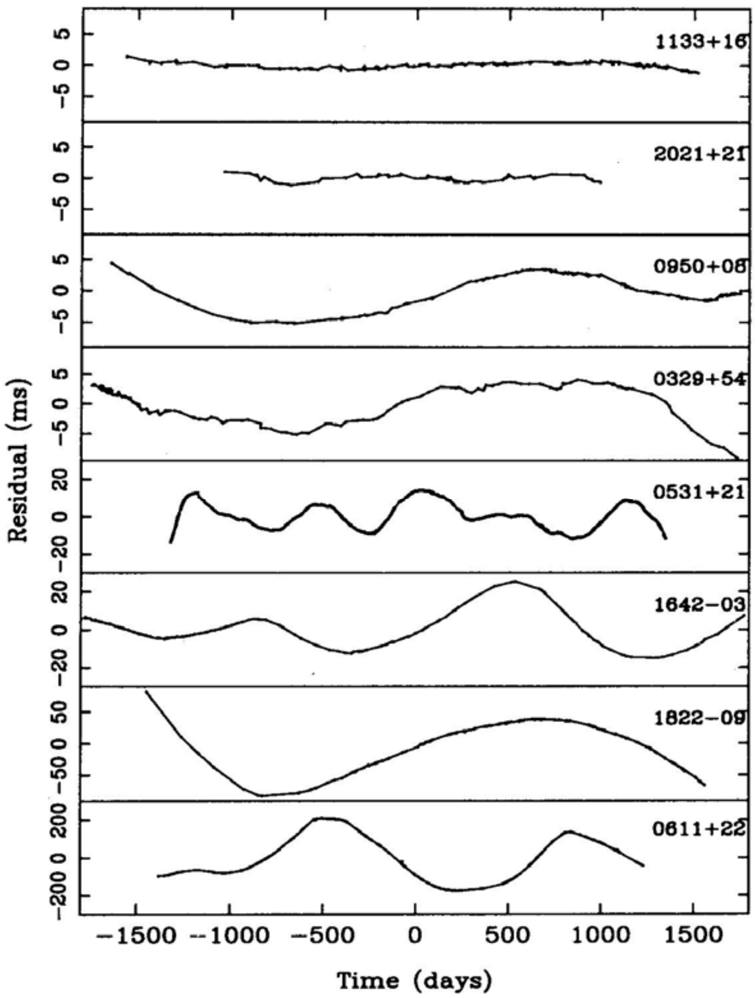

Figure 1: Examples of timing noise in 8 pulsars over about a 10 year period, showing increasing amounts of activity from the top to bottom.

2. Irregular Slowdown

This normal slowdown described above is steady and predictable. However some pulsars show unpredictable behaviour of two types: timing noise and glitches. Both are apparently associated with the transfer of angular momentum from the fluid interior (Lyne 1992) as the pulsar slows down and we discuss each of these in turn.

3. Timing Noise

Timing noise is characterised by a continuous, unpredictable, phase wandering of the pulses relative to a simple slow down model. It is seen most prominently in the Crab and other pulsars with large period derivatives (Cordes and Helfand 1980). Some examples of timing noise in a number of pulsars are shown in Fig. 1 where the unpredictability of the period in these pulsars is clear. The amount of this timing noise can be quantified by measuring the residuals relative to a simple slow-down model as described above. Fig. 2 shows the activity parameter, a logarithmic measure of the timing noise, as a function of the period derivative for a number of pulsars (Cordes and Downs 1985). The millisecond pulsars with very small period derivatives are found to be very stable, as indeed might be expected from the extrapolation of the trend in this diagram to their position in this diagram (Arzoumanian et al. 1994).

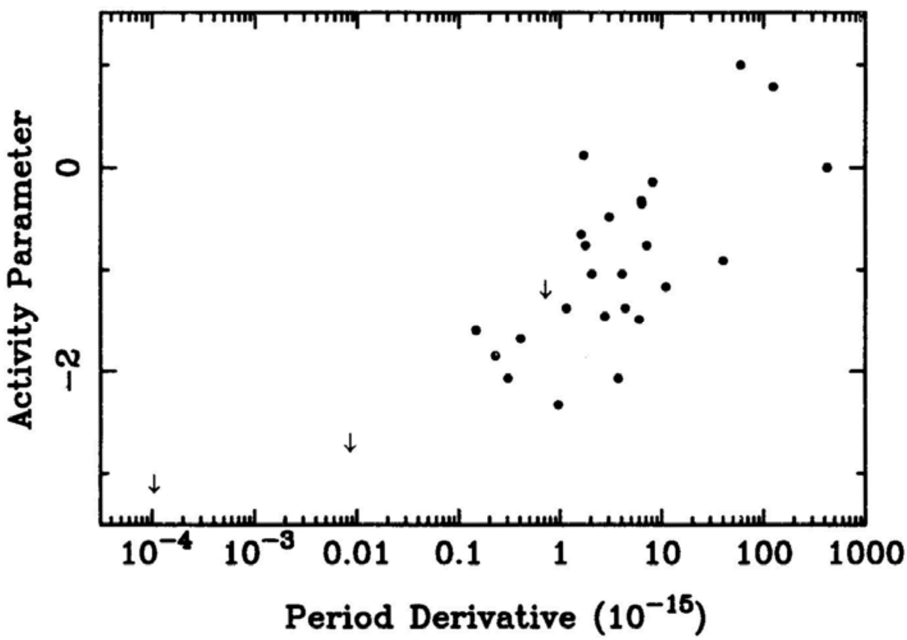

Figure 2: The timing activity parameter plotted as a function of period derivative

The most natural explanation is that timing noise is due to an irregular flow of angular momentum from a fluid component in the interior of the star for which direct evidence is provided by the glitches described in the next section.

4. Glitches

These are seen as sudden increases in the rotation rate $\nu = \Omega / 2\pi$, usually followed by an exponential recovery or relaxation back towards the pre-glitch period. For example, the slowdown of the Vela pulsar is shown in Fig. 3 over a 11-year period: during this interval, 4 glitches can be easily seen, each resulting in a fractional increase in rotation rate of about 2 parts in 10^6.

This behaviour can be explained by the presence of a fluid component in the interior of the neutron star which is loosely coupled to the rigid crust whose rotation we observe (Baym et al. 1969) through the emission beam which is tied to it. This simple model gives rise to the "glitch function" which describes the exponential recovery: $\Delta\nu(t) = \Delta\nu_0 \times [1 - Q\ (1 - e^{-t/\tau})]$. Here, $\Delta\nu_0$ is the initial rotational frequency increase and Q is the fraction of this which recovers on a timescale τ.

There are two main aspects of glitches which may or may not be related: firstly, the cause of the glitch, which might result from either a starquake or superfluid unpinning, and secondly, the post glitch relaxation, which gives information on the amount of fluid in the star and the physics of the angular momentum transfer from the core. First we discuss the possible causes of the glitches and then the possible implications of the recovery.

A starquake might arise from changing ellipticity of the crust of the neutron star as it slows down. The oblateness of an equilibrium spheroid will decrease as the rotation rate decreases. Stresses build up in the rigid crust as the departure from the equilibrium shape increases, until it cracks and assumes a shape closer to the equilibrium spheroid. The moment of inertia I decreases and conservation of angular momentum results in a spin-up given approximately in terms of the change in oblateness:

$$\Delta\epsilon = \Delta I/I = -\Delta\Omega/\Omega \tag{7}$$

For the Crab pulsar $\Delta\epsilon = -10^{-7}$ every 10 years and the current value of ϵ is about 10^{-3}. Clearly the time scale on which ϵ will decay due to this glitch activity is much greater than the age of the pulsar and this is quite satisfactory. However for the Vela pulsar $\Delta\epsilon = 2\times10^{-6}$ every 3 years and $\epsilon = 10^{-4}$. Clearly in this case ϵ would disappear in only about 100 years which is only about 1% of the age of the pulsar (Pines, Shaham &· Ruderman 1972). The current rate of glitching cannot be sustained, and another source of the discrete spin-ups is necessary.

It was suggested that superfluid neutrons probably exist in the inner part of the crust (Baym, Pethik & Pines 1969) and that these may be responsible for the glitches in the following way. The rotation rate of the superfluid is determined by the density of vortices and hence slowdown corresponds to an outward drift of vortices. However it is possible that the vortices pin to lattice nuclei in the inner part of the crust, so preventing them from drifting outwards (Anderson & Itoh 1975). The stress which drives the outward motion (the magnus force) builds up until the strength of the pinning is exceeded. There is then a sudden catastrophic unpinning and a subsequent outward flow which causes an increase in the angular momentum of the crust. This is then probably followed by a re-pinning of the vortices and outward drift is reduced again. It is possible that, as the magnus force builds up, high temperature can permit vortex drift to occur, so relieving the pressure and reducing the rate of glitching (McKenna & Lyne 1990).

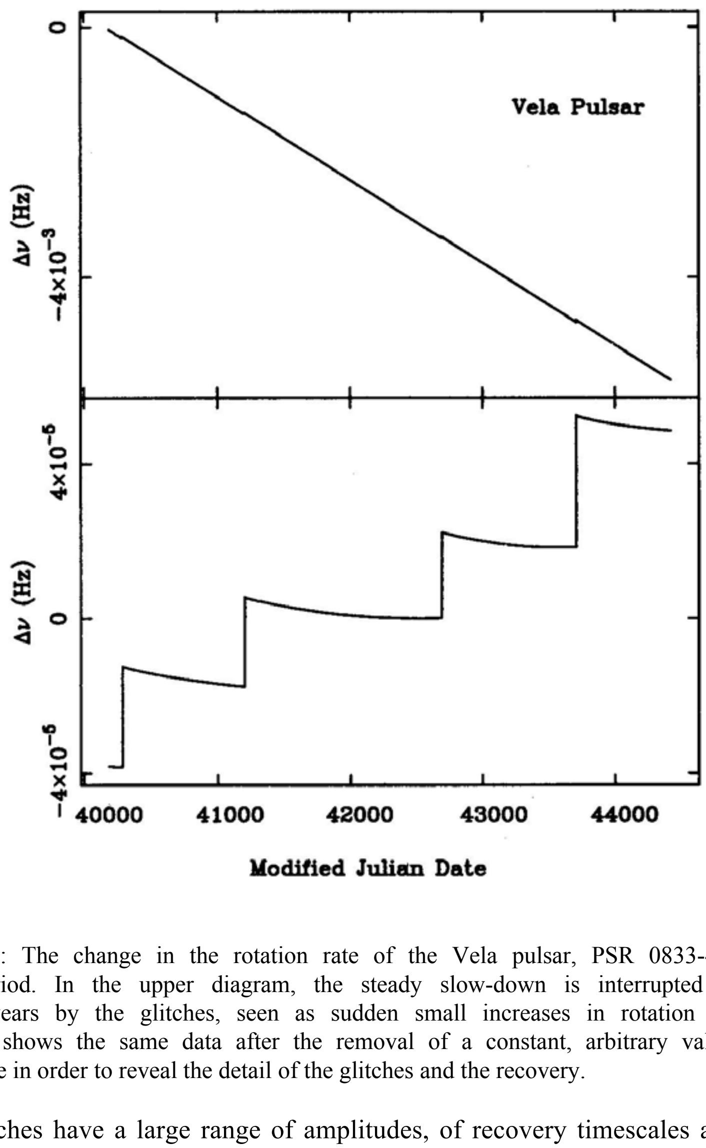

Figure 3: The change in the rotation rate of the Vela pulsar, PSR 0833-45, over an 11-year period. In the upper diagram, the steady slow-down is interrupted at intervals of a few years by the glitches, seen as sudden small increases in rotation rate. The lower diagram shows the same data after the removal of a constant, arbitrary value of frequency derivative in order to reveal the detail of the glitches and the recovery.

Glitches have a large range of amplitudes, of recovery timescales and of recovery amplitudes. As discussed earlier, the Vela pulsar is a frequent glitcher and 9 glitches have been observed over a 24 year period, the average fractional increase in rotation rate being about 2×10^{-6}. Recovery timescales seen in this pulsar are a few hundred days and less than a few days and the amount of recovery in rotational frequency is only about 20% of the glitch amplitude. Alpar et al. (1993) have interpreted the recovery from these glitches in terms of both linear and non-linear relaxation in a number of regions within the crust.

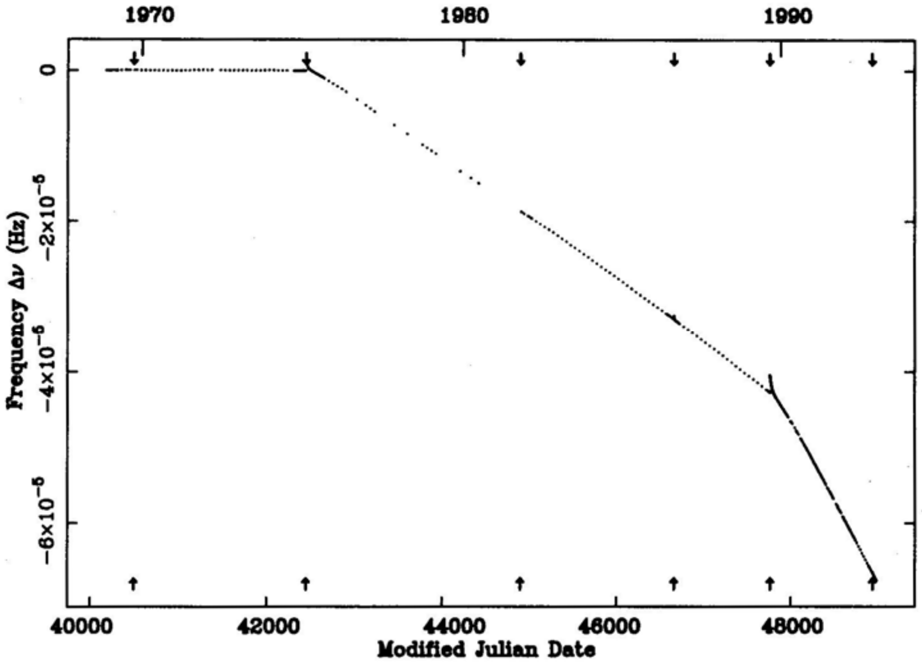

Figure 4: The rotation frequency of the Crab pulsar, PSR 0531+21, over a 23-year period, relative to a slow-down model fitted to the first few years of data. Two major glitches and their transient recoveries can be seen as small excursions in 1975 and 1989. However, their major effect was a permanent change in slowdown rate, seen as a sudden change in slope.

The Crab pulsar behaves rather differently (Lyne, Pritchard & Graham-Smith 1993) and has shown a series of glitches of magnitude 10^{-8} to 10^{-7}, which can be seen in figure 4 as changes in the rotation rate relative to a simple slow-down model fitted to the earliest data. The main effect of these glitches seems to be a persistent increase in slowdown rate amounting to about 0.1 % in total over a period of 23 years. How can this arise? Since the slowdown rate is primarily determined by B_0 and I (equation 3), there are 2 main possibilities. Firstly, the value of B_0 could have increased or its configuration could have changed. So far there is no observational evidence that this has occurred. The second possibility is that I has decreased. Now this cannot be due to a change in ellipsoid since the current moment of inertia is no more than 0.01% different from its value if it were rotating slowly. One possibility is that the decrease in I is due to an increase in vortex pinning as the star cools. Over the lifetime of the star this rate of pinning implies that more than 5% of the moment of inertia must now be tied up in the form of pinned superfluid neutrons.

5. The Frequency of Glitches

Until recently the study of glitches has been limited by their small number. Excluding Vela, only about 10 glitches were observed in about 20 years up to 1987. This was mainly due to the lack of known young pulsars. The small number arises both from the fact that pulsars do not stay young for very long, and also that there are strong selection effects against the discovery of young pulsars in most searches. Their short periods made them difficult to detect in the early surveys and their low z-distances give rise to a high sky background temperature, high dispersion, and high scattering at low frequencies, all of which were detrimental to their detection. To combat such effects, two surveys have been conducted at low latitude and high radio frequency. The survey at Jodrell Bank (Clifton & Lyne 1986) discovered 40 new pulsars in a sample which has a mean characteristic age of only 0.8 million years compared with 6 million years for all pulsars found in previous surveys (Clifton et al. 1992). Already 12 glitches have occurred in 5 years in 6 of these pulsars (Shemar & Lyne 1995). The subsequent high frequency Parkes survey of the southern galactic plane has shown a similar success rate Johnston et al. 1992a; Johnston et al. 1995).

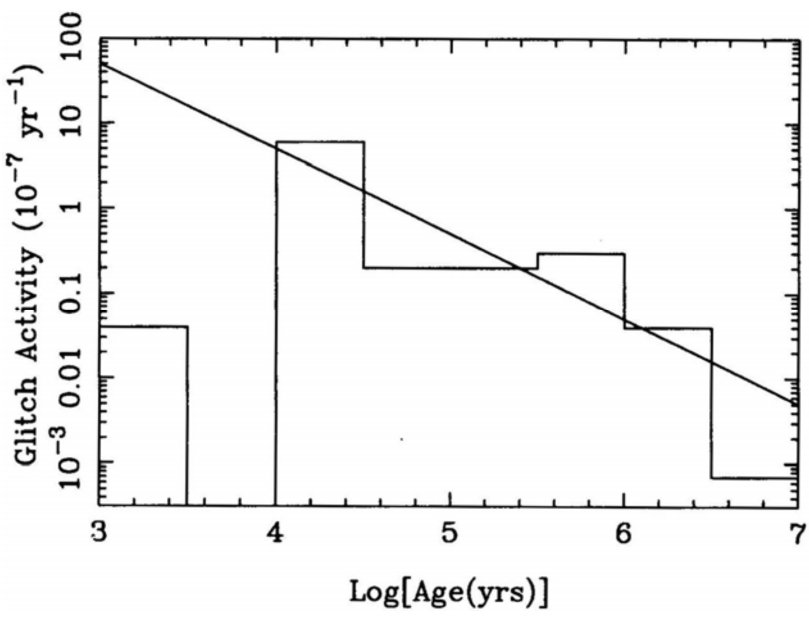

Figure 5: The glitch activity parameter, the fractional increase in rotation rate due to glitches/year, averaged over all observed pulsars in semi-decade ranges of characteristic age.

Table 2 provides a summary of the 20 pulsars which have glitched, together with the number of glitches, the fractional increase in rotational frequency at each glitch and the observational references. These data show that glitches occur predominently in young pulsars which account for only about 3% of the known population. The rest of this section describes the frequency of glitches and their recovery as a function of the pulsar spin-down parameters.

TABLE 2: Known Glitching pulsars

Pulsar	N_{glitch}	$\Delta\Omega/\Omega \times 10^6$	References
0355+54	2	0.006, 4.4	A
0525+21	2	0.0013, 0.0003(?)	B
0531+21	4	0.01, 0.04, 0.01, 0.08	C,D,E,F
0833-45	9	2.3, 2.0, 2.0, 3.1, 1.1, 2.0, 1.3, 1.8, 2.7	G,H,I,J,K,L,M,N,O
1325-43	1	0.12	P
1338-62	3	1.5, 0.03, 1.0	Q
1508+55	1	0.0002(?)	R
1535-56	1	2.8	S
1641-45	1	0.2	T
1706-44	1	2.1	S
1727-33	1	3.1	S
1736-29	1	0.003	U
1737-30	6	0.42, 0.03, 0.007, 0.03, 0.60, 0.70	V
1758-23	3	0.20, 0.23, 0.35	W
1800-21	1	4.1	U
1823-13	2	2.7, 3.1	U
1830-08	1	1.9	U
1859+07	1	0.03	U
1907+00	1	0.0007(?)	X
2224+65	1	1.7	Y

REFERENCE KEYS:
A:Lyne (1987) B:Downes (1982) C:Boynton et al. (1972) D:Lohsen (1975) E:Lyne & Pritchard (1987) F:Lyne, Pritchard & Graham-Smith (1992) G:Radhakrishnan and Manchester (1969) H:Reichley & Downes (1971) I:Manchester, Goss & Hamilton (1976) J:Manchester et al. (1983) K:McKulloch et al. (1983) L:Cordes, Downes & Krause-Polstorff (1988) M:McKulloch et al. (1987) N:Flanagan (1989) O:Flanagan (1991) P:Newton, Manchester & Cooke (1981) Q:Kaspi et al. (1992) R:Manchester & Taylor (1974) S:Johnston et al. (1992b) T:Manchester et al. (1978) U:Shemar & Lyne (1995) V.McKenna & Lyne (1990) W:Kaspi et al. (1993) X:Gullahorn et al. (1976) Y:Backus, Taylor & Damashek (1992)

Apart from the youngest pulsars, most pulsars which have glitched have done so only once. The implication here is that the intervals between glitches in these objects and in similar ones is much greater than the observational timespan and, given enough time, they will all display glitch activity. For this reason, in order to understand the frequency of glitches, we have to consider the length of time that pulsars of similar characteristics have been observed. Dividing the number of glitches by the total observation time gives a rate of glitch activity (Shemar & Lyne 1995). Figure 5 shows the pulsar glitch activity as a function of age. We clearly see that the glitch activity is greatest for pulsars with ages between about 10,000 and 30,000 years. For greater ages, it seems that the activity falls off roughly as the frequency derivative, presumably as the flow of angular momentum from the interior decreases. To first order, this can be understood in terms of glitches undoing of a fixed fraction of the normal rotational slow-down. This fraction amounts to about 0.03, suggesting that about 3% of the angular momentum in these pulsars is carried by superfluid neutrons whose outward flow to the crust is held up by vortex pinning and only moves in a stepwise manner. Since there is no significant recovery between glitches (see next section), this implies that there is little drift occurring in these vortices.

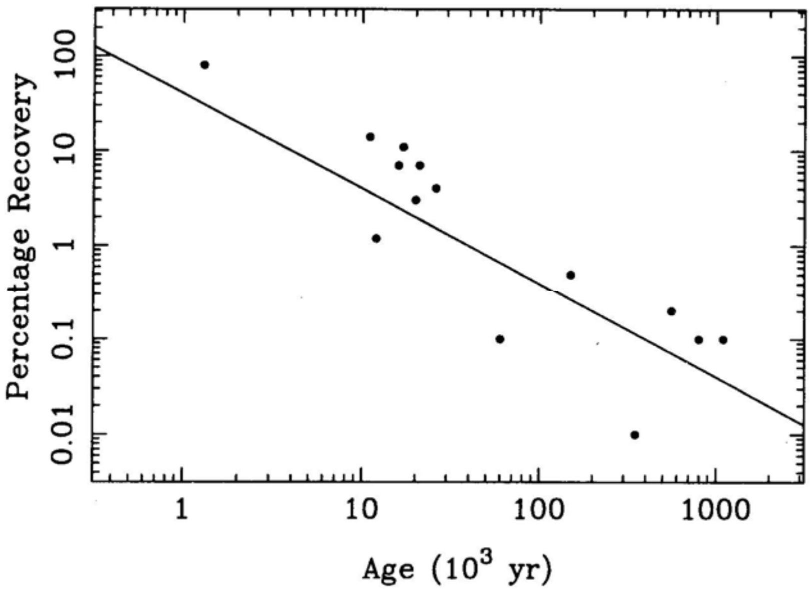

Figure 6: The percentage recovery of the initial frequency step, Q, as a function of pulsar characteristic age.

Somewhat surprising is the low level of glitch activity in the youngest pulsars such as the Crab pulsar, PSR 1509-58 and PSR 0540-69. Although these pulsars have very large slow-down rates, the angular momentum flow seems to be reasonably continuous. One possible reason for this is the youth of these pulsars and their corresponding high internal temperature, which may allow the stresses on the pinned vortices to be relieved by thermal drift of the vortices from one pinning site to another in a gradual fashion (McKenna & Lyne 1990).

6. The Recovery from Glitches

There is a wide range of recovery from glitches and again this seems to be related approximately to the age of the pulsar (figure 6). For glitches in the younger pulsars, both the frequency and frequency derivative steps of the glitch recover substantially over the following months. In those glitches which have been observed closely following the event, exponential recoveries on up to 3 timescales are often recorded (McKulloch et al. 1990). For the older pulsars, the main effect of a glitch is a large step in frequency and there is very little recovery in this over the following years. In fact the small amount of frequency recovery depends inversely upon the characteristic age, suggesting that, as discussed above, in older pulsars the vortex pinning is strong and little vortex drift occurs.

7. Conclusion

The trends described above are only recently becoming quantifiable and are still somewhat preliminary. However, as more glitches are observed in the newly discovered young pulsars, the study of neutron star interiors will become more detailed and may impose limits upon the equation of state of matter at the super nuclear densities within these objects (Pines 1991).

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