Pulsars : Problems & Progress
ASP Conference Series, Vol. 105, 1996
S. Johnston, M. A. Walker and M. Bailes, eds.

Rotational Instabilities in Pulsars

A. G. Lyne

University of Manchester, Nuffield Radio Astronomy Laboratories, Jodrell Bank, Macclesfield, Cheshire SK11 9DL, UK.

Abstract. In general, radio pulsars are superb clocks. However a few years after their discovery, it became clear that some pulsars show significant departures from their regular slow-down which make their rotation unpredictable. Two main forms of irregularities have been identified – glitches and timing noise – which are most marked in, but not confined to, young pulsars. Both are probably related to the internal structure of the neutron star and the properties of the internal neutron superfluid which prevent the smooth outward flow of angular momentum as the star slows down. In this review, the observational status and statistical aspects of the phenomena are described. We do not discuss in any detail their implications for neutron star structure. Rather, we consider them in so far as they limit studies in which the rotational stability is paramount and may limit the use of pulsars as astronomical chronometers. Glitch activity, the amount of post-glitch relaxation and the amplitude of timing noise all depend roughly linearly on the frequency derivative, implying that even the millisecond pulsars are prone to these effects.

1. Introduction

Pulsars slow down through the loss of kinetic energy in the form of low frequency electromagnetic waves or high energy particles. In a general slowdown, the braking torque is proportional to the rotation rate ν according to the spin-down equation $\dot{\nu} = -K\nu^n$, where n is the braking index, which depends upon the physics of the braking mechanism. For magnetic braking by a dipolar field or particle loss from a completely aligned rotator, n has an expected value of 3 (Pacini 1968, Goldreich & Julian 1969). The value of the magnetic field B_0 at the surface of the star of radius R can be obtained in terms of the period, $P = 1/\nu$, giving $B_0 = \sqrt{3Ic^3P\dot{P}/8\pi^2R^6} = 3.3 \times 10^{19}(P\dot{P})^{1/2}$ Gauss, where the neutron star is taken to have a radius $R = 10$ km and moment of inertia $I = 10^{45}$ gm cm^2. In the case where the initial rotation rate is much greater than the present one, the age of the pulsar can be estimated as $\tau = -\nu/(n-1)\dot{\nu} = +P/(n-1)\dot{P} = +P/2\dot{P}$, for $n = 3$. 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

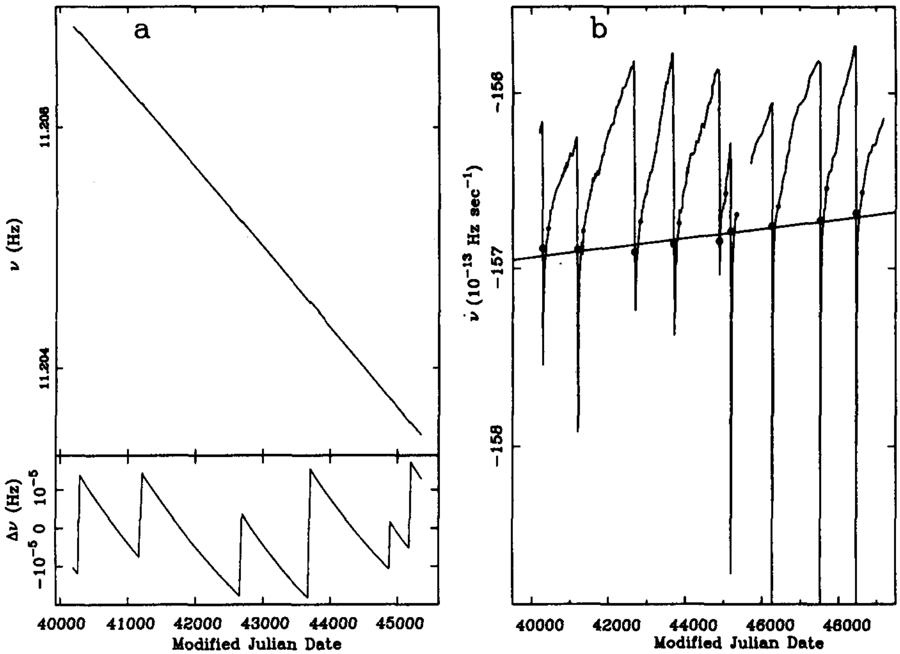

Figure 1. The slowdown of the Vela pulsar. a) The rotation frequency ν over 14 years, showing 6 glitches, before and after subtraction of a constant value of $\dot{\nu}$. b) The run of $\dot{\nu}$ over 25 years.

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, the value of n can be checked by differentiation of the spin-down equation, giving $n = \nu\ddot{\nu}/\dot{\nu}^2$. A stable value of n has been measured in this way for only 4 pulsars, the Crab (B0531+21), B0540−69, B1509−58 and Vela (B0833−45), giving values of 2.509±0.001 (Lyne et al 1988), 2.01±0.02 (Manchester & Peterson 1989), 2.838±0.001 (Kaspi et al 1994) and 1.4±0.2 (Lyne et al 1996) respectively. These values are all somewhat less than 3. While these small values may result from the non-dipolar nature of the magnetic field or the presence of particles in the magnetosphere, it seems more likely that the magnetic field or moment of inertia of the pulsar may be evolving with time (Lyne et al 1996; Camilo - this volume). For older pulsars, timing noise and the recovery from glitches usually dominate the measured value of $\ddot{\nu}$ (see section 3), and the value of n is variable and is not related to the braking mechanism.

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

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2. Glitches

Glitches are seen as sudden increases in the rotation rate, usually followed by an exponential recovery or relaxation back towards the pre-glitch frequency. For example, the slowdown of the Vela pulsar over a 14-year interval is shown in Fig. 1a. During this time, 6 glitches can barely be seen in the top diagram against the normal slowdown but, after a slope is removed, they are clear, each step corresponding to a fractional increase in rotation rate of $\Delta\nu/\nu \sim 2 \times 10^{-6}$. The relaxations can be most clearly seen in Fig. 1b which shows the variation in $\dot{\nu}$, over a 25-year period.

The Crab pulsar behaves rather differently (Lyne, Pritchard, & Smith 1993) and has shown a series of glitches of magnitude $\Delta\nu/\nu \sim 10^{-8}$ to 10^{-7}. Following an initial short-term transient, 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. This may be attributed to either a growing value of magnetic field or possibly to a decreasing moment of inertia.

There are two main aspects of glitches which may or may not be related: firstly, the cause of the glitch, which might be either a starquake or the result of catastrophic superfluid vortex 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 briefly 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 (Ruderman 1969). 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: $\Delta\epsilon = \Delta I/I = -\Delta\nu/\nu$.

While this provided a satisfactory explanation for the glitches in the Crab pulsar, it soon became clear that the magnitude and frequency of the glitches in the Vela pulsar were too great to be sustained by this mechanism (Pines, Shaham, & Ruderman 1972). More likely, it seems that in this case the glitches result from the catastrophic unpinning of superfluid neutron vortices from the nuclei of the solid crust (Baym, Pethick, & Pines 1969, Anderson & Itoh 1975).

3. The Frequency of Glitches

Glitches are rare – only about 20 out of over 700 pulsars have suffered a total of 45 glitches and 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, mainly due to a lack of known young pulsars. Such pulsars are rare since they do not stay young for very long, and also because there are strong selection effects against the discovery of young pulsars in most searches. To combat such effects, two surveys have been conducted at low latitude and high radio frequency, with 40 pulsars found at Jodrell Bank (Clifton & Lyne 1986, Clifton *et al.* 1992) and 45 at Parkes (Johnston *et al.* 1992a, Johnston *et al.* 1992b). These new samples have a mean characteristic age of less than

TABLE 1: Known Glitching pulsars

Pulsar	Age(kyr)	N_g	$\Delta\nu/\nu \times 10^6$	References
0355+54	560	2	.006, 4.4	A,U
0525+21	1480	2	.0013, .0003(?)	B,U
0531+21	1.3	4	.01, .04, .01, .08	C,D,E,F
0833−45	11	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	2800	1	.12	P
1338−62	12	3	1.5, .03, 1.0	Q,U
1508+55	2340	1	.0002(?)	R
1535−56	790	1	2.8	S,U
1641−45	350	1	.2	T
1706−44	17	1	2.1	S,U
1727−33	26	1	3.1	S,U
1736−29	650	1	.003	U
1737−30	21	6	.43, .03, .03, .60, .64, .05, .02, .01, .17	V,U
1757−24	15	1	2.0	W
1758−23	59	3	.22, .23, .35, .06	X,U
1800−21	16	1	4.1	U
1823−13	21	2	2.7, 3.0	U
1830−08	150	1	1.9	U
1859+07	4360	1	.03	U
1907+00	2950	1	.0007(?)	Y
2224+65	1120	1	1.7	Z,U

REFERENCE KEYS:
A:Lyne(1987) B:Downs(1982) C:Boynton et al(1972)
D:Lohsen(1975) E:Lyne & Pritchard(1987) F:Lyne et al(1992)
G:Radhahrisnan & Manchester(1969) H:Reichley & Downs(1971)
I:Manchester et al(1976) J:Manchester et al(1983 K:Mculloch et al(1983)
L:Cordes et al(1988) M:Mculloch et al(1987) N:Flanagan(1989)
O:Flanagan(1991) P:Newton et al(1981) Q:Kaspi et al(1992)
R:Manchester & Taylor(1974) S:Johnston et al(1992) T:Manchester et al(1978)
U:Shemar & Lyne(1996) V:McKenna & Lyne(1990) W:Lyne et al(1996)
X:Kaspi et al(1993) Y:Gullahorn et al(1976) Z:Backus et al(1982)

a million years compared with 6 million years for all pulsars found in previous surveys (Clifton *et al.* 1992). Already 20 glitches have occurred in these pulsars (Shemar & Lyne 1996).

Table 1 provides a summary of the 21 pulsars which have glitched, together with the their characteristic ages, the number of glitches, the fractional increase in rotational frequency at each glitch and the observational references. These data show that glitches have been observed in only about 3% of the known population, predominently in young pulsars. The rest of this section describes the frequency of glitches and their recovery as a function of the pulsar spin-down parameters.

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 times-

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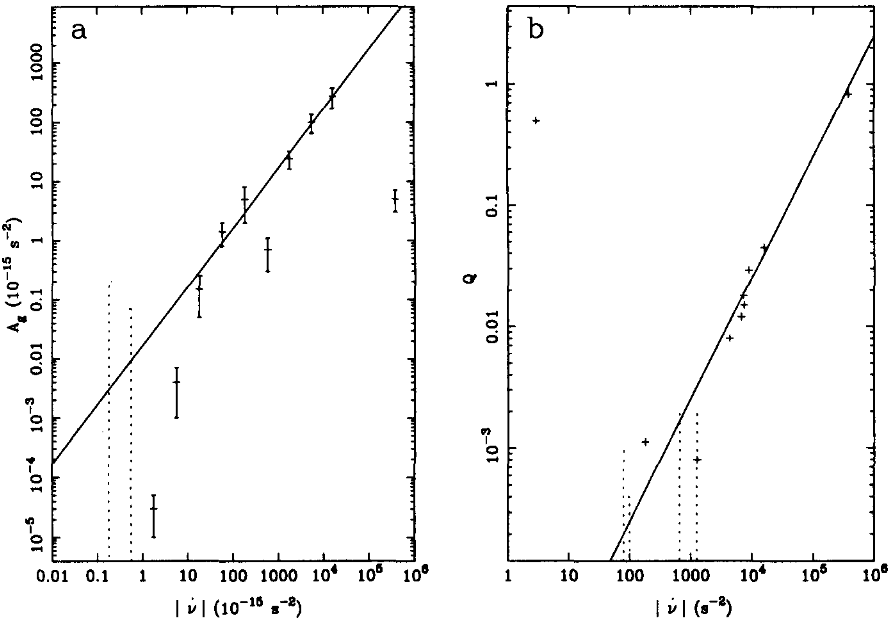

Figure 2. a) The glitch activity parameter, the rate of increase in frequency due to glitches, averaged over all observed pulsars in semi-decade ranges of frequency derivative. b) The fraction Q of the frequency step $\Delta\nu$ which is recovered in short-term, quasi-exponential post-glitch relaxation. In both diagrams, the dotted lines represent upper limits and the lines have slopes of unity.

pan and, given enough time, many more will 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 total change in frequency occurring at glitches by the total observation time for a group of pulsars gives a rate of glitch activity, A_g, which is a measure of the amount of frequency derivative $\dot{\nu}$ which is "undone" by glitches(McKenna & Lyne 1990, Lyne, Shemar, & Smith 1997). Fig. 2a shows the pulsar glitch activity as a function of $\dot{\nu}$. We clearly see that A_g is greatest for pulsars with $|\dot{\nu}| \sim 10^{-11}$ s^{-2}, corresponding to 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 little significant recovery between glitches (see next section), this implies that there is little drift occurring in these vortices.

Somewhat surprising is the low level of glitch activity in the youngest pulsars such as the Crab pulsar, PSR B1509−58 and PSR B0540−69 which are collectively responsible for the most extreme right-hand point in Fig. 2a. 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 to be relieved by thermal drift of the vortices from one pinning site to another in a gradual fashion (McKenna & Lyne 1990).

4. 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. For glitches in the younger pulsars, both the frequency and frequency derivative steps of the glitch recover substantially over the following months, and there is often a persistent and non-decaying permanent offset in $\ddot{\nu}$, as seen between the Vela glitches (Fig. 1b). In those glitches which have been observed closely following the event, exponential recoveries on up to 3 timescales are often recorded (McCulloch *et al.* 1990, Alpar *et al.* 1993). 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 (Shemar & Lyne 1996). 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.

The short-term quasi-exponential behaviour following each glitch can be explained by the presence of a fluid component in the interior of the neutron star (Baym *et al.* 1969) which is loosely coupled to the rigid crust whose rotation we observe through the emission beam which is tied to it. 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.

5. 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 & Helfand 1980). Some examples of timing noise in a number of pulsars are shown in Fig. 3a 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. On the whole, timing noise is very red and the timing residuals relative to a simple slow-down model are usually dominated by a cubic term which corresponds to a period or frequency second derivative. Fig. 3b shows the magnitude of $|\ddot{P}|$ plotted against $\dot{P}$, for 218 pulsars (Martin & Lyne 1996). There are a few dozen additional upper limits, not included in this diagram, which lie mostly above the diagonal line, and which are for pulsars wth short data timespans. This clearly confirms that young pulsars, with large slow-down rates, have much timing noise (see also Arzoumanian et al 1994). While there are roughly equal numbers of positive and negative values of $\ddot{P}$ in this diagram, it is noteworthy that of the 30 pulsars

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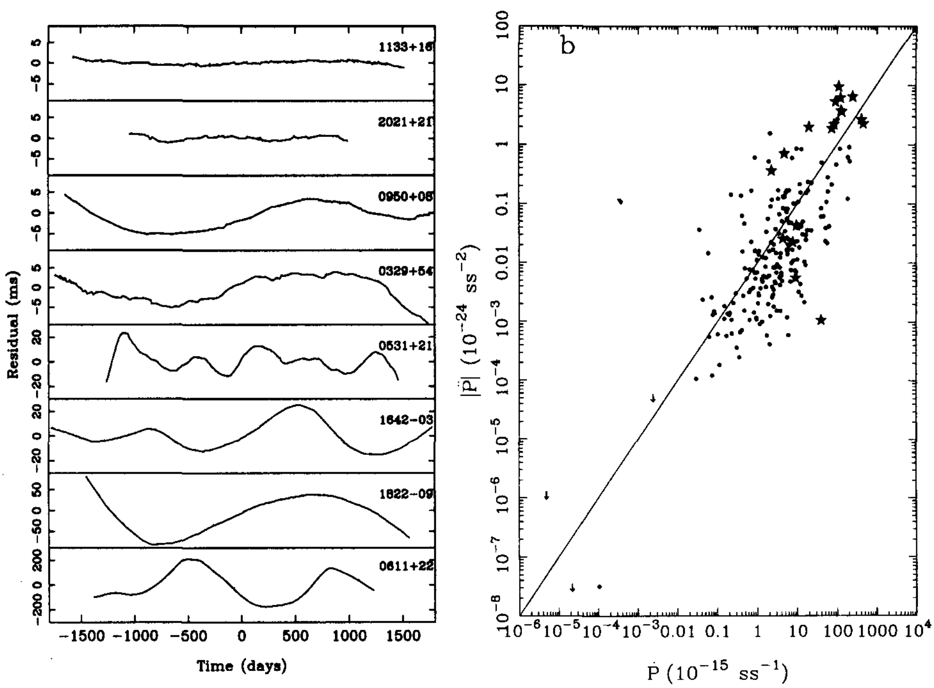

Figure 3. a) Examples of timing noise in 8 pulsars over about a 10 year period, showing increasing amounts of activity from the top to bottom. b) The magnitude of $\ddot{P}$, a measure of the amount of timing noise, plotted against $\dot{P}$, showing high level of timing noise in young, rapidly braking pulsars. Pulsars which glitch are shown by a star. The line has a slope of unity.

with $\dot{P} \geq 3 \times 10^{-14}$, the 11 that have glitched all have negative values of $\ddot{P}$, as expected from the exponential form of the recoveries. Of the remaining 19, 14 have positive values, suggesting that the recovery from (unseen) glitches mostly dominates any timing noise present. While most millisecond pulsars, having very small period derivatives, are found to be very stable, note that PSR B1937+21, with a relatively high $\dot{P}$ for a millisecond pulsar, has shown significant timing noise (Kaspi, Taylor, & Ryba 1994).

6. Conclusion

Glitches and timing noise are a widespread phenomenon in the pulsar population and are likely to be mostly due to an irregular flow of angular momentum from a neutron superfluid component in the interior of the stars. The trends described above are only recently becoming quantifiable and are still somewhat preliminary, but show clearly that over the bulk of the pulsar population, the amount of glitch activity, the amount of subsequent recovery and the amount of timing noise all depend approximately linearly on the magnitude of $\dot{\nu}$. However, as more glitches are observed in the newly discovered young pulsars, and the data spans for the study of timing noise increase, 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).

While glitches have affected only about 3% of the observed population since their discovery, it seems very likely that most pulsars will experience them in due course, the interval between glitches being much greater than the observation time hitherto. As for timing noise, the evidence of Fig. 3b suggests that most pulsars, even the millisecond pulsars, will display its effects in due course. For use as clocks, even those with the smallest derivatives are likely to be limited in their precision.

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