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Glitches as Probes of Neutron Star Interiors

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Glitches as probes of neutron star interiors

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In several young pulsars, the steady slow-down in rotation rate as they lose kinetic energy is occasionally interrupted by a sudden small increase in rotation rate, followed by a recovery which is often closely exponential in its form. This recovery provides strong evidence for the existence of a fluid component inside the neutron star. This fluid can be identified with superfluid neutrons in the inner part of the stellar crust. Detailed studies of the phenomenon can give information on the amount of fluid present, on the physics of the outward flow of angular momentum as the pulsar slows down, what causes the glitches and why some pulsars show much more glitch activity than others.

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1. Introduction

The narrow pulses from pulsars allow us to monitor their rotation with very high precision and show us that they have a remarkable uniformity of rotation rate. This is not, however, a surprising observation since uniform rotation is exactly what is expected of an isolated spinning body with a large, stable moment of inertia. There is of course the steady increase in period due to the slow-down torque arising from the loss of energy due to magnetic dipole radiation and some particles. Because this slow-down is predictable, most pulsars make excellent clocks and several in binary systems have been used to study the binary orbits and the effects of general relativity with remarkable precision (Taylor, Damour, this symposium). They have even been used to detect the presence of such small orbiting bodies as planets (Wolszczan & Frail 1992). Nevertheless, some very interesting irregularities in rotation have been observed which probably have their origin within the neutron star and which give a remarkable insight into its internal structure.

Two categories of timing irregularities exist: fairly continuous, erratic variations, known as timing noise, and more spectacular step changes in rotation rate, known as glitches.

2. Timing noise

Timing noise, such as that seen in figures 1 and 2, is predominantly found in young pulsars, i.e. those which have the largest electromagnetic braking torque because of their large magnetic fields and high rotation rates. This was clearly demonstrated by Cordes & Downs (1985) who showed how the amount of timing noise is greatest for those pulsars having the largest period derivative (figure 3). While young objects like the Crab pulsar (figure 2) are very unpredictable, millisecond pulsars, having small period derivative, show no detectable timing noise and, with their narrow pulses, compete with the best banks of terrestrial atomic clocks. This variation in behaviour

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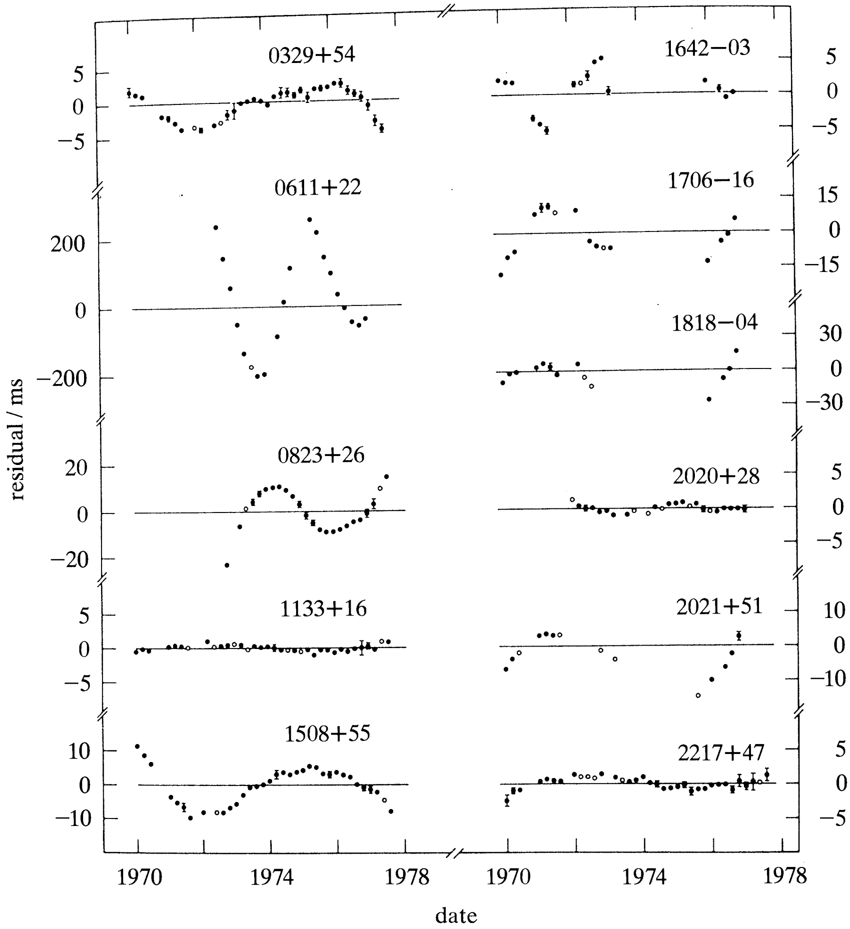

Figure 1. Examples of timing noise in 11 pulsars (Helfand *et al.* 1980).

Figure 2

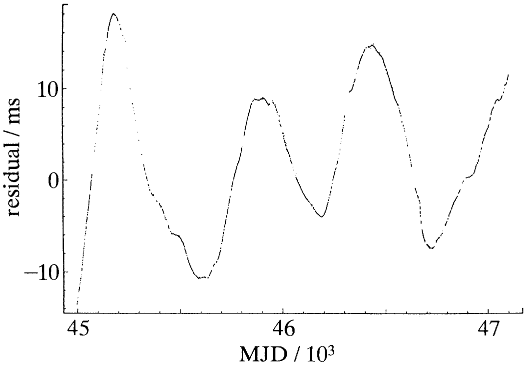

Figure 3

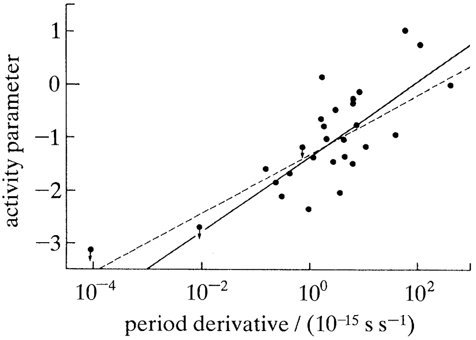

Figure 2. Timing noise in the Crab pulsar (Lyne *et al.* 1988).

Figure 3. The relationship between timing noise and period derivative (Cordes & Downs 1985). The activity parameter is a logarithmic measure (base 10) of the rms timing noise relative to that observed in the Crab pulsar.

Figure 4

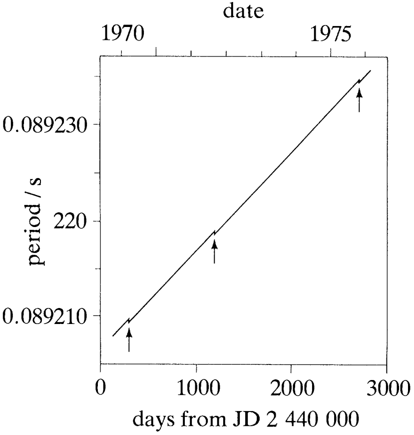

Figure 5

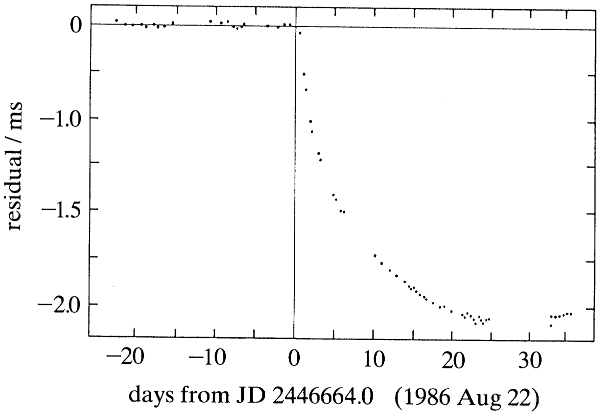

Figure 4. Variation in the period of the Vela pulsar over an eight-year period, showing three glitches superimposed upon the regular increase in period.

Figure 5. The exponential recovery following the 1986 glitch in the Crab pulsar (Lyne & Pritchard 1987).

provides some evidence that there is a fluid component within the neutron star: the timing noise possibly results from an irregular flow of angular momentum from the fluid interior to the crust as the star spins down.

3. The glitch phenomenon

Glitches are rare. In the first 20 years of pulsar astronomy, glitches were only observed in eight pulsars and about half of the 22 glitches were observed in the Crab and Vela pulsars, showing that, like timing noise, it is the youngest pulsars which are most likely to display glitch activity.

A glitch is usually characterised by a sudden increase in rotation rate, followed by an exponential decay back towards the pre-glitch rate. Figure 4 shows three glitches in the Vela pulsar. Here, the glitches are seen as steps superimposed on the steadily increasing period. Figure 5 shows the detail immediately following one of the glitches in the Crab pulsar and reveals a typical exponential decrease in rotation rate with a characteristic timescale which lies between days in the younger objects and many years in older ones. This recovery can be understood in purely classical terms. In this two-component model (Baym *et al.* 1969), the neutron star consists of a rigid crust and an interior viscous fluid. During steady slow-down in which the braking torque is applied to the crust via the magnetic field, there is a lag in rotation rate so that the fluid rate is always somewhat greater than that of the crust. If there is a sudden change in the rotation rate of the crust, for whatever reason, there will follow an exponential recovery as the steady-state differential rotation rate is re-established. The dynamics are much like those of an uncooked egg, the interior constitution of which can be determined in simple experiments by observing the effects resulting from sudden perturbations applied to its steady rotation.

Table 1 lists the main glitches which have been reported to date and gives the magnitude of the events in both rotation rate and its derivative. The largest glitches have spin-ups amounting to several parts in a million, the smallest about one part in 10^9. The fractional increases in the derivative are often much greater, but usually

Table 1. *Known glitches*

pulsar	date	MJD	$\Delta\Omega/\Omega$ (10^{-6})	$\Delta\dot{\Omega}/\dot{\Omega}$ (10^{-3})	τ_{rec} (days)	reference
0355+54	1985 Jan	46079	0.006	1.8	—	Lyne (1987)
	1986 Feb	46468	4.4	100	44	Lyne (1987)
0525+21	1974 Jan	42064	0.0013	5	143	Downs (1982)
	1978 Nov	43834	0.0003	—	—	Downs (1982)
0531+21	1969 Sep	40494	0.01	—	4	Boynton *et al.* (1972)
	1975 Feb	42448	0.04	1	10	Lohsen (1975)
	1986 Aug	46664	0.01	—	6	Lyne & Pritchard (1987)
	1989 Aug	47768	0.08	4	17	Lyne *et al.* (1992)
0833−45	1969 Feb	40280	2.3	8	400	Radhakrishnan & Manchester (1969)
	1971 Aug	41192	2.0	10	—	Reichley & Downs (1971)
	1975 Sep	42683	2.0	7.5	500	Manchester *et al.* (1976)
	1978 July	43692	3.1		400	Manchester *et al.* (1983)
	1981 Oct	44888	1.1	7.2	233	McCulloch *et al.* (1983)
	1982 Aug	45192	2.0	1.0	60	Cordes *et al.* (1988)
	1985 July	46285	1.3	6.2	397	McCulloch *et al.* (1987)
	1988 Dec	47520	1.8	80	—	Flanagan (1989)
	1991 Jul	48448	2.7	—	—	Flanagan (1991)
1325−43	1978 Mar	43590	0.12	—	—	Newton *et al.* (1981)
1508+55	1973 Feb	41740	0.0002	—	—	Manchester & Taylor (1974)
1641−45	1977 Jul	43327	0.2	—	—	Manchester *et al.* (1978)
1736−29	1987 Jun	46955	0.003	0.3	—	Lyne *et al.* (1992)
1737−30	1987 Jul	47003	0.42	2.8	—	McKenna & Lyne (1990)
	1988 Apr	47281	0.03	1.7	—	McKenna & Lyne (1990)
	1988 Jun	47332	0.007	—	—	McKenna & Lyne (1990)
	1988 Nov	47458	0.03	—	—	McKenna & Lyne (1990)
	1989 May	47670	0.60	2.0	—	McKenna & Lyne (1990)
	1990 Oct	48193	0.70	1.3	—	Lyne *et al.* (1992)
1800−21	1990 Dec	48254	4.1	8.2	—	Lyne *et al.* (1992)
1823−13	1986 Mar	46500	2.7	—	560	Lyne *et al.* (1992)
1830−08	1990 May	48031	1.9	1.1	—	Lyne *et al.* (1992)
1859+07	1987 Mar	46861	0.03	40	1400	Lyne *et al.* (1992)
1907+00	1974 Apr	42162	0.0007	—	—	Gullahorn *et al.* (1976)
2224+65	1976 Oct	43070	1.7	—	—	Backus *et al.* (1982)

they decay back to very close to the original pre-glitch value, although there are exceptions to this, as will be discussed later. Because of the sparseness of observations, for many glitches, the first post-glitch observations were made long after the glitch event itself, so that the time of the glitch and details of any recovery were not recorded. Only with the more recent frequent monitoring of a large number of pulsars has this information been available.

There are two main aspects of glitches which are to some extent separable: the cause of the initial spin-up and the post-glitch relaxation and I discuss briefly each of these in turn. The glitch event itself allows a sort of 'rotation seismology' so that we can study the amount of fluid and the viscous coupling between the fluid and the crust.

4. The origin of glitches

The first proposed cause of the spin-up seen in glitches was starquakes, caused by discontinuous changes in the ellipticity or oblateness of the neutron star crust (Baym *et al.* 1969). As the star slows down, the equilibrium oblateness decreases. The crust is believed to be sufficiently rigid that it cannot follow the changes continuously, so that stresses build up until a critical value is exceeded and the crust cracks and relaxes to the equilibrium, more spherical shape. Conservation of angular momentum demands that the resulting decrease in moment of inertia I is accompanied by an increase in rotation rate Ω. The oblateness ϵ is defined in terms of the spherical moment of inertia I_0 by $I = I_0(1+\epsilon)$ and the change in oblateness is related to changes in I and Ω by $\Delta\epsilon = \Delta I/I = -\Delta\Omega/\Omega$.

For the glitches in the Crab pulsar, this provided a satisfactory explanation. The present day oblateness is about 10^{-3}, with observed changes in ϵ at the four glitches amounting to a total of about 10^{-7} in 20 years, so that there is plenty of 'available' oblateness to sustain such a glitch rate over the 1000-year lifetime of the pulsar. On the other hand, the Vela pulsar has much larger glitches ($\Delta\Omega/\Omega = \Delta\epsilon \approx 2 \times 10^{-6}$) and shorter intervals between glitches (3 years), so that the present day oblateness of 10^{-4} would disappear in only about 100 years, or only 1 % of the age of the pulsar. Clearly, starquakes cannot provide the origin of the glitches in the Vela pulsar and we must look further afield for an explanation.

The most likely origin lies in the expected superfluid nature of part of the neutron star interior (Anderson & Itoh 1975; Ruderman 1976). It is believed that the inner region of the crustal lattice is permeated by a 'sea' of superfluid neutrons. The angular momentum is carried in the form of microscopic, quantized vortices, rather than in bulk motion of the material, and the rotation rate is determined by the density of the vortices. As the rotation rate slows, the vortex density must decrease and this would occur naturally through the outward drift of vortices, resulting in the outward flow of angular momentum. However, it is possible for the vortices to become pinned to nuclei in the crustal lattice, preventing this outward drift. As the pulsar slows, the vortex density imbalance increases, causing stresses (the Magnus force) which eventually give rise to a catastrophic unpinning of vortices which suddenly move outward, imparting their angular momentum to the crust, causing the observed rapid spin-up.

5. The post-glitch recovery

The post-glitch recovery described by the two-component model has to be considered in the light of the superfluid nature of the liquid. The equilibrium slow-down situation probably does not involve a complete pinning of the vortex lines to the crustal lattice, but a steady outward creep of vortices, in a similar fashion to the movement of dislocations in crystal lattices. The creep rate depends upon the energetics of the pinning, upon the temperature and upon the differential rotation rate between the creep region and the crust. Immediately after a glitch, the vortex density is probably close to that required by the rotation rate of the crust, pinning is complete and the angular momentum of the superfluid is therefore fixed and the superfluid is therefore effectively decoupled from the crust, so reducing the effective moment of inertia and giving rise to an increase in slowdown rate. As the crust slows

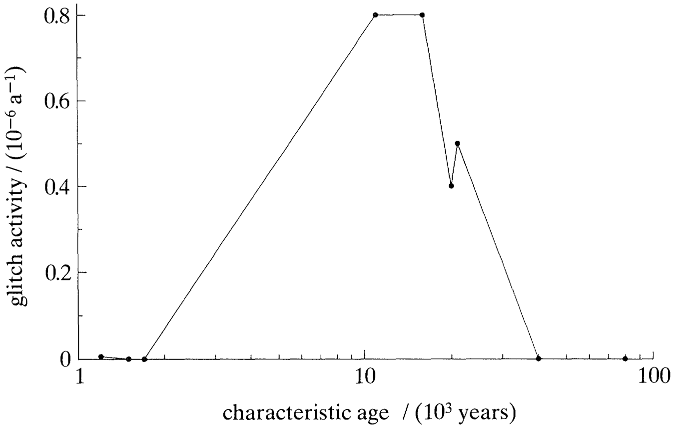

Figure 6. The glitch activity parameter as a function of age for the 10 youngest pulsars.

down, the differential rotation increases and creep is reestablished, resulting in a decrease in slowdown rate and the exponential recovery.

6. The frequency of glitches

Until the last few years, the study of glitches has been limited by the small number of observed events. Excluding the Vela pulsar, before 1987, only about 10 glitches were observed over a 20-year period. This was basically due to the lack of young pulsars. Not only do they not stay young for long, but, because of their birth at low galactic z-distance, there are severe selection effects arising from the high sky background temperature and the pulse smearing due to interstellar dispersion and scattering at low radio-frequency. Their short period makes them particularly susceptible to these effects. Recent high-frequency surveys of the galactic plane have provided about 100 new pulsars, having a median characteristic age of less than 1 Ma, compared with 6 Ma for pulsars discovered in previous surveys. As a result, the rate of glitching has increased dramatically. For instance in the sample of 40 new pulsars discovered in the Jodrell Bank survey (Clifton *et al.* 1992), a total of 11 glitches have already been observed in six pulsars during a five-year period. One of these is PSR 1737-30 which has now been observed to glitch six times in as many years (McKenna & Lyne 1990). Most of its glitches are somewhat smaller in magnitude than the 'giant' Vela glitches.

With this substantial improvement in the statistics of glitches, it is now possible to see more detailed trends within the population. One can assign a 'glitch activity' parameter to quantify how much a pulsar glitches. This is defined (McKenna & Lyne 1990) as the fractional decrease in rotation period due to glitches per year and amounts to about 10^{-6} a^{-1} for Vela and the most active pulsars and zero for the vast majority of pulsars. Figure 6 shows the glitch activity parameter plotted against age and period derivative for the 10 pulsars with the smallest ages.

While the older pulsars, not surprisingly, show relatively little activity, the youngest pulsars like the Crab, PSR 0540-69 and PSR 1509-58 also show very little. It is the youthful pulsars with ages of (10–20) × 10^3 years which seem to be most prone to glitching. The most natural explanation can be understood in terms of vortex creep: the high temperature of the youngest pulsars permits the vortices to

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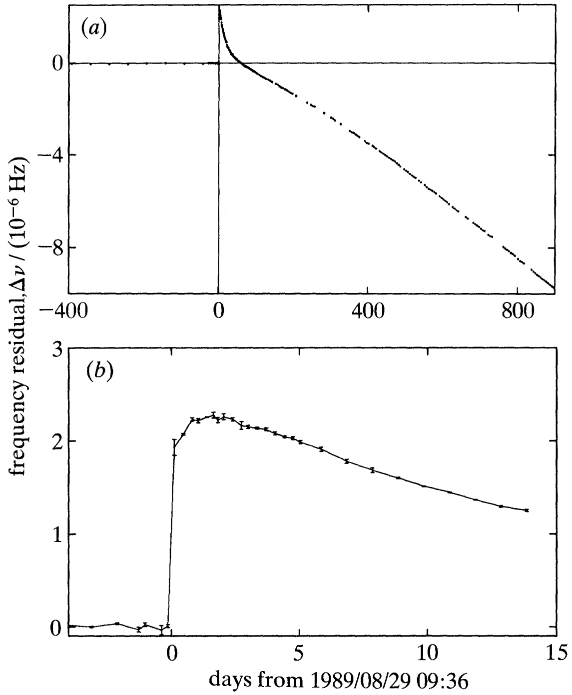

Figure 7. (*a*) The rotation rate of the Crab pulsar spanning the large glitch of 1989, relative to a simple slow-down model fitted to one year of data before the glitch. Note the permanent change in slope, or period derivative, following the glitch. (*b*) Detail of the glitch event itself. Note the spin-up on a timescale of a day, superimposed on the 14-day initial recovery.

creep at a relatively high rate under the Magnus force (Ruderman 1976). This prevents the build-up of the large stresses which give rise to the giant glitches. As a pulsar cools down, creep rates cannot relieve the stresses, giving rise to the large Vela-type glitches. In the older pulsars, because of the much slower rate of spin-down, it takes much longer for the stresses to build up to a critical level, and hence we observe only very occasional large glitches, as seen in PSR 0355 + 54 for instance which, although nearly 1 Ma old, has suffered the largest known glitch.

7. The Crab pulsar

As seen in table 1, the Crab pulsar has undergone four significant glitches in the course of the past 22 years, the largest being about two orders of magnitude smaller than the Vela glitches, the smallest more than an order of magnitude smaller still. The last glitch occurred in 1989 while observation was in progress (figure 7), and the resulting recovery was studied in unprecedented detail (Lyne *et al.* 1992). The most notable feature of the glitch was a permanent change in $\dot{\Omega}$, similar to that following the glitch of 1975 (Demiański & Prószyński 1983), amounting in both cases to about 1 part in 4000. These changes can be explained by changes in either the braking torque, presumably due to an alteration in the magnetic field configuration, or in the moment of inertia. The required changes in oblateness of the neutron star are too large to be sustained by the present day oblateness of 10^{-3}. It seems more likely that, at the glitch, many of the superfluid vortices become permanently pinned to the crustal lattice, so that vortex drift can no longer occur, thus reducing the outward flow of angular momentum to the crust from which they are effectively decoupled, reducing the effective moment of inertia.

For the first time in any glitch, the spin-up itself was resolved by the observations of the 1989 glitch, showing that a significant fraction of the increase in rotation rate built up on a timescale of somewhat less than a day (figure 7*d*). This shows evidence for a relatively loose coupling between the superfluid vortices and the crust.

8. Conclusion

I have given a brief qualitative description of the glitch phenomenon and what can be learned about the internal structure of a neutron star from observations of glitches. Thorough reviews of the theoretical understanding of crustal neutron superfluid and the interpretation of pulsar glitches is given by Alpar (1991) and Pines (1991). Clearly we are studying matter under uniquely extreme conditions of density and temperature in the objects. With the recent observations which have caught pulsars in the act of glitching and with the much improved statistics coming from the newly discovered youthful pulsars, this insight is likely to continue to improve.

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