Thursday 7 September 2017

https://doi.org/10.1017/S1743921317009607 Published online by Cambridge University Press

Pulsar Astrophysics the Next Fifty Years
Proceedings IAU Symposium No. 337, 2017
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doi:10.1017/S1743921317009607

Pulsar Glitches

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Abstract. The first known pulsar glitch was discovered in the Vela pulsar at both Parkes and Goldstone in March 1969. Since then the number of known glitches has grown enormously, with more than 520 glitches now known in more than 180 pulsars. Details of glitch parameters and post-glitch recoveries are described and some implications for the physics of neutron stars are discussed.

Keywords. pulsars: general, stars: neutron

1. The discovery of glitches and the starquake model

In late 1968 and early 1969, I was at Parkes and, among other things, helping Radhakrishnan with the observations of the Vela pulsar that ultimately led to the "rotating vector model" for pulsar polarisation (Radhakrishnan & Cooke 1969). In mid-March, 1969, we set up the signal-averager to fold the Vela pulsar data at the predicted topocentric period and noticed that the pulse was slowly drifting backwards on the screen, indicating that the folding period was not quite correct. After exhaustively checking the equipment and observing other pulsars, we concluded that everything was working correctly and, consequently, that the pulsar period P was not as predicted. The implied period decrease ΔP was 196 ns, corresponding to a relative change $\Delta\nu/\nu = -\Delta P/P \sim 2.2 \times 10^{-6}$, where the pulsar rotation frequency $\nu = 1/P$. We contacted Paul Reichley and George Downs, whom we knew were timing the Vela pulsar using the Goldstone antenna of the Jet Propulsion Laboratory (JPL) in California, and confirmed that they also had seen the glitch (Figure 1).† Back-to-back papers reporting the discovery were published in the April 19 Nature (Radhakrishnan & Manchester 1969; Reichley & Downs 1969). The JPL observations limited the glitch epoch to between February 24 and March 3, and also revealed a change in the slow-down rate $\Delta\dot{\nu}/\dot{\nu} = \Delta\dot{P}/\dot{P} \sim 10^{-2}$. Both groups suggested a sudden decrease in the neutron-star moment of inertia, which could account for the changes in both ν and $\dot{\nu}$. The required effective change in the radius of the neutron star was about 1 cm.

Within a few months, Baym *et al.* (1969) had refined this "starquake" model, suggesting that the change in moment of inertia was due to relaxation of the neutron-star crust to the current equilibrium oblateness, which of course changes because of the gradual slow-down in rotation. They also predicted that the observed increase in $|\dot{\nu}|$ would decay on a timescale of years because of the weak frictional coupling of a more rapidly rotating superfluid interior, earlier predicted to exist by Russian theorists (Migdal 1960; Ginzburg & Kirzhnits 1965), and the neutron-star crust to which the emission beams are locked.

A prediction of this model was that it would be at least 300 years before the stresses due to the oblateness differential built up sufficiently to cause another starquake. The JPL group continued their regular monitoring and, just 2.5 years after the first glitch,

† The term "glitch" was not initally used to describe these events. The first published use of the term appears to be by Rees *et al.* (1971).

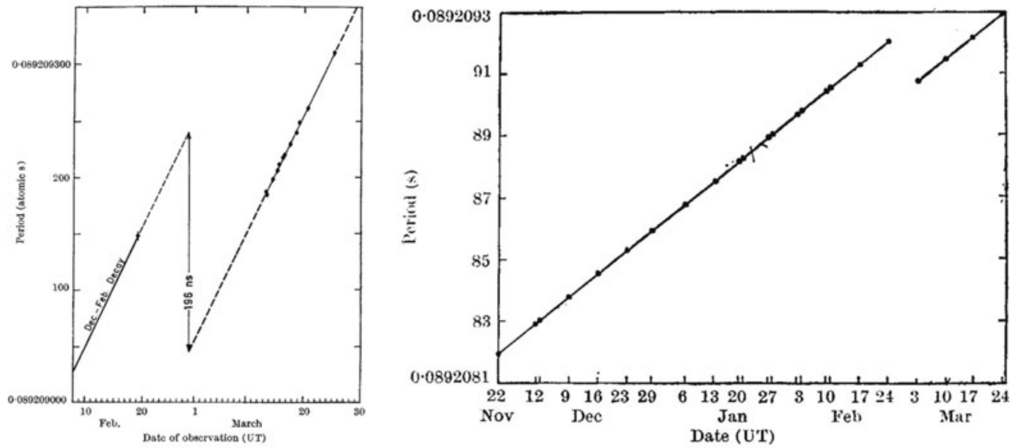

Figure 1. Changes in the Vela pulsar period in late 1968 and early 1969 showing the first detections of a pulsar glitch. The left panel shows the Parkes observations (Radhakrishnan & Manchester 1969) and the right panel shows the JPL Goldstone observations (Reichley & Downs 1969).

announced the detection of a second large glitch with $\Delta\nu/\nu \sim 2.0 \times 10^{-6}$ (Reichley & Downs 1971). This of course ruled out relaxation of crustal oblateness as a mechanism for the glitch trigger. Alternative models quickly followed, with "corequakes" suggested by Pines *et al.* (1972) and the sudden unpinning of interior superfluid vortices, with a consequent transfer of angular momentum to the crust, first suggested by Anderson & Itoh (1975). As will be discussed in Section 3 below, the latter idea forms the basis for most subsequent interpretations of the glitch phenomenon.

Both Radhakrishnan & Manchester (1969) and Reichley & Downs (1969) pointed out in their concluding remarks that glitches could be expected in the Crab pulsar period. Sure enough, about six months later, Boynton *et al.* (1969) and Richards *et al.* (1969) announced the discovery of a glitch in the Crab pulsar period. The relative glitch size, $\Delta\nu/\nu \sim 7 \times 10^{-9}$, was about 300 times smaller than for the Vela glitches suggesting a different mechanism. Observations over the next few years at Jodrell Bank and optical observatories (e.g., Lohsen 1981; Lyne *et al.* 1993) revealed several glitches, including larger ones in 1975 and 1989. These observations also showed that the post-glitch behaviour in the Crab pulsar was quite different to that for Vela, being dominated by a persistent increase in the slow-down rate $|\dot{\nu}|$.

2. The glitch population

Tables of observed glitches are maintained by Jodrell Bank Observatory (JBO)* and as part of the ATNF Pulsar Catalogue‡. While these two tables broadly contain the same information, there is some information in one, but not the other. In particular, the JBO table contains details of about 80 otherwise unpublished glitches. Collating the data from the two tables gives a total of 520 known glitches in 180 different pulsars. Figure 2 shows the distribution of glitching pulsars on the $P - \dot{P}$ diagram. This figure shows that glitches in young pulsars, including magnetars, are generally large with $\Delta\nu/\nu \sim 10^{-6}$. However, the youngest pulsars, e.g., the Crab pulsar, PSR J0537−6910 and PSR J0540−6919,

*http://www.jb.man.ac.uk/pulsar/glitches/gTable.html
‡http://www.atnf.csiro.au/research/pulsar/psrcat/glitchTbl.html

https://doi.org/10.1017/S1743921317009607 Published online by Cambridge University Press

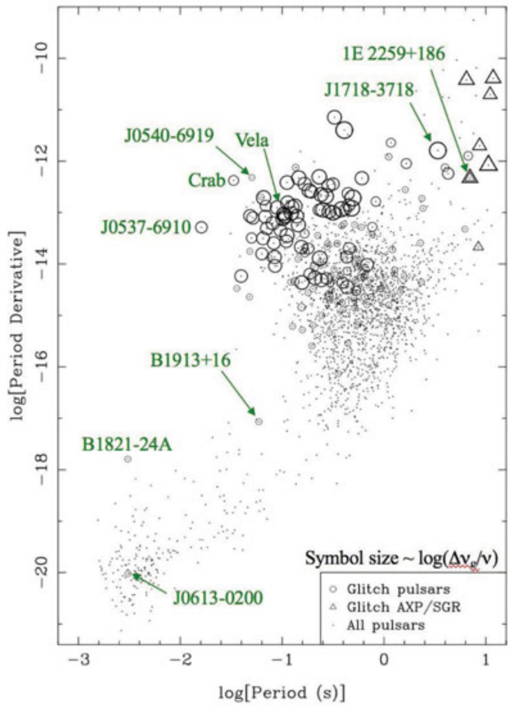

Figure 2. Distribution of the 180 glitching pulsars on the P – $\dot{P}$ diagram. The symbol size is proportional to the logarithm of the largest fractional glitch size $\Delta\nu/\nu$ observed for each pulsar. Glitching pulsars and AXPs/SGRs (magnetars) and non-glitching pulsars are marked with different symbols as labelled.

tend to have more frequent and smaller glitches with $\Delta\nu/\nu \sim 10^{-7}$ or 10^{-8}. The most frequently glitching pulsar is PSR J0537−6910, located in the Large Magellanic Cloud which, on average, glitches about three times per year (Marshall *et al.* 2004). Only two millisecond pulsars, PSRs B1821−24A and J0613−0200, have been observed to glitch and each of these have had just one very small glitch with $\Delta\nu/\nu \sim 10^{-11}$ (Cognard & Backer 2004; McKee *et al.* 2016). It is interesting that the Hulse – Taylor binary pulsar, PSR B1913+16, also had a small glitch in 2003 of about the same magnitude (Weisberg *et al.* 2010).

Large glitches are relatively common in magnetars. While their magnitudes are similar to those in other young pulsars, they have a number of distinguishing features. For example, they are sometimes accompanied by radiative changes, either X-ray bursts or associated changes in the pulse profile (see, e.g., Dib & Kaspi 2014). Such X-ray bursts and profile changes are very common in magnetars and are generally accompanied by timing irregularities, but only a small proportion of them are associated with glitches. Since magnetar glitch properties are broadly similar to those in other young pulsars, it seems plausible that the glitch mechanism is the same or similar, i.e., related to changes in the superfluid interior of the star. In this case, the radiative associations suggest some connection between the stellar interior and the magnetosphere of the star.

However, Archibald *et al.* (2013) reported the detection of an “anti-glitch”, i.e., an abrupt spin-down, in the period of the magnetar 1E 2259+586 (PSR J2301+5852) of relative magnitude about 3.1×10^{-7}. Several large glitches, one with $\Delta\nu/\nu \sim 1.6 \times 10^{-5}$, have also been seen in this pulsar (Dib *et al.* 2009). The anti-glitch was associated with

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a short-duration hard X-ray burst and an increase in the soft X-ray flux which decayed over 100 days or so. These properties suggest that the anti-glitch was magnetospheric in origin.

Although glitches in normal young pulsars are generally not associated with radiative changes, glitches observed in the very young pulsar PSR J1119−6127 are exceptions. Weltevrede *et al.* (2011) observed that, for about three months after a large glitch ($\Delta\nu/\nu \sim 1.6 \times 10^{-6}$), intermittent strong pulses and a second profile component were observed. An even larger subsequent glitch ($\Delta\nu/\nu \sim 5.7 \times 10^{-5}$) was observed by Archibald *et al.* (2016) to be accompanied by X-ray bursts and X-ray pulsations. It seems as though this pulsar is half-way to being a magnetar.

3. Glitch properties and their interpretation

Glitch activity in pulsars can be quantified by the relation

$$A_g = \frac{1}{T}\frac{\Sigma(\Delta\nu_g)}{\nu} \tag{3.1}$$

where T is the total data span for glitch monitoring and $\Sigma(\Delta\nu_g)$ is the sum of all observed glitch frequency jumps. These jumps reverse some fraction of the regular slow-down due to electromagnetic and wind torques. Many studies (see, e.g., Espinoza *et al.* 2011; Yu *et al.* 2013) have shown that for pulsars with characteristic ages $\tau_c = P/(2\dot{P})$ between about 10^4 and 10^5 years, about 1% of the slowdown is reversed by glitches. For the Crab and other very young pulsars, glitches have about two orders of magnitude less effect on the slow-down. In the two-component superfluid models (e.g., Alpar *et al.* 1981), the glitch results from the sudden unpinning and then repinning of vortex lines transferring angular momentum from the more rapidly spinning interior superfluid to the crust. The moment of intertia of the pinning/unpinning superfluid I_s is related to the glitch activity by the "coupling parameter"

$$G = 2\tau_c A_g = \frac{\dot{\nu}_g}{|\dot{\nu}|} \sim \frac{I_s}{I} \tag{3.2}$$

where I is the total moment of inertia of the neutron star.

Many different types of post-glitch behaviour are observed. In some pulsars, most or all of the initial frequency jump decays, whereas in other cases the glitch is like a step jump in frequency with little or no change in $\dot{\nu}$ (e.g., Espinoza *et al.* 2011; Yu *et al.* 2013). Figure 3 shows the observed long-term variations in $\dot{\nu}$ for the Crab and a number of other young pulsars. Glitches are marked by a sudden decrease in $\dot{\nu}$. The fractional increase in slow-down rate $|\dot{\nu}|$ is typically about 1% although for some pulsars the increase is much smaller, even not detectable. For most pulsars, much of this initial increase decays exponentially on a timescale of 10 − 100 days. For the Crab pulsar, about 90% of the increase quickly decays, but the remaining 10% persists as a long-term increase in the slow-down rate. For large glitches in other pulsars, typically about half of the initial increase decays exponentially. Following that, there is a basically linear increase in $\dot{\nu}$ until the next glitch.

The simple two-component model of Baym *et al.* (1969) cannot account for these different post-glitch behaviours. In a series of papers, Ali Alpar and his colleagues have developed this model with different regions within the neutron star having different properties to account for the different post-glitch behaviours (e.g., Alpar *et al.* 1981, 1993, 1996). For example, in regions with weakly pinned vortices, vortex creep can occur, whereas in strongly pinned regions, there is no creep following the repinning of vortices

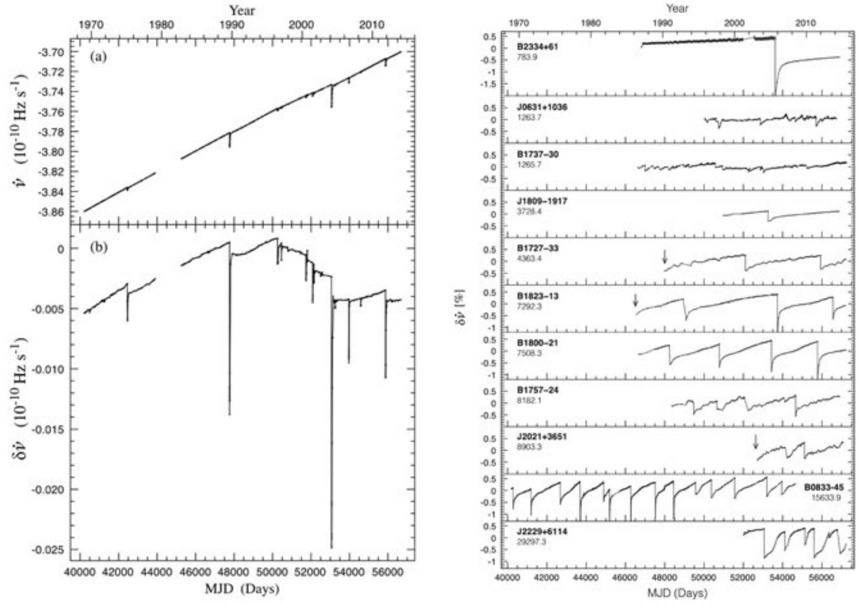

Figure 3. Variations of spin-down rate $\dot{\nu}$ for the Crab pulsar (left, Lyne *et al.* 2015) and a sample of young pulsars (right, Espinoza *et al.* 2017)). For the Crab pulsar, the lower subpanel shows the $\dot{\nu}$ variations after subtraction of the linear trend evident in the upper subpanel.

after a glitch. Weakly pinned regions have a linear dynamical response and can give the observed exponential recoveries in $\dot{\nu}$. More strongly pinned regions have a non-linear dynamical response that can result in a long-term linear increase in $\dot{\nu}$ as observed for Vela and other young pulsars.

While the Alpar *et al.* models have been broadly successful in accounting for the properties of pulsar glitches, they depend on many assumptions about poorly known properties of neutron star interiors. Various authors have proposed alternative views about some of these assumptions. For example, Chamel (2012) has argued that "entrainment" of the neutron superfluid by the crystalline structure of the crust greatly reduces its mobility. Consequently, unpinning of the crustal superfluid is insufficient to account for large glitches, and other mechanisms, e.g., unpinning of core superfluid neutrons, are required. However, in a recent paper, Watanabe & Pethick (2017) argue that entrainment is not a significant issue and there is no need to invoke core superfluid. In another recent paper, Link (2014) has argued that the "linear-response" regime invoked by Alpar *et al.* is strongly suppressed by a high vortex activation energy. If this is the case, the interpretation of the exponential post-glitch decays invoked by, e.g., Alpar *et al.* (1993) would not be viable.

Various authors have used observed glitch properties as a probe to investigate the mass of neutron stars. For example, Pizzochero *et al.* (2017) used the largest observed glitch in a given pulsar to limit the neutron-star mass on the assumption that there was complete unpinning of vortices at a glitch, transferring the entire excess angular momentum to the crust. They gave mass estimates for all pulsars in which at least two large glitches had been observed. For Vela and PSR J0537−6910 in particular, they obtained mass estimates of 1.35 ± 0.08 $M_{\odot}$ and 1.25 ± 0.06 $M_{\odot}$, respectively. In contrast, Ho *et al.* (2017) used detailed modelling of neutron-star thermal evolution combined with nuclear equation-of-state and superfluid models to interpret the size and rate of

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observed glitches as a function of the neutron-star mass. For the same two pulsars, Ho *et al.* (2017) obtained mass estimates of 1.51 ± 0.04 $M_\odot$ and 1.83 ± 0.04 $M_\odot$, respectively. The differences between these derived masses clearly indicate that uncertainties in the physical properties of neutron-star interiors lead to large systematic offsets in estimated neutron-star masses. A positive aspect of this is that pulsar glitches can provide useful input into the determination of these properties.

Acknowlegements

I thank the organisers of this Symposium for inviting me to review this topic and my colleagues with whom I have had many fruitful discussions and collaborations over the past five decades or so.

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