We briefly discuss a handful of topics in pulsar astrophysics, first some general well-known features, then an overview of the glitch phenomenon and the sort of information gathered about the internal structure and dynamics, and finally the quandary posed by the precession of PSR B1828-11 a very important clue pointing towards a novel paradigm for structure of the core regions. We point out that “exotic” solutions for the precession puzzle would force a consideration of exotic glitch mechanisms as well.

1. Pulsars and their environments

Pulsars are now a “classical” subject of modern astrophysics after almost four decades of intense work. Shortly after their discovery in 1967, beautiful theoretical work convincingly argued that neutron stars (and not, for example, white dwarfs) were responsible for the emission. As a brand new field at that time, several ideas were put forward and contributed to fundament the broad-brush picture of pulsars available today. Thus, concepts such as the charged magnetosphere, light cylinder and so on form now (in spite of the lack of exact solutions for this complicated plasma problem), a body of concepts subject to continuous testing (see Ref.4 for a comprehensive discussion.

This is not the appropriate place to recall the spectacular advances in high-resolution instrumentation (see this volume), but the availability of enhanced ground (Keck, Arecibo, etc.) and space (HST, Chandra, XMM, etc.) facilities, coupled with the intensive long-term monitoring (radio) of a handful of objects and targeted searches have now revealed a wealth of phenomena not always fitting into the “standard” view. This has in turn enriched our vision of pulsars, and also created puzzles for the models which are being worked out, as is the case of the glitch phenomenon in particular. We may say that pulsar physics is definitely entering its maturity where more detailed models can be constructed and tested.
2. Torques, braking and glitches: basic picture and challenges

Pulsars are often depicted as giant rotating dipoles. The simplest vacuum torque of a magnetized rotating neutron star (with magnetic dipole \( BR^3 \), angular velocity \( \Omega \) and angle \( \alpha \) between the magnetic and rotation axis) reads

\[
I \dot{\Omega} = -\frac{2}{3c^3}(BR^3)^2 \Omega^4 \sin^2 \alpha
\]  

(1)

in spite of the modifications introduced by the currents, it is expected that the r.h.s. in eq. (1) remains a good representation of the torque as long as the field remains dipolar (i.e., multipole contributions are negligible). If so then so-called braking index \( n = \dot{\Omega}/\Omega^2 \) and jerk parameter \( m = d^2\dot{\Omega}/dt^2 \times (\Omega/\dot{\Omega})^3 \) adopt simple, fixed numerical values (3 and 15 respectively) and deviations may be interpreted as evidence of varying geometry or non-dipolar character of the emission.

Occasionally, the (otherwise smoothly decreasing) pulsar rotation frequency \( \Omega \) experiences sudden increases (glitches) and relaxes back to pre-glitch values. The average pulse, on the other hand, is not observed to change and therefore it is widely believed that these phenomena reflect the dynamics of the internal rotating components rather than magnetospheric phenomena. Because the observed relaxation timescales are very long on microscopic standards, glitches are currently interpreted as evidence for superfluid components, which decouple and recouple as observed.

As is well-known, the first model devised to explain glitches invoked cracking of the solid crust (i.e. a starquake) stressed by the slowdown of the pulsar. It is now believed that these models are no longer tenable if they are to reproduce the large glitches observed from the Vela pulsar and a few other objects, because not enough elastic energy could be stored in it, although we shall see below that cracking may still play a role in glitches.

The most recent approach to a glitch model states that some interior component displays a variable coupling to the environment. If glitches actually reflect instead

![Fig. 1. Schematic draw of a glitch. In this case the angular rotation frequency relaxes back to its pre-glitch value, as is often the case, on a variety of increasingly long timescales.](image)
a variable coupling between the crust (producing the observed pulses through rigid coupling to the magnetosphere) and a superfluid interior (see below), the natural questions to ask are: where does this coupling occur? how is the decoupling triggered? and how does relaxation proceed? Each of these questions are closely related to the issue of the microphysical state of the matter, and hence to the structure of the neutron star. Because the candidate superfluids are likely to be located relatively near the surface (for instance, neutron superfluids are thought to exist between the neutron drip point and the nuclear saturation density with neutrons paired in the $^1S_0$ state), their properties should be calculable to a high degree of confidence, or at least better than the supranuclear regime.

One of the issues that has been discussed over the years which provides a concrete way of addressing these questions is the possible pinning of the superfluid vortices to the lattice of nuclei in the inner crust. This is an “ideal” place to see some action (decoupling and recoupling), since calculations suggest that vortices are energetically forced to pin to a site in the lattice (with energy differences $\leq 1 \text{MeV}$) at least for a static structure. Because of the rotation slowdown, torques brake the crust and a velocity difference develops between the lattice and the superfluid. The vortices actually creep radially outwards through the lattice in steady state. However, this is a gentle collective motion, and therefore cannot be responsible for the sudden hiccup of the crust shown in Fig. 1. What is needed to explain the observations is a sudden motion of the vortices away from the rotation axis. The basic picture of pinned vortices is depicted in Fig. 2.

If pinned vortices are responsible for the glitch behavior (not taking into account the starquake model in its original form) two broad classes of glitch mechanisms, may be constructed to provide the sudden motion of them. The mechanical models postulate that vortices unpin catastrophically (for example, because of a critical threshold of the velocity difference between the lattice and the superfluid). The thermal models in turn search for a big perturbation of the vortex creep process (for example, because of an energy deposition). Even though the models are constructed using the available knowledge of the microphysics (but see below), they happen to have different relaxation after the glitch and a few other features. Thus, careful observations can in principle discriminate between the two.

Since the thermal models require a trigger to perturb the steady motion of the vortices, it is interesting to note that the old idea of starquakes has gained a new role as such. The key feature is that an amount of energy in the form of heat

$$E_{\text{heat}} \propto \mu \theta^2 \leq 10^{42} \text{erg}$$

is released per quake event (where $\mu$ is the bulk modulus of the crust and $\theta$ the critical strain for the fracture to occur). Since the vortex creep is exponentially sensitive to the temperature, a starquake trigger turns it into a highly dissipative motion. A prediction is that $\Omega$ should rise slower than the mechanical models and relax following the behavior of the local temperature $T(t)$. 

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*Pulsar astrophysics: the glitch phenomenon*
Fig. 2. Pinning of superfluid vortices to the nuclear lattice. Quantum mechanics requires vortex formation in a neutron superfluid coexisting with a lattice of neutron-rich nuclei, and these vortices minimize the energy by pinning to the lattice sites. The exact realization of the pinning (interstitial, multiple, etc.) is being debated, but some form of pinning is required by modern glitch models, differing otherwise in several important details.

What do observations tell us? A general overview may be found in Lyne, Shemar and Graham Smith. In the framework of vortex pinning theory, the huge difference in the glitch behavior of the Vela and Crab pulsars suggest that the force per unit length exerted by the vortices on the lattice is different by many orders of magnitude, thus requiring either a very different structure in both objects, or rather suggesting again a whole reinterpretation of the glitch phenomenon (see, for example, Ref. 8 for an argument of this kind). On the other hand, work performed by Larson and Link showed that fitting of actual glitches is possible within both the mechanical and thermal models, although (strangely again) the former seem preferred for the Vela events and the latter for the Crab. This again may be indicative of some fundamental flaw in the models if one believes that a single underlying mechanism should be operating. An alternative would be to put the blame on evolutionary causes for these differences, as done, for example, in Ref.10.

3. More trouble with glitches: quick jumps and “anomalous” behavior

The glitch characterization and understanding may seem complicated enough according to the above remarks. However, accurate observations continue to reveal a great richness of the glitch phenomenon, still searching for a firmly established paradigm. A recent example of that observations can be found in the work by Dodson, McCulloch and Lewis, which report accurate observations of the largest Vela
pulsar glitch, fully accelerating in less than 40 s and relaxing on a series of timescales with a very short one of $\sim 1 \text{ min}$. Even more puzzling than the short relaxation timescale is the report of the lack of relaxation in some of the Crab events, pointing to an increase of the external torque or an extremely long $\sim \text{years}$ recoupling of a fraction of the decoupled components in the standard interpretation (see Fig. 3).

Working within the varying torque hypothesis, models of a growing angle between the magnetic and rotation axis $^{12,13}$ have been published. Even the growth of the magnetic field intensity $B$ as suggested earlier $^{14}$, although on longer timescales is in principle possible. Related consequences were worked out, most notably specific predictions for the non-canonical braking indices of a small group of selected pulsars. This quantity is directly measurable and picks up extra terms which cause deviations from the pure dipole value when the torque increases after a glitch. The present observational situation is unclear to us, but there may be indications of a complete relaxation back to the pre-glitch values on very long timescales. Nevertheless, it is certain that a successful model of glitches must have a built-in explanation for very long relaxation timescales and very short ones, preferably supported by detailed microphysical calculations.

![Fig. 3. The “anomalous” glitches of the Crab pulsar. In these events the pulsar is observed to relax only partially to its pre-glitch state. Since the torque is $\propto \dot{\Omega}$, which increases after all the observed relaxation, one possible explanation is that the geometry of the field or the field itself have changed. Even if the relaxation is complete after several years, models would have to explain why some component remains decoupled for such a long time](image)

4. **Precession vs. vortices: type I superfluids or exotic stars?**

Given that a complex dynamical behavior is present in the data, and of course that we would like to know more about neutron star interiors as a whole, it is important to seek for other evidence to obtain further clues. In a recent paper Link $^{15}$ has argued that the evidence for precession from PSR B1828-11 is incompatible with the current models of the outer core of a compact star. He showed that the
interaction of flux tubes (permeating the charged superconductor) with rotational vortices (threading the neutron superfluid) would damp out the precession quickly and allow high frequency motion only, not one with \( \tau_p \simeq 1 \text{yr} \) as suggested by the existing data. There are a few ways out from this problem, one is that the outer core is actually a type I superconductor, and therefore expulsion of \( B \) by the Meissner effect happens. Another is that the superfluid and superconductor do not coexist anywhere in the core. A third possibility, already raised in that work \(^{15}\), is that an exotic core occurs, the one we would like to comment on here.

Even though it might appear as if Link’s argument may find a natural realization in the already existing “hybrid” structure models (i.e. compact stars with quark cores), the actual situation is much worse than that: since the existence of nuclear matter in the outer core would quickly damp the precession motion, its place in the star must then be taken by the exotic core. However, this is quite difficult to achieve, because then the transition at which the phase change starts has to be tuned to be \( \simeq \rho_0 \). Needless to say, this is far too low to be fashionable. To quantify the difficulty it is enough to note that in the models of hybrid stars with CFL cores constructed by Alford and Reddy \(^{16}\) the central density is above \( \rho_0 \) for stellar masses \( M \leq 0.4 M_\odot \). The “exotic core” solution can then be restated in a strong form: unless the nuclear saturation density is the true threshold value for quark matter to appear, the quark region is rather likely to extend all the way up to zero pressure, (i.e. it “naturally” corresponds to a self-bound state like strange matter \(^{17}\) or color-flavor-locked strange matter \(^{18}\) ). Based on this observation we contend that, if exotic cores as needed to justify the existence of precession are present, then the *locus* of observed glitches must also be “exotic” (i.e. unrelated to neutron vortex arrays), simply because the normal inner crust would not exist. This “exotic” glitching models are a promising arena of research for the next future.

“Ancient” models involving differentiated structures in quark matter (a prerequisite for any successful attempt to model glitches) \(^{19,20}\) have not been explored because of a disbelief in the employed physics, but are revived in different new forms from time to time \(^{21}\) and may be worth the effort. Of course, it is also possible to find out a non-exotic solution within neutron physics, although it would bring striking novelties in itself for pulsar structure almost by definition. So stay tuned for the precession news!

5. Conclusions

We have given a broad overview of one of the most spectacular dynamical features of pulsars (glitches), repeatedly associated with perhaps the most gigantic quantum fluids found in nature, namely the components of the crusts of neutron stars. Accurate timing for over three decades have provided very good data still waiting for a comprehensive explanation. Strong limits to the idea of heat release in a glitch have been set recently by Helfand et al. \(^{22}\) and Pavlov et al. \(^{23}\) using Chandra data to show that the temperature of the pulsar did not change by more than 0.2% one
month after the Vela glitch of January 2000. Even though it is not impossible that some mechanism can get rid of the heat very quickly, these observations constrain the thermal models in which a large energy input is needed. An even more serious challenge has been posed by some authors (notably Jones, 24 and references therein) suggesting that vortices in the crust do not pin at all (see also Donati and Pizzochero 25 for a general analysis). May be the core plays a role 26, but as discussed above, this component surely hides some (big ?) surprises and would require extensive studies. We are far from a thorough understanding of the body of evidence of glitches, whereas additional complications from related observations have enriched the general picture recently. A whole new synthesis is needed soon, and perhaps a change in the paradigm as well to pin down the essentials of pulsar dynamics.

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