Radio Pulsar Observations and the Challenges of the Neutron Star Interior

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Abstract. Radio pulsars are, by far, the most common observable manifestation of the fascinating neutron star. Timing observations of the emitted radio pulses remain one of the best probes of the neutron star interior. Such observations have led to a number of models describing the various components of the neutron star interior and the manner in which they couple with each other. The extent to which such models have been successful in explaining varieties of observed neutron star characteristics is discussed.

Sommaire. Les pulsars radio sont de loin la manifestation observable la plus commune de la fascinante étoile à neutrons. Le chronométrage des impulsions radio émises restent l'une des meilleures investigations de l'intérieur d'une étoile à neutrons. De telles observations ont conduit à un nombre de modèles qui décrivent les différentes composantes de l'intérieur d'une étoile à neutrons et la manière avec laquelle elles s'associent les unes avec les autres. On discute dans quelle mesure de tels modèles ont réussi à expliquer la diversité des caractéristiques des étoiles à neutrons observées.

Introduction

The interior of the neutron star consists, broadly speaking, of the core superfluids, crust superfluid and the lattice crust to which the charged components are tightly coupled (Fig. 1).

Although neutron stars have now been recognised in a variety of stellar systems, radio pulsars are by far the most common observable manifestation of neutron stars. The emitted radio pulses allow us to measure directly the rotation of the underlying star. This rotation rate is, in comparison with most other astronomical measurements, exceptionally stable and easy to measure with high accuracy.

Pulsars slow down steadily, due to the loss of kinetic (rotational) energy via the emission of high-energy particles and radiation. In other words, the pulsar spin rate, \( \dot{\nu} \), has a negative derivative, \( \ddot{\nu} \). This is easily observable and is traditionally used to determine the age of the pulsar. Departures from the expected regular behaviour of the pulsar give us a window into the interior of the neutron star. Some of these departures are discussed in the following sections.

Pulsar Glitches

Glitches are perturbations of this regular spin down of the pulsars. Observations of pulsar glitches remain one of the best probes of the neutron star interior. Pulsar post-glitch recovery is known to exhibit a wide range of timescales, from hours to years (e.g. Alpar et al.\[4\] and references therein). This recovery has been explained in terms of the superfluid components of the neutron star interior and their coupling to the lattice crust.

In the original two-component model of Baym et al.\[5\] the glitch recovery was understood in terms of the coupling of the core superfluid to the crust. The model provided for an internal torque, \( N_{\text{int}} \), due to the core neutron superfluid of inertial moment, \( I_p \), and angular velocity, \( \Omega_p \), of the form

\[
N_{\text{int}} = I_p \frac{\dot{\Omega}}{\Omega - \Omega_p}\]

(1)

where \( I_p \) is the moment of inertia of the crustal lattice plus whatever other stellar material that is rigidly coupled to it, and \( \Omega_p \) is its angular velocity, \( \tau_p \). The crust-core coupling time is \( \tau_p \), while \( I \) is the total moment of inertia of the star. This model gave a good fit only to the initial post-glitch data from

Fig. 1. A schematic representation of a possible cross-section of a 1.4 solar mass neutron star (Lamb\[7\]).
the Crab and Vela pulsars. With more data and detailed analysis of subsequent glitches in those two pulsars, the simple two-component model failed to provide adequate explanations. Alpar & Saulis[11] argued that the relaxation of the superfluid core to the crust plasma after a sudden spin-up is governed by a dynamical time scale \( \tau_d \) given as

\[
\tau_d \approx 100(m_p / \delta m_p^*)^2 P, \tag{2}
\]

where \( P \) is the rotation period of the pulsar (\( \sim 1 \) s for typical pulsars); \( m_p, \delta m_p^* \) are, respectively, the proton effective mass and the difference between its effective and bare mass. On the basis of the above equation the core superfluid is understood to be coupled on time scales no longer than \( \sim 400P - 10^6 P \) and as a result would not be involved in the observed post-glitch relaxation. This led to new two-component models in which the recovery is explained in terms of the coupling of the crust superfluid to the rest of the neutron star (core superfluid, plasma and lattice crust – all assumed to be rotating rigidly).

More recently, there has been renewed interest in the involvement of core superfluids in glitch recovery. Sedrakian & Sedrakian[12] showed that the generation of a vortex cluster around each neutron vertex line leads essentially to larger effective friction than that implied by previously proposed friction mechanisms. A dynamical coupling time which is density dependent and proportional to the square of the pulsar rotation period was proposed. It was argued that the scattering process is a varying function of the core density thus leading to the core superfluid having a wide range of dynamical coupling times \( \sim 10^4 - 10^6 \) days. It has also been reasoned (Ruderman et al.[10], Jones[11,12], Urama[13]) that parts of the core superfluid could be involved in glitch recovery, in which case a reassessment of the canonical assumption of an observably tight coupling between the core superfluid and the charged components of the neutron star would be necessary. Near real-time glitch detections have been made only on the Crab and Vela pulsars. With such a limited sample, sufficient testing of various models of the coupling of the interior components has yet to be made. However, many unusual glitch behaviours, including microglitch signatures, are difficult to understand based on any single model. Any good model of the coupling of the interior components of the neutron star should be able to provide sufficient explanations for observed glitch characteristics such as their magnitude and intervals.

### Free Precession of Neutron Stars

Free precession of a pulsar arises from a misalignment between its angular velocity and the angular momentum. This occurs if the neutron star has a nonspherical shape and its spin axis is not aligned with the symmetry axis. The angle, \( \chi \), between the spin axis and the magnetic moment varies over the precessional cycle. Evidence of free precession has been reported in a number of pulsars (e.g. Stairs et al.[19], Shabanova et al.[19]).

One of the questions that has been raised about neutron star free precession is about the interior fluid(s) that participate in the free precession. Jones & Andersson[10] considered two extremes. In one, the frictional coupling between the crust and core is very weak so that the crust precesses on top of a non-precessing core. At the other extreme, when the frictional forces are very strong, the star precesses as a single unit. Based on the arguments of Alpar et al.[21] and Alpar & Saulis[11], they concluded that the frictional interaction is too weak to cause the core neutron superfluid to participate in the free precession of the star's crust. Also, they found that for most of the reported observations, setting the pinnned superfluid component to zero provides a good fit to their model. This is in total disagreement with the theories of the neutron star interior based on the interpretation of glitch processes. There have been suggestions (e.g. Link et al.[14]) that in frequently glitching neutron stars, the fractional moment of inertia that is pinned is greater than 1.4%. Jones & Andersson[10] have argued that for non-zero pinning, the maximum pinned component \( \leq 10^8 I \). This is a serious challenge to what had, hitherto, been accepted as the standard theory of the coupling of the interior components of the neutron stars. This will only be resolved with a larger sample of observational results on both the precessing pulsars and real-time monitoring of different sizes and signatures of pulsar glitches. Even the ‘big’ question of why the neutron stars are precessing is still far from being convincingly addressed.

### ‘Anomalous’ Braking Indices

Pulsars are assumed to be born with a high rotational frequency and subsequently slow down according to a simple power law

\[
\dot{\nu} = -K\nu^a \tag{3}
\]

where \( n \) is called the braking index, \( \nu \) is the rotational frequency, \( \nu \) is the slow-down rate and \( K \) is a constant. For a pulsar born with a high rotational frequency \( \nu \) and evolving as given in equation (3), the standard expression for the characteristic age \( \tau \) is

\[
\tau = \frac{\nu}{(n - 1)\nu} \left[ 1 - \left( \frac{\nu}{\nu_0} \right)^{n-1} \right] \tag{4}
\]

Based on the vacuum dipole model (Goldreich et al.[20]), the braking index \( n = \nu \nu^2 / \nu^2 = 3 \). Due to timing irregularities, precise measurements of \( \dot{\nu} \) and \( n \) have been possible in only four pulsars: the Crab pulsar, PSR B1509–58, B0540–69 and J1119–6127. Interestingly, these four pulsars are very young \( \sim 10^3 \) yrs. Lyne[21] argued that for older pulsars, timing noise and the recovery from glitches usually dominate the measured value of \( \nu \), and the value of \( n \) is variable and is not related to the braking mechanism.

Equation (3) assumes a constant \( K = B^2R^6 \sin^2 \alpha / 6\alpha \) for the vacuum dipole model. It has been shown (Link & Epstein[13], Allen & Horvath[22]) that if \( K \) is not constant but changing at an average rate of \( \dot{K} \), the observed braking index, \( n_{obs} \equiv \dot{\nu} / \nu^2 \), will differ from \( n \) in equation (1) by

\[
n_{obs} - n = 2\tau \frac{\dot{K}}{K} \tag{5}
\]

where \( \tau = \nu / 2|\dot{\nu}| \), the conventional spin-down age, differs from the true age if \( K \) is evolving.
For a non-constant $K$, one of the many possibilities is that the evolution of $K$ is due to the changing moment of inertia. Under that assumption, an observed braking index of 3 would imply an unchanging moment of inertia, where an increasing or decreasing moment of inertia would result in the observed braking index being greater than or less than 3 respectively. This could provide an explanation for the very large braking indices earlier reported for a number of pulsars (e.g. D'Alessandro et al.\cite{6}), some of which are negative. (Glendenning et al.\cite{7}) argued that a pulsar could have a braking index that is far removed from the canonical index, possibly by orders of magnitude, and that can be of either sign.

Various suggestions have been given for the time evolution of $I$. These include a structural change of the star, a decoupling of a portion of the star's liquid interior from the external torque (Link \& Epstein\cite{13}), or the conversion of nuclear matter to quark matter in the core of a rotating neutron star (Glendenning et al.\cite{7}). Link \& Epstein\cite{13} argued that explanations based on either decoupling of the interior liquid or changes in the star's structure cannot accommodate the drastic decreases in $I$ observed in the Crab pulsar. However, Glendenning et al.\cite{7} suggested that the conversion of matter from the incompressible nuclear matter phase to the highly compressible quark matter phase could lead to some structural changes in the star such as its size and moment of inertia. Unfortunately, most of these models contain lots of parameters that are not directly observable. As a result, they cannot easily be tested even with the available timing data. Hopefully, as very long term (>30 yr) data spans become available, the large departures of the observed braking indices from the canonical value of 3 could throw more light on some of the features of the neutron star interior.

**Conclusion**

Neutron stars keep turning up new and often unexpected features. Such behaviours keep on stretching the theories of these fascinating objects. Many of these theories lack sufficient data for an adequate test. The result is that many aspects of the neutron star, especially the interior components and their interactions, remain poorly understood. Most of the theoretical models on the neutron star, so far, cannot account for many of the observations. Longer term data spans are needed for a better understanding of many of the neutron star behaviours. Also, there is the need for more pulsar-dedicated telescopes engaged in continuous monitoring of a larger sample of pulsars.

**References**