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Magnetized Matter in Neutron Star Dynamics: Challenges Ahead

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Abstract

Matter at ultra-high densities finds a physical realization inside neutron stars. It is generally acknowledged that huge magnetic fields are present in these stellar objects, and if not for the presence of the magnetic fields, neutron stars would be much more "silent" and practically invisible. However, a series of questions still remain concerning the role of magnetic fields in the neutron star structure and internal dynamics. We present an overview of these topics, pointing out the importance of a new set of observations (glitches and related events, and precession) and old questions that must be accommodated by a more complete theory of neutron star physics.

Keywords: magnetic fields; neutron stars; magnetized dense matter; pulsar dynamics

1. Introduction

Almost sixty years ago, J.Bell Burnell and the Cambridge group achieved a remarkable landmark by discovering the first pulsar [1], now within an enlarged class of >4000 objects. Quickly recognized as manifestations of Landau's neutron stars [2,3], as a prime example of extreme physics, these compact objects continue to challenge us. It is widely acknowledged that the general study of neutron stars (NSs), of which pulsars are just a subset, provides insights into fundamental aspects of physics, from the state of matter at ultrahigh densities to the production of heavy elements. Regarded as novel physical tools, they have been shown to offer extremely precise tests for General Relativity (GR) [4] and contribute in general to the understanding of Stellar Evolution, binary interactions and many other issues. The field is very dynamic, and the last decades of research have brought some important novelties and paradigm shifts, correcting previously unquestioned beliefs in the field.

The suggestion that NSs are formed at the end of the life of massive progenitor stars, originally due to Baade and Zwicky [5], and the confirmed associations with supernova remnants [6], helped constructing the widely known scenario for their origin. Initially, a variety of ideas were put forward for this origin [7], but after the initial years, the prevailing notion was that NSs are formed after the collapse of an "iron" core (actually ^{56}Fe and many related isotopes), developed at the center of progenitor stars with initial masses ranging from 8 to around 25 $M_{\odot}$ (later, the low mass range 8–9 $M_{\odot}$ was identified as evolving a O-Mg-Ne core only). However, a fundamental ingredient for the pulsar phenomenon discovered by the Cambridge team, namely the presence of a high magnetic field [2,3], called for an extended set of thoughts about its very origin, since it is entangled with the exact nature of matter and also with the process(es) that can amplify it during or immediately after the formation. Furthermore, the development of a detailed internal structure refined the earliest views, but created a complex picture when the magnetic field

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is considered as a prime actor of NSs secular evolution. We shall briefly touch on all these issues in this work, and outline the emerging view and also some relevant problems that are important for a deeper comprehension of the structure and evolution of NSs.

2. Standard Neutron Star Structure and the Simplest Expectations for the Magnetic Field

Although the detailed composition of the neutron star interior may produce quite large differences in the structure (this is specially true for self-bound models of the strange matter-type [8,9]), within a "normal" (i.e., protons + neutrons + nuclei) hadronic composition, the existence of a multilayer structure is now generally accepted and discussed in the literature. These layers, from the surface downwards, are named and characterized as follows:

(a) Beneath a tiny atmospheric layer, an *outer crust* composed of nuclei + free electrons likely form a nuclear lattice from $\sim 10^3$ g cm^{-3} to $\sim 4 \times 10^{11}$ g cm^{-3} (the so-called *neutron drip density*)

(b) An *inner crust* composed of increasingly heavy nuclei in a lattice, and free neutrons escaping from them. The latter, due to the attractive channels, form a *superfluid*. The end of these layer happens at 1/2–1/3 of the nuclear saturation density, at around $\geq 10^{14}$ g cm^{-3}. The interactive dynamics between these components give rise to a complex timing behavior of the pulsars, as we shall see later.

(c) A *core* composed of homogeneous matter in which the nuclear structure has dissolved at the lower densities (up to 2–3 times the saturation value), and possibly exotic states at densities beyond that (including quark matter), up to the central value $\sim 10^{15}$ g cm^{-3}. Sometimes, this division is labeled as "outer core" and "inner core" (see below).

The strength of the magnetic field is always small compared to the matter pressure and energy density. However, even though the former can be ignored (with a few caveats) for the structure calculations, it is important to have some features in mind. The first is the reasonable expectation of highly degenerate matter, extremely conductive of electric charges, with this property increasing towards the core. The magnetic field may not be structurally important, but its presence is related, for example, to the composition of matter and its chemical equilibrium, especially for large values of the magnetic field strength. In addition, the state of matter would be relevant for the topology of the field itself; for instance, tube fluxes are expected to allow the magnetic field to permeate the inner crust. We shall return to these issues in due time. In the rest of this work, "internal" refers to the magnetic field strength at the core, "crustal" refers to the one at the crust, and "external" refers to the magnetospheric magnetic field, for definiteness.

It is interesting that, even without performing any detailed calculation, we can formulate some general statements for the magnetic field. Imagine, for instance, that you discuss with a physicist that never heard of a neutron star before, and state these expected facts about the structure and the field. If requested to construct a simple toy model, or a "zeroth order" for the magnetic field, he/she would probably draw a sphere of large (infinite) conductivity, ignore the detailed structure of the core, and argue that the interior field should be something like the one in Figure 1, i.e., a field that looks approximately *constant* inside, as a tentative and reasonable solution of Maxwell's equations. If further asked why a large number of astrophysicists insist on extrapolating a *dipolar* expression all the way down to the center, his/hers answer would be unpredictable. However, this procedure is quite widespread, and gigantic field strengths are invoked based on the dipole extrapolation and then used to justify other hypotheses related to phase transitions, electron level quantization and many other features.

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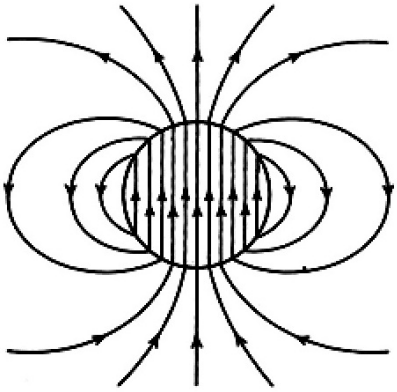


Figure 1. A toy "all-core" neutron star and its central magnetic field.

In turn, the physicist may ask what is the evidence for a *dipolar* field outside. We do know, for example, that Jupiter's field is very dipolar (the upper limit of the deviations has been used to put tight constraint on the mass of the photon in the past [10]), but neutron star magnetic fields were never measured with such a precision. Theoretically, it is true that the dipole is the lowest multipole surviving decay after long times, but there is a considerable degree of uncertainty about the decay times, and in fact, recent observations [11,12] have been interpreted as evidence for local anisotropies of the surface temperature which may be related to the topology of the field. In summary, a dipolar magnetospheric field is reasonable, and emerges from detailed simulations on large scales. However, it has not been precisely measured, and we are not certain how long the decay time would be to achieve a "pure" dipole topology. The usual employment of a dipole expression for the dynamics of the braking should be interpreted as just a simplifying hypothesis and a fiducial theoretical result, but in fact, it is has been challenged by several research groups [13–16] as the only component of the external torque. As it stands, the crust–core transition and the exact state of the field are even more challenging, affecting several timing observations in turn, and all this should be kept in mind.

At this point, is worth stressing that in some X-ray sources containing neutron stars, a distinctive feature of *cyclotron lines* appear to give a quite direct measurement of the photospheric magnetic field, more precisely, the radial component near the neutron star pole. The lines arise because electronic levels are quantized in their motion perpendicular to the magnetic field. These *Landau levels* manifest themselves in the position of the centroid of the lines located at

$$E_{cycl} = 11.6 \frac{n}{(1+z)} \times B_{12} \text{ keV} \quad (1)$$

where $n = 1$ corresponds to the fundamental Landau level scattered to the first excited and $n \geq 2$ to the harmonics, and z is the gravitational redshift exerted by the neutron star mass. Today, around 40 sources have shown cyclotron lines, which confirm the high values of B external to the neutron stars, as shown in Table 1. A thorough review of these lines can be found in Staubert et al. [17].

Table 1. A selected set of sources showing electron cyclotron lines.

Name	E_{cycl} (keV)	B_{12} (G)
Her X-1	37	3.83
Cen X-3	28	2.90
Vela X-1	25	2.60
GX 301-2	37	3.83
A 0535+26	50	5.17

3. Origin of the Magnetic Fields

The magnetic fields inferred for neutron stars are orders of magnitude higher than in any other astrophysical object. Therefore, extreme physics is needed to make them grow to these scales. Two types of scenarios have been discussed over the years concerning the *origin* of the magnetic fields. The first and quite immediate one is the conservation of the magnetic flux. Provided the original collapsing core is magnetized enough, the conservation of the flux would amplify the magnetic field as

$$\langle B_{CC} \rangle \times R_{CC}^2 = \langle B_{NS} \rangle \times R_{NS}^2 \quad (2)$$

where $\langle B_{CC} \rangle$ and $\langle B_{NS} \rangle$ are the average magnetic fields of the collapsing core and the neutron star, respectively. Given that $R_{CC} \sim R_\odot$ and $R_{NS} \sim 10$ km approximately, this back-of-the-envelope calculation indicates that the pre-collapse value of the magnetic field should be at least 10^3 G to comply with the "garden-variety" pulsar fields. However, the simulations of pre-supernova cores never granted such fields, and even less when the magnetar-scale magnetic field were discovered, ranging up to 10^{15} G. Suggestions about their origin in the accretion-induced collapse of magnetic white dwarfs were made [18], although the presence of magnetars in some supernova remnants suggest that a core-collapse origin is quite likely, at least for many magnetars, and just a fraction of them may originate in AIC events.

Hence, the study of magnetic field generation through dynamos was employed to deal with this problem. The idea is also quite simple: currents inside the star, mainly along the collapse and the early stages, could enhance the magnetic field strength. However, the same extreme conditions present in these environments contain physical ingredients that may conspire against the field growth and stabilization. We will sketch a few features related to the dynamo action.

The most promising version of the dynamo, entertained with frequency after the magnetar fields were discovered, is the so-called α-Ω dynamo (where α is the coefficient of helicoidal turbulence and Ω stands for a differential angular rotation). It is expected to work at convective zones, primarily driven by strong differential rotation, such as in the first instant of a just born proto-neutron star. The α-Ω dynamo, on the other hand, produces a twisting of the poloidal fields, to achieve a toroidal field at its expense (it is also widely known that a stationary dipolar field cannot be purely poloidal). Detailed simulations of the magneto-thermal evolution of the crust have recently shown that Ohmic dissipation can be overcome by the direct cascade and, even if the generated topology is very complex, the dipole component is quite stable on scales of $\sim 10^6$ yr [19]. The field can reach very high toroidal field values (even without a large contribution from the α effect), but their poloidal components are not strongly shaped by the dynamo [20], and these figures depend on the rotational state of the proto-neutron star object. These features are also welcome to help explaining the burst activity of the magnetars [21], in fact powering the sources for 10^4–10^5 yr, which seems to match the observations [22]. On the other hand, local inhomogeneities of the field could be entangled with the surface distribution of the temperature, which has been found to feature "hot spots" [12], as already noted above.

Another version of a dynamo, in fact expected whenever hydrodynamic instabilities act, is the so-called α^2-Ω, or Tayler–Spruit dynamo. While the differential rotation for this dynamo to operate is still needed, it may *not* require convection. The dynamo twists the toroidal field, mixing the fluid and transporting angular momentum. It has been recently suggested [23] that this mechanism may be the one behind the so-called "low-field" magnetars, in which the dipolar fields are just $\leq 10^{13}$ G, i.e., two orders of magnitude lower than the "classical" magnetar range. Nevertheless, this dynamo can produce small-

scale inhomogeneities and induce crustal failures, a feature tentatively associated with X-ray burst activity. This scenario is entirely possible, although no clear separation of the "low-field" and "classical" magnetars is presently visible, for example, in the P-$\dot{P}$ plane, and remains to be fully studied.

For completeness, we should mention that the early idea of pulsars being permanent magnets has been generally discarded since the necessary physical conditions are too extreme. However, the last version of this origin has been put forward by Hansson & Ponga [24] and termed "neutromagnets", meaning that the magnetic moments could become aligned because of energetic reasons. This idea has not been followed up to say something definitive about it.

4. Timing, Torques and External Magnetic Fields

As generally considered (i.e., [25,26]), the torque equation governing the spin-down of the pulsar is simply

$$I_{tot}\ \dot{\Omega}\ =\ \tau_{ext}. \tag{3}$$

where I_{tot} is the sum of the moment of inertia components which are rigidly coupled to the crust of the star, and τ_{ext} is the external torque, calculated by integrating the Poynting vector over a surrounding surface. With the usual assumption that a pure rotating dipole is the only sink of energy, the torque is of the form $\tau_{ext}\ =\ -K\Omega_c^3$ (note that the subindex "c" indicated the torque acting on the crust, to which the core is strongly coupled). Actually, the "pure" vacuum dipole expression is just $K\ =\ \frac{2}{3c^3}\,|m|^2\,\sin^2\alpha$, where α is the angle between m and Ω_c, $|m|\ =\ B_o\,R^3$ and B_o, R are the magnetic field and the radius of the star, respectively.

Now, it is widely accepted that the field induced by the rapid rotation will produce a huge electric field lifting the electric charges from the surface. Therefore, even starting from an empty (vacuum) exterior, these charges will fill the *magnetosphere*. However, it can be shown that the functional dependence of the torque remains the same, and therefore a pulsar braking by dipole radiation only, with a pre-factor K independent of time, is governed by $n\ =\ 3$. An interesting feature is that within this framework, the accuracy of the dipole-braking picture can be further checked observationally by calculating the *braking index* $n_b$as $n_b\ =\ \frac{\ddot{\nu}\nu}{\dot{\nu}^2}$ (the frequency $\nu = 1/P_{spin}$ is used alternatively with the angular frequency Ω). The expected theoretical value $n_b\ =\ 3$, provided the dipole is the only sink of energy and none of the other parameters depend on time. As we shall see below, there is evidence against this naïve picture, and therefore a suffix "obs" should be added to the observed braking index to distinguish it from the expected theoretical value for the pure dipole $n_b\ =\ 3$. Table 2 shows the plain values of the braking indexes for the small set of cases in which $\ddot{\nu}$ could be measured and n_b determined.

Table 2. The braking indices confirmed for a sample of pulsars. The case of J0537-6910 with a tentative negative value is thought to stem from contamination of the timing after a *glitch* (see Section 8.1).

Pulsar	n_{obs}
J1640-4631	3.15 ± 0.03
Crab	2.519 ± 0.002
B1509-58	2.832 ± 0.003
J1119-6127	2.684 ± 0.002
Vela	1.7 ± 0.2
J1846-0258	2.65 ± 0.01
B0540-69	2.140 ± 0.009
J1734-3333	0.9 ± 0.2
J0537-6910	~ -1.2 (?)

As it stands, no braking index corresponds to the "pure dipole" expectation, and in fact, some of them are quite far away for this value. The simplest explanation is that the braking is *not* due to a pure dipole term. This is in line with another fact: in the few cases in which the dipole radiation power $\dot{E}_{dipole}$ could be estimated, its value is far below the rotational energy variation $\dot{E}_{rot} = I\Omega\dot{\Omega}$, although Equation (3) implies that all the energy should be carried away by this component. Since the actual estimated value $\dot{E}_{dipole}$ is $\leq$0.2 of the $\dot{E}_{rot}$, most of the rotational energy is being carried away by some other "invisible" component. It may correspond to low-frequency waves, a particle wind or something else. But the important remark here is that most of the works assume and impose that the rotating dipole losses are all there is, and do not consider an extra component, even with the evidence gathered by the lower-than-expected braking indices in Table 2.

An immediate consequence of this assumption is that the inversion of the torque Equation (3), usually performed to estimate the strength of the external magnetic field,

$$B = 10^{15}\sqrt{\left(\frac{P}{10\,\mathrm{s}}\right)\left(\frac{\dot{P}}{10^{-10}\,\mathrm{ss}^{-1}}\right)}\,\mathrm{G}, \tag{4}$$

must be off by a numerical factor (to which the bold setting, $\sin^2\alpha = 1$, usually made also contributes). If another component or a time-dependent coefficient K (see Section 8.1) are considered, the correction to the value of the external field is expected to be larger, one order of magnitude or more [13,27].

One of the best studied components is precisely the *particle wind*, known to be present because of the presence of Pulsar Wind Nebulae (PWNs) in the Crab, Vela and other objects. Instead of insisting that the wind is not important, there are reasons to incorporate it to the very basic torque Equation (3) as a continuous component of the pulsar braking [16,26,28,29]. An analysis of the torque form yields, on quite general grounds [30]

$$-BR^3\sin^2\alpha\sqrt{\frac{L_p}{2c^3}}\Omega \tag{5}$$

where L_p is the particle luminosity escaping the star. The torque of the wind is linear in the frequency Ω, as if a monopolar contribution. Note that the wind term scales with as $\propto L_p^{1/2}$, and it may vary with age. The wind term will dominate the braking at some large period (at least for a non-declining L_p). It has been suggested [27] that such a component may be involved in the recently discovered *long-period* sources [31], whose nature is very uncertain and show very unusual features, like extremely extended pulses. We should keep in mind the potential importance of winds for pulsar astrophysics, in spite of their "heterodox" but increasingly clear presence.

5. The Crust State and Its Dynamical Behavior

The crust (inner and outer) is a relatively thin but important component of neutron star models, and the place in which interesting phenomena happen. Technically, the crust extends all the way down to a fraction of the saturation density (1/2–1/3, depending on the model), and hence it is agreed that its composition contains nuclei, free neutrons (in the inner crust) and free electrons. These nuclei are increasingly heavy and neutron rich, and in fact, the further division between the outer and inner crust is related to the so-called *neutron drip density*, where the neutrons start dripping outside the nuclear structure and roam freely, at about 4×10^{11} g cm^{-3}. This point is defined as the beginning of the inner crust extending inwards.

The crust is believed to contain a solid lattice of nuclei, with a rigidity unlike any other material in the Universe. As the conditions for the frozen magnetic field are satisfied,

the crust is pictured as a collection of patches with some global topology, each one carrying a definite value of the magnetic field. This solid crust prompted early models [32] for a very interesting observed set of events, termed "glitches", which will be discussed in Section 8 together with the latest variety of similar events [33].

The structure of the crust is often assumed to be known given that the sub-nuclear equation of state is established. In practice, there are still uncertainties related to the symmetry energy and other factors [34], but this is far from being the whole story. Due to these uncertainties, added to the possibility of the existence of topologically non-trivial *pasta phase* nuclei, the full structure and composition of the crust is actually less known than usually assumed. Measurements of neutron star radii would need to reach the ∼100 m level of precision to separate different versions of the crust models [35]. The alternative gravity proposals complicate the determination even more, and even assuming the GR to hold, successive approximations can not be presently disentangled, as illustrated in Figure 2.

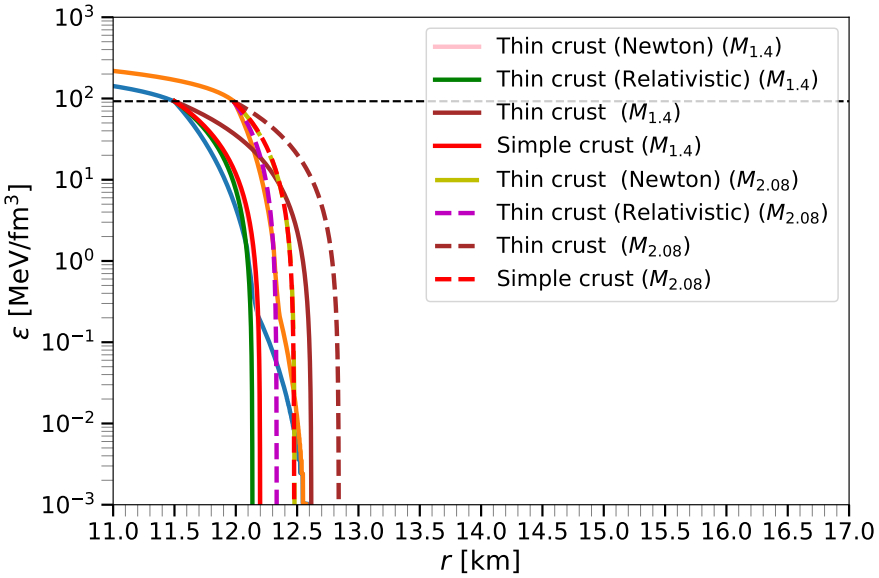


Figure 2. Approximations to the crust structure for the MPA1 supranuclear equation of state, for two values of the total stellar mass $M = 2.08\ M_\odot$ and $M = 1.4\ M_\odot$. "Simple crust" denotes just a slab without any self-consistent structure integration, while the so-called "thin crust approximations" in the Newtonian and relativistic versions are indicated. A firm ∼500 m uncertainty remains, as discussed in Ref. [35].

Even admitting the incomplete knowledge of the structure of the crust, there is a consensus about the state of the free neutrons in the inner crust to become a *superfluid* because of attractive N-N interactions and zero electric charge of the pair. A macroscopic superfluid is expected to have important consequences, and produce observable diagnostics of the state of the crust, as we shall see in Section 8. However, one of the most important quantities, the superfluid gap, is still uncertain by a factor of ∼2 or more ([36] and references therein), which produces not only a range of neutrino cooling possibilities (not addressed here), but also a range of *pinning* values. This pinning is the attachment of the superfluid vortices to sites in the nuclear lattice (nuclear pinning) or locations between nuclei (interstitial pinning), as shown in Figure 3.

In summary, the crust is a relatively thin region containing ≤10% of the stellar mass, but a crucial component to understand the physics involved in neutron stars, not only in their structure but also in their composition and dynamics. We shall see the findings involving the crust and some of the implicit clues below.

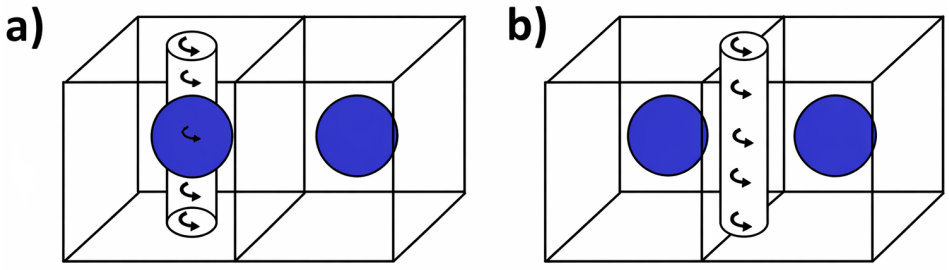


Figure 3. Pinning of the superfluid to the nuclear lattice. In (**a**) the energy is reduced by attaching to the nucleus (nuclear pinning). In (**b**) the lower energy configuration is achieved by pinning to the interstitial sites of the lattice (interstitial pinning). In both cases, the superfluid gap is the most relevant quantity to determine how much of the moment of inertia is coupled to the solid component.

6. The Core and Its Mysteries

It is a common place to state that the physics of the core is unknown. This is not totally true, at least within normal models (if exotics are present this may be an understatement). Still, up to $\sim 2\rho_0$ (twice the saturation density), the composition of matter is often considered as "known". This is why sometimes the core is also divided into *inner* and *outer* sections, with the latter being the most external one with a structure usually modeled with nucleons with Skyrme forces or some other known scheme [37]. The real problem starts above $\sim 2\rho_0$, in which hyperons should quickly dominate the composition, but since they are different species, their presence would *soften* the equation of state to a point incompatible with the known masses of heavy neutron stars [38]. This is known as the *hyperon puzzle*, and some attempts to solve this quandary have been presented recently [39,40]. Basically, either the hyperons suffer stronger-than-expected repulsive interactions, or their appearance is delayed to higher densities, leading to the situation termed the "hyperonless hyperon puzzle" [41]. Since the equation of state at these high densities is the most important ingredient to calculate the theoretical stellar sequences, and with them, the maximum mass of a neutron star, a detailed and ample discussion is given in [37].

Concerning the magnetic fields of the core, the situation is also quite unclear: it is thought that above the saturation density, the neutrons still form a superfluid, but in the P (anisotropic) wave, not the S isotropic wave. This superfluid of neutrons coexists with the protons, which are superconductors (not superfluids because they have electric charge), and thus forms fluxoids/flux tubes with the magnetic field at the center. Within the standard classification, type II superconductors retain the magnetic flux (there is a degree of penetration of the magnetic field via vortices), and type I superconductors fully expel it (Meissner effect). The uncertainties in the equation of state and the interactions between vortices and flux tubes are reflected in the issue of magnetic flux *expulsion*, a feature revised in the literature from time to time (Figure 4). There is a range of conditions in the core for which the superconductor could be expelled on *kyr* or even *Myr* timescales, producing an interesting phenomenology [42,43]. Note that it is entirely possible that the injection of the core magnetic flux into the crust can make the magnetic field of the pulsar *increase* well after its birth. Therefore, there would be a theoretical ground to justify some kind of field variation $\dot{B}$ (see Section 8 below).

I believe it is safe to state that the hardness of the core equation of state has been established overall by the very existence of massive neutron stars. Still, the presence of phase transitions inside is quite possible, and this statement is critically dependent on the (very) unknown degree of interactions in the quark phase(s). If the repulsive interactions are ignored and free quarks are postulated, as was fashionable 40 years ago, the cold quark phase can not appear in general. But successful models of hybrid stars have been constructed with a quark phase harder than expected [44,45]. Bayesian inferences on the

existence of phase transitions are a useful tool to be employed to clarify this important but elusive aspect of the core physics. To be sure, in self-bound models, these considerations are deeply modified, as discussed in [46].

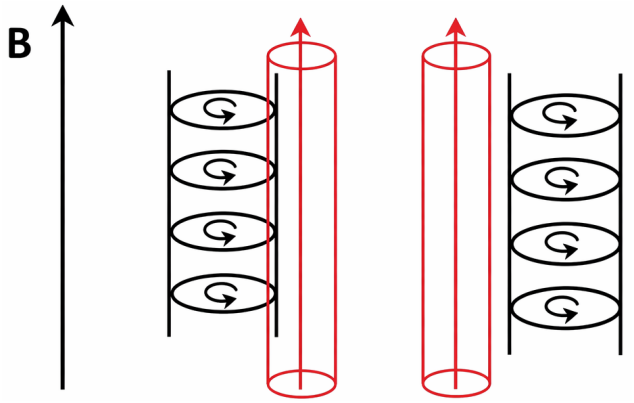


Figure 4. The coexistence of flux tubes (fluxoids) in the superconductor protons, with the magnetic field threading their centers (red), interact with the vortices in the anisotropic neutron superfluid in the outer core. Although the glitches could be modeled in this region, the crust continues to be the place invoked in most of the works.

7. Anisotropies in the Stellar Structure and Magnetic Fields

The consideration of anisotropies in neutron star interiors is a venerable old subject, motivated by the expectation of a variety of physical effects [47]. A general picture dealing with anisotropic solutions, their boundary conditions and related topics was elaborated and presented over the years [48–50]. One of these effects is precisely the existence of strong magnetic fields as discussed above. Detailed stellar models need as ingredients the stress-energy tensor $T_{\mu\nu}$ and a metric *ansatz* that complies with the anisotropies present in the former. A great number of anisotropic metrics are available ([51–53] and references therein) to construct the stellar models. For GR experts, it is well-known that anisotropy of $T_{\mu\nu}$ does not automatically lead to *deformation*. In other words, anisotropic models may be spherically symmetric. Of course, deformation of the star sets in at some point, which may be physically relevant or unphysical, depending on each case [54]. Anisotropy, from the point of view of model construction, has some interesting and useful features: a few extra free parameters present in an anisotropic metric can make room for a good match to the equation of state quantities. This is not always possible for isotropic metrics, and leads to whole new families of solutions that may be useful for actual stars ([51,52,55] and references therein). The issue of the stability of these solutions is also important, and should be studied thoroughly on a case-by-case basis (e.g., [56]).

Strongly magnetized stellar models, within an anisotropic metric approach, present an additional challenge. As an additional quantity to be determined in the problem, only very special cases of the magnetic field, not always realistic ones, can be analytically worked out. These include radial magnetic fields and a few others. Sometimes, even constant fields cannot be easily solved, depending on the chosen metric. On the other hand, a full numerical approach of the type developed for the interior solutions in GR [19,21] has not been attempted for the anisotropic cases. It is a big task to explore the available models and truly determine the magnetic field configurations without a priori symmetries imposed. As of today, this topic remains largely uncharted.

Finally, we would like to stress that anisotropy (produced by magnetic fields or any other effect) may affect the existing determinations of radii, presently stated as the "equatorial" values [57]. There is no information on the polar radii extracted so far, therefore the existence of deformation due to anisotropy is unknown. It is important that the mass is

also affected by anisotropies, and could be higher than the Rhoades–Ruffini limit of 3.2 $M_{\odot}$, which has been recently revised upwards [58]. A glimpse of the effects of the orientation of magnetic fields on the mass and radii can be seen in the work by Deb, Mukhopadhyay & Weber [48]. As it stands, there is ample room for improvements on this anisotropy topic.

8. New Phenomena and How They Relate to the Internal Structure and Magnetic Fields

With the brief introduction and overview of the crust–core status, with emphasis on the microphysical state and the issue of the magnetic fields, we shall now address a set of relatively new phenomena that serves to examine the interior physics, and revise, to a good extent, the existing models invoking ingredients that may force a revision because of these findings. The list is not exhaustive, but enough to rethink neutron stars from a more ample perspective, as needed.

8.1. Glitches, Anti-Glitches and Permanent Changes of the Spin-Down

Sudden irregularities (glitches) of the spin frequency Ω have been observed in many pulsars, with most of the positive jump going to zero after days/months. These events do not provoke a change in the pulse, and since their scale is large in terms of the ordinary microscopic times, a low-friction component decoupling and re-coupling on that timescale was postulated (a first version of the glitch model invoked a cracking of the solid crust submitted to mechanical tensions because of the spin-down, but this idea was discarded when the "giant glitches" of the Vela pulsar made them unlikely because of the available elastic energy). The natural choice for this decoupling/recoupling is the superfluid neutrons in the crust, believed to rotate by creating vortices that gain energy by pinning to sites in the nuclear lattice, as explained above. The superfluid rotates with a velocity Ω_{sf} different from the crust one Ω. Therefore, there is a velocity lag $\Delta\Omega = \Omega_{sf} - \Omega$ between the two, which grows with time, and an avalanche of unpinning vortices suddenly ensues when critical lag is achieved, since a lag too large cannot be held by pinning forces. The sudden decoupling reduces the moment of inertia and produces a spin-up of the crust, observed as a positive "jump". Figure 5a depicts the behavior of the rotational frequency observed. These vortices recouple, totally or partially, later on in the relaxation stage.

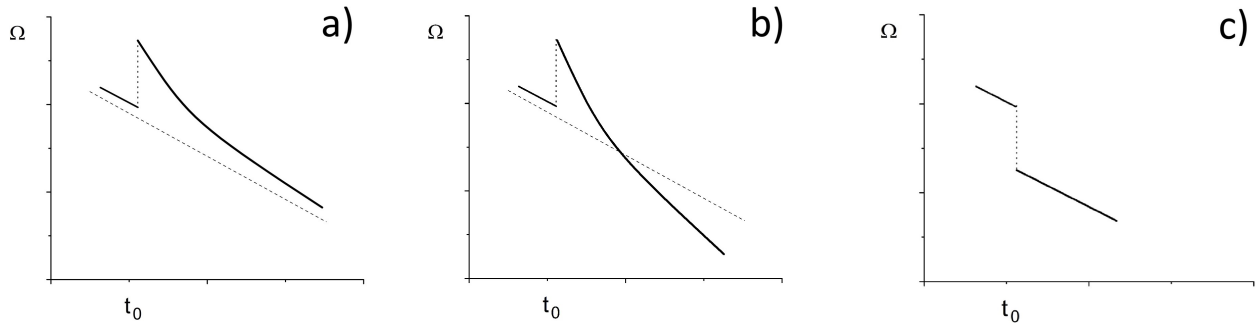


Figure 5. Schematic depiction of (**a**) a glitch; (**b**) a glitch with a permanent change in the frequency derivative $\dot{\Omega}$; and (**c**) an "anti-glitch".

A simple mathematical description of this mechanism can be appreciated in the so-called *two-component* model, formally written as

$$I_c\dot{\Omega} = \tau_{ext} + \frac{I_{sf}}{\tau_{rel}}(\Omega_{sf} - \Omega) \tag{6}$$

$$I_{sf}\dot{\Omega}_{sf} = -\frac{I_{sf}}{\tau_{rel}}(\Omega_{sf} - \Omega) \tag{7}$$

where I_{sf} is the neutron superfluid moment of inertia, I_c is the moment of inertia of the crust plus all the components rigidly coupled to it on very short timescales (assuming no pinning of vortices in the core, this time will be $\leq$2 min [59], and τ_{rel} is a relaxation (recoupling) timescale. This simple mathematical scheme is enough for a description of the glitches provided there is enough moment of inertia of the superfluid component participating in the process. However, a more recent investigation [60] involving I_{sf} claimed that the non-dissipative *entrainment* coupling between the superfluid and the nuclear lattice effectively reduces the moment of inertia of this component, and the lack of enough I_{sf} returns, this time because of a different effect. Fourteen years later, the situation is quite unclear: although it has been claimed that there might be enough I_{sf} provided nuclear parameters are in a certain range [61], they seem to belong to the extreme possible range, and in any case, they could not be confirmed. A recent calculation within a linear response theory [62] yielded a positive answer for the amount of superfluid neutrons contributing to I_{sf}. On the other hand, alternative calculations claimed that no glitch could be actually explained, since entrainment is too strong. The construction of a flexible successful model for the glitches is an important task to be undertaken.

Even if the popular glitch ideas may not align with the fundamental physics of superfluid–nuclei interactions, there are also additional problems to consider. One of these is $\geq$30 yr old, when glitches with the angular velocity relaxing to a state that was *not* the pre-glitch one were identified [63,64] in the Crab pulsar, retaining a permanent variation in the spin-down derivative $\frac{\dot{\Omega}}{\Omega}\mathrm{s}^{-1}\sim 10^{-4}$ (Figure 5b). Since the relaxation of the glitch model, Equations (6) and (7), does not allow such behavior, being bounded from below by the pre-glitch extrapolation, one is forced to conclude that a small increase in the torque happened across the event.

When looking at the physical cause of this increase, it is clear that if any of the parameters of the torque change, the observed braking index will be, in general, different from the theoretical definition. Thus, the observed value of the braking index will be

$$n_{obs} = n + \frac{\ddot{\nu}\nu}{\dot{\nu}^2} = n + \left(-\frac{\dot{I}}{I} + 2\frac{\dot{\alpha}}{\tan\alpha} + 2\frac{\dot{m}}{m} \right) \tag{8}$$

Therefore, in this simple model, either the moment of inertia I [65], or the angle α between the magnetic and the rotation axes [13,66], or the magnetic moment m [67], should have changed. In fact, all three possibilities have been considered, and while it is not possible to decide which one is correct, we believe that the changing angle (i.e., changing the topology of the magnetosphere), is more consistent with a general picture of the crust dynamics. The reason is that the solid crust and its magnetic patches/platelets [68] can be cracked and rearranged with a slight change in the topology quite easily.

Moreover, even events that are not strictly glitches can be accommodated in principle within this picture, and it seems the less contrived physical mechanism to invoke. In some cases, the jump in the angle needs to be tiny, and the braking index will not show detectable changes [69]; however, there might be other associated events, such as the ones of the "Crab Twin" PSR B0540-69. This pulsar has suffered events in which the braking index changes dramatically, even accompanied by an increase in the X-ray emission. In Barão & Horvath [70], a minimal phenomenological model of platelet dynamics was formulated to account for this observation in terms of a drift of the magnetic axis, as a kind of benchmark to understand the permanent changes in a unified form. There is a positive expectation that platelet tectonics can harbor the "anti-glitch" phenomenon (Figure 5c), a sudden spin-down of the neutron star.

8.2. Sudden Magnetospheric Changes in PSR B1931+24, Magnetar Braking and Other Sources and Models

While the evolution of spin-down is pictured as steady, detailed study of individual pulsars has revealed a very interesting and potentially game-changing feature. Twenty years ago, the detection of PSR B1931+24 showed that the pulsar has two states, and that a discrete change in the braking goes back-and-forth, revealing an intermittent component [71]. The "on" state brakes 50% more than the "off" state, interpreted as the effect of launching a wind because of magnetospheric changes, which are reversible. As seen from Equation (3), the braking index $n = \frac{\nu\ddot{\nu}}{\dot{\nu}^2}$ now picks a second contribution from the wind, in line with the observed enhanced braking when it is "on".

In fact, this launching was postulated earlier by Harding et al. [30] when noting that magnetar outbursts behave in the same way: a second braking agent suddenly turned on and later vanished. In spite of the fact that magnetar braking indexes have not been measured, the similarities between the two cases is quite suggestive and leads to similar conclusions. Both cases point towards the consideration of transient wind braking.

The question raised by these transient winds is also important for other situations in which *steady* winds may be present. In fact, we have already stated that winds are directly seen in PWN cases, although dismissed as dynamically irrelevant. However, the discrepancy between the theoretical and measured braking indexes may be solved if steady winds are present, at least partially. It is commonly thought that winds are synonymous of high energy, but their presence may be largely "invisible" (if not for the braking index), a postulate that is also related to the scarce fraction of the whole rotational energy carried away by the pulses. Of course, the inclusion of winds from scratch will spoil the utter simplicity of the pure rotating dipole picture, but I suggest it is time to face these consequences and work towards a global picture including them.

8.3. Confirmation of the Precession of Her X-1 and Other Sources

The last important advance in pulsar dynamics is the confirmation of the long-sought cause of the 35-d periodic modulation observed in the source Her X-1. This accreting binary was suspected to undergo (Eulerian) *precession* motion, although the exact nature of this precession was debated. Recently, observations [72] yielding a high value of the polarization suggested that the accretion disk is not undergoing precession, and therefore the neutron star is the one that fits into this dynamical regime (Figure 6) (an orbital precession is also present). This is unexpected from the point of view of the neutron star interior ideas discussed before: Link [73] pointed out that a long period is in conflict with existing ideas about the nature of the proton superconductor threaded by flux tubes, since a Type II is not consistent with them. Therefore, some solution has to be found. One possibility is that the neutron superfluid and the proton superconductor do not coexist inside the neutron star (which could make a case for an exotic interior, see [74]). The other could be that the superconductor is actually Type I, hence expelling the magnetic field at some point along the history of the object. Finally, domains of Type I may form in the core alternating normal and superconducting states [75]. It is difficult to decide at this moment which one actually happens.

In addition to the long-known case of Her X-1, precession was put forward to explain the several periods detected in the observations of the pulsar PSR B1828-11, which would be freely precessing. Moreover, a magnetar following an X-ray outburst was observed to undergo free precession, damped on a ∼months timescale [76]. These observations are telling us something important about the interior, with consequences for the glitch and related event models, in the spirit of the attitude of Ref. [77].

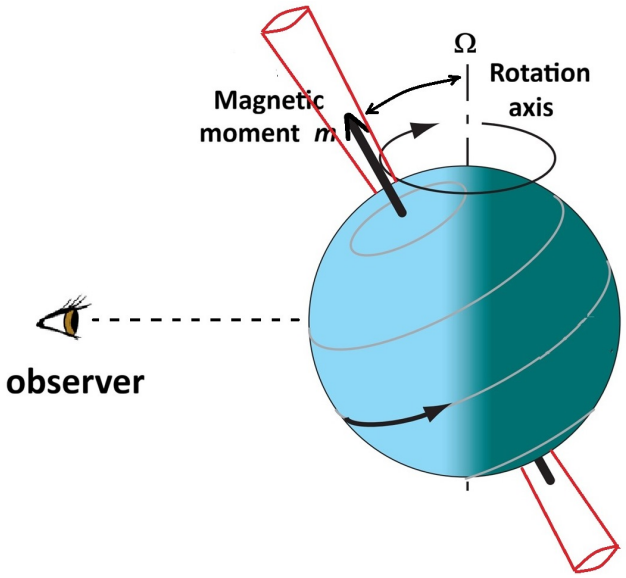


Figure 6. A scheme of the precession seen in some neutron star sources. The emission cone, assumed to be along with the magnetic moment m, is not aligned with the rotation axis, and a periodic modulation depending on the parameters yields the long precession period. The accretion disk is likely to play a key role, yet to be studied in detail.

9. Challenges and Final Remarks

We have outlined several issues related to the state of matter/magnetic fields inside neutron stars, and their relevance for the observed phenomena. As it stands, we still have a fragmented and tentative knowledge of fundamental physics and the overall relation among components is not completely established. As a partial and biased list of problems to be solved, we may list the following:

- Establishing a firm upper limit to the value of the central field, preferentially in a model-independent way, would be important to go ahead with the physics of the core. A simple calculation using the Virial theorem with the addition of magnetic energy indicates $B_{central} \leq 10^{18}$ G, but values as high as 10^{20} G or more are employed many times in theoretical calculations. This is why an upper limit could be useful to discard extreme possibilities.
- Concerning the core, the quandary of magnetic field expulsion is an outstanding problem to be solved. The composition is still uncertain to a large degree, although a "minimal" stiffness is mandatory because of the empirical evidence in favor of high neutron star masses (with an upper limit yet not known). It may be stated that the magnetic field is not really important for the core structure, but this is only if a "normal" composition can be confirmed. If an exotic nature is the ultimate answer, it is likely that the upper limit of 10^{18} G stemming from a Virial relation with a magnetic term is enough to produce huge modifications, by quantizing quark single-particle levels [78,79], and even anisotropic stellar models would have to be considered [80,81].
- The winds should be seriously considered as a standard component of pulsars and magnetars [14,16,25,28,29,82]. This is coupled to the long-standing problem of the magnetosphere solutions (to which advances could be counted, see [83], and a lot of theoretical [84] and observational work should be dedicated). In particular, the "invisibility" of the winds in the majority of cases when they are suspected to be present but no PWN or any other obvious signal is detected should be clarified.
- Vortex creep models are now 40+ years old [85], but they seem insufficient to accommodate the full phenomenology of glitches, anti-glitches, spin-down events, etc., which suggests an interplay between the solid crust and the superfluid component

mediated by plate tectonics [68,69,73–75,86], extending its predictive power to (some?) FRB sources [81]. It must be remembered that even the basics of this model, the pinning to the lattice, have been questioned over the years [87] and cannot be taken for granted. The precession issue is now compelling and closely related to the ultimate glitch models as well.

- The usefulness of anisotropic models should be established. It is not enough to label them as interesting formal problems, but rather to advance towards the observables that may be revealing anisotropic interiors. As noted above, numerical simulations of the type already available for isotropic models should be attempted and determine, for example, the topology of the field and its maximum value.

A new round of high-precision observations is coming [88], and will surely bring novel perspectives to the exciting field of neutron star astrophysics. The true science of the 21st century certainly lies ahead for present practitioners and newcomers.

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