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Modeling the structure of magnetic fields in Neutron Stars: from the interior to the magnetosphere

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Abstract. The phenomenology of the emission of pulsars and magnetars depends dramatically on the structure and properties of their magnetic field. In particular it is believed that the outbursting and flaring activity observed in AXPs and SRGs is strongly related to their internal magnetic field. Recent observations have moreover shown that charges are present in their magnetospheres supporting the idea that their magnetic field is tightly twisted in the vicinity of the star. In principle these objects offer a unique opportunity to investigate physics in a regime beyond what can be obtained in the laboratory. We will discuss the properties of equilibrium models of magnetized neutron stars, and we will show how internal and external currents can be related. These magnetic field configurations will be discussed considering also their stability, relevant for their origin and possibly connected to events like SNe and GRBs. We will also show what kind of deformations they induce in the star, that could lead to emission of gravitational waves. In the case of a twisted magnetosphere we will show how the amount of twist regulates their general topology. A general formalism based on the simultaneous numerical solution of the general relativistic Grad-Shafranov equation and Einstein equations will be presented.

1. Introduction

Neutrons Stars (NSs) are known to show a diverse phenomenology, that allows us to separate them into several classes. Among these classes, Anomalous X-Ray Pulsars (AXPs) and Soft Gamma-ray Repeaters (SGRs) have attracted attention because of their extraordinary energetic properties: a persistent X-ray emission with luminosities $L_X \sim 10^{33} - 10^{36} \text{ erg s}^{-1}$; flaring activity with X-ray bursts lasting $\sim 0.1 - 1 \text{ s}$ and with peak luminosities $\sim 10^{40} - 10^{41} \text{ erg s}^{-1}$, and in a few cases violent events, known as giant flares, during which an amount of energy $\sim 10^{44} - 10^{46} \text{ erg}$ is released [1, 2, 3].

Today SGRs and AXPs are grouped in the same class of NSs called *magnetars* [4, 5]. These are young (with a typical age of 10^4 yr), isolated NSs with rotational period in the range $\sim 2 - 12 \text{ s}$, and with a typical magnetic field in the range $10^{14} - 10^{15} \text{ G}$ [6]. Since they are slow rotators, spin-down energy losses cannot power their emission, which is instead believed to come from the dissipation and rearrangement of their magnetic energy.

The magnetic field has important implication on the way NSs manifest themselves in the electromagnetic spectrum. In particular for Pulsars, models of the outer magnetosphere have been developed since the '60 [7], up to the present day [8]. On the other hand, the interest on



the interior structure has been mostly driven by questions of nuclear and theoretical physics, especially their Equation of State (EoS) [9, 10] and their cooling properties [11, 12].

The simultaneous presence of high density, strong gravity, and strong magnetic fields makes magnetars a unique environment. The study of the properties and geometry of the internal magnetic field in NSs is thus an important step towards a complete understanding of magnetars. The analysis of equilibrium configurations has mainly focused on understanding the effects of the magnetic field on the structure of the star. Strong magnetic fields deform the star, and such deformations, in conjunction with fast rotation, could lead to emission of Gravitational Waves (GW) [13, 14]. Particular efforts have been recently aimed at investigating the stability of various magnetic configurations. However due to the complexity of the problem, models have been worked either in Newtonian regime [15, 16, 17], or in GR with a perturbative approach [18, 19, 20], and with currents purely confined to the interior. Only recently [21, 22] they have been worked out in the fully non-linear GR regime, including the possibility of currents extending outside into a magnetosphere [23].

We present and review here a study conducted by our group, aiming at modeling magnetized NSs in general relativity. Our approach is based on the simultaneous solution of the Einstein equations for the GR metric, of the general-relativistic Euler equation for the hydromagnetic equilibrium, and the general-relativistic Grad-Shafranov equation for the magnetic field structure, using a formalism that allows electric currents to flow outside the star. We have investigated several new functional forms for the current distribution, and studied the properties of the resulting magnetic field.

2. Solving Einstein equations

Given a generic spacetime, the line element can be written as [24, 25]:

$$ds^2 = -\alpha^2 dt^2 + \gamma_{ij}(dx^i + \beta^i dt)(dx^j + \beta^j dt), \quad (1)$$

where α is called the *lapse* function, β^i is the *shift vector*, γ_{ij} is the *three-metric*, and $i, j = r, \theta, \phi$, if a spherical coordinate system $x^\mu = (t, r, \theta, \phi)$ is chosen. The assumptions of *stationarity* and *axisymmetry* imply that all metric terms are only a function of r and θ .

For neutron stars endowed with an axisymmetric magnetic field the metric can be approximated to a high degree of accuracy as *conformally flat* [26], such that in spherical coordinates:

$$ds^2 = -\alpha^2 dt^2 + \psi^4(dr^2 + r^2 d\theta^2 + r^2 \sin^2 \theta d\phi^2), \quad (2)$$

where ψ is the conformal factor, and for simplicity we have neglected frame dragging given that magnetar are typically slow rotators.

The conformally flat condition (CFC) allows us to cast Einstein's equations in a simpler and numerically stable form and, as a consequence, it can handle stronger fields and deformations without compromising the accuracy of the results as we will discuss. With this approximation Einstein's equations reduce to the following Poisson-like equations:

$$\Delta\psi = -[2\pi\psi^6(e + B^2/2)]\psi^{-1}, \quad (3)$$

$$\Delta(\alpha\psi) = [2\pi\psi^6(e + B^2/2) + 2\pi\psi^6(6p + B^2)\psi^{-2}](\alpha\psi), \quad (4)$$

where Δ is the standard Laplacian operator in spherical coordinate while e , p and B^2 are respectively the energy density, the pressure and the magnetic field energy density as measured in the lab frame.

For the non-linear Poisson-like equations Eq. 3-4 we employ the XNS algorithm [27, 28, 29]. The code is designed to compute hydromagnetic equilibria even in the presence of rotation.

Axisymmetric solutions are searched in terms of a series of spherical harmonics $Y_l(\theta)$:

$$q(r, \theta) := \sum_{l=0}^{\infty} [A_l(r) Y_l(\theta)]. \quad (5)$$

The Laplacian can then be reduced to a series of radial 2nd order boundary value ODEs for the coefficients $A_l(r)$ of each harmonic, which are then solved using tridiagonal matrix inversion. This procedure is repeated until convergence, using in the source term the value of the solution computed at the previous iteration. We found that 20 spherical harmonics for the elliptic solvers and a grid in spherical coordinates in the domain $r = [0, 30]$ km, $\theta = [0, \pi]$, with 250 points in the radial direction and 100 points in the angular one, are sufficient to achieve a numerical accuracy of the order of 10^{-3} . Comparison with results already present in literature for fast unmagnetized rotators, shows that the CFC approximation is correct to an accuracy $\sim 10^{-3}$ even for highly deformed stars.

3. Magnetic equilibria

The only non-vanishing equation of the static GRMHD system is the Euler equation in the presence of an external electromagnetic field:

$$\partial_i p + (e + p) \partial_i \ln \alpha = L_i := \epsilon_{ijk} J^j B^k, \quad (6)$$

with $i = r, \theta$, and where L_i is the Lorentz force and $J^i = \alpha^{-1} \epsilon^{ijk} \partial_j (\alpha B_k)$ is the conduction current. Assuming a *barotropic* EoS $p = p(\rho)$, $e = e(\rho)$ (ρ is the rest mass density), we find

$$\partial_i \ln h + \partial_i \ln \alpha = \frac{L_i}{\rho h}, \quad (7)$$

where the specific enthalpy is $h := (e + p)/\rho$. Integrability requires the existence of a scalar function $\mathcal{M}$ such that $L_i = \rho h \partial_i \mathcal{M}$.

In the case of a purely toroidal field, the Lorentz force is conveniently written in terms of αB_ϕ , and the Euler equation reads

$$\partial_i \ln h + \partial_i \ln \alpha + \frac{\alpha B_\phi \partial_i (\alpha B_\phi)}{\rho h \alpha^2 \psi^4 r^2 \sin^2 \theta} = 0, \quad (8)$$

such that

$$B_\phi = \alpha^{-1} \mathcal{I}(\mathcal{G}), \quad \mathcal{M}(\mathcal{G}) = - \int \frac{\mathcal{I}}{\mathcal{G}} \frac{d\mathcal{I}}{d\mathcal{G}} d\mathcal{G}, \quad \text{with} \quad \mathcal{G} = \rho h \alpha^2 \psi^4 r^2 \sin^2 \theta. \quad (9)$$

Among all possible functional choices we have selected a *magnetic barotropic law*:

$$\mathcal{I}(\mathcal{G}) = K_m \mathcal{G}^m, \quad \mathcal{M}(\mathcal{G}) = - \frac{m K_m^2}{2m - 1} \mathcal{G}^{2m-1}. \quad (10)$$

where the parameter m plays the role of the polytropic index for magnetic pressure.

In the case where a poloidal magnetic field is present a formulation based on the so-called *Grad-Shafranov equation* for the toroidal component of the vector potential A_ϕ is more convenient. In this case:

$$L_i = \rho h \partial_i \mathcal{M} = \rho h \frac{d\mathcal{M}}{dA_\phi} \partial_i A_\phi \rightarrow \ln \left(\frac{h}{h_c} \right) + \ln \left(\frac{\alpha}{\alpha_c} \right) - \mathcal{M}(A_\phi) = 0, \quad (11)$$

where constants are calculated at the stellar center. Moreover, the ϕ component of the Lorentz force, which must also vanish, implies

$$B_\phi = \alpha^{-1} \mathcal{I}(A_\phi). \quad (12)$$

Introducing $\sigma := \alpha^2 \psi^4 r^2 \sin^2 \theta$ and $\tilde{A}_\phi := A_\phi / (r \sin \theta)$ and the new operator

$$\tilde{\Delta}_3 := \Delta - \frac{1}{r^2 \sin^2 \theta} = \partial_r^2 + \frac{2}{r} \partial_r + \frac{1}{r^2} \partial_\theta^2 + \frac{1}{r^2 \tan \theta} \partial_\theta - \frac{1}{r^2 \sin^2 \theta}, \quad (13)$$

for which $\tilde{\Delta}_3 \tilde{A}_\phi = \Delta_* A_\phi / (r \sin \theta)$ (it coincides with the ϕ component of the *vector laplacian* in spherical coordinates), after some calculations we retrieve the *Grad-Shafranov* equation for the magnetic flux function A_ϕ :

$$\tilde{\Delta}_3 \tilde{A}_\phi + \frac{\partial A_\phi \partial \ln(\alpha \psi^{-2})}{r \sin \theta} + \psi^8 r \sin \theta \left(\rho h \frac{d\mathcal{M}}{dA_\phi} + \frac{\mathcal{I}}{\sigma} \frac{d\mathcal{I}}{dA_\phi} \right) = 0. \quad (14)$$

Again we have investigated several functional forms for the scalar functions $\mathcal{M}$ and $\mathcal{I}$, including non-linear terms that allow us to model different current distributions inside the star. In principle one can set the function $\mathcal{I}$ to vanish outside the star, leading to the so called *twisted torus configurations*, where a twisted magnetic flux rope is present inside the star. On the other hand if one allows $\mathcal{I}$ to be non-zero also outside the star, one finds models with a so called *twisted magnetosphere*.

Interestingly the Grad-Shafranov equation Eq. 14 can be reduced to the solution of a non-linear vector Poisson equation, which is formally equivalent to the elliptic equations that one needs to solve in the CFC approximation. It is thus possible to use the same algorithm, with a combination of vector spherical harmonics decomposition for the angular part, and matrix inversion for the radial part, that was used in the metric solver [27].

4. Results

We begin by describing the results for purely toroidal magnetic fields. By modifying the currents profile it is possible to obtain different configurations where the magnetic field can be concentrated either toward the center or toward the edge of the star. In Fig. 3 we show the outcome for different magnetic field configurations. In all cases the maximum strength of the magnetic field is the same as well as the mass of the Neutron Star. However it is immediately evident that the deformation of the star is quite different, being much stronger for fields concentrated at the center. Given that a toroidally dominated configuration is expected to result from the core-collapse of a rapidly rotating core, due to differential rotation during infall, our results show that the important parameter is not just the global strength of the differential rotation, but its profile, which can be related to the pre-collapse evolution of the progenitor.

In general for purely toroidal models we find that, as the magnetic field increases the star inflates and its radius grows. Interestingly this leads to a saturation of the maximum value that the magnetic field can reach inside the star. Increasing the magnetization leads to a bigger star and not a stronger field. We also find that the effect of the magnetic field is more pronounced in low mass stars, while more compact configurations, of higher central density, tend to show smaller deformations, but can support stronger fields.

Models with purely poloidal field instead tend to show an oblate deformation. Again it is possible to modify the current distribution to achieve configurations where the field is distributed differently. Interestingly now, for fields concentrated toward the edge of the star, the deformation tends to be larger than in the case of magnetic field concentrated toward the center. It is also possible to obtain configurations where the magnetic field at the surface can differ substantially

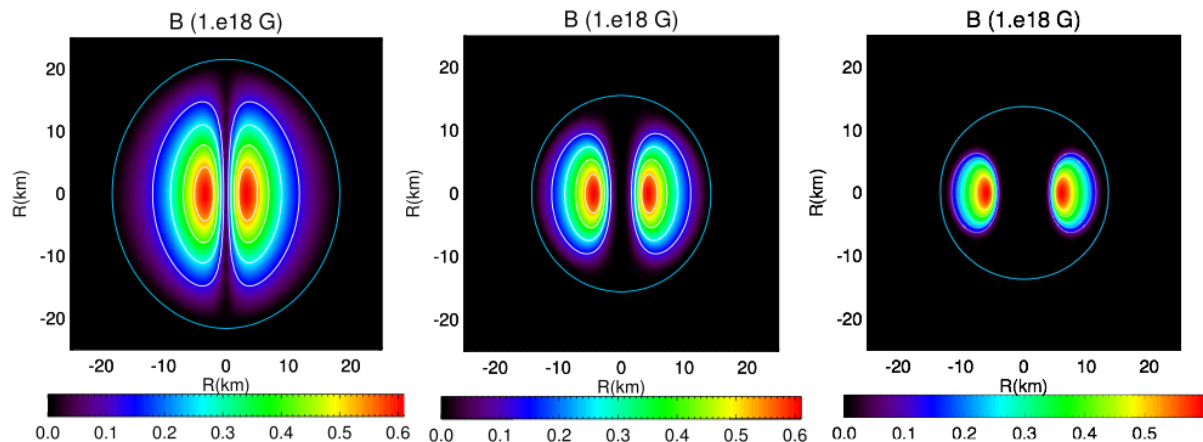


Figure 1. Neutron stars with purely toroidal field. Panels show the strength of the magnetic field for a star of mass $M = 1.68M_{\odot}$. From left to right $m = 1, 2, 4$. The blue line is the stellar surface.

from a simple dipole shape. By adopting different prescriptions, we can make it either higher at the equator, or concentrated toward the axis, in a configuration where the bulk of the star is demagnetized. Such configurations are reminiscent of recent full multidimensional results in core-collapse simulations, where demagnetized neutron stars are obtained due to turbulent flux expulsion [30]. For very strong magnetic fields it is possible to obtain even configurations where the density maximum is displaced from the center due to magnetic field support.

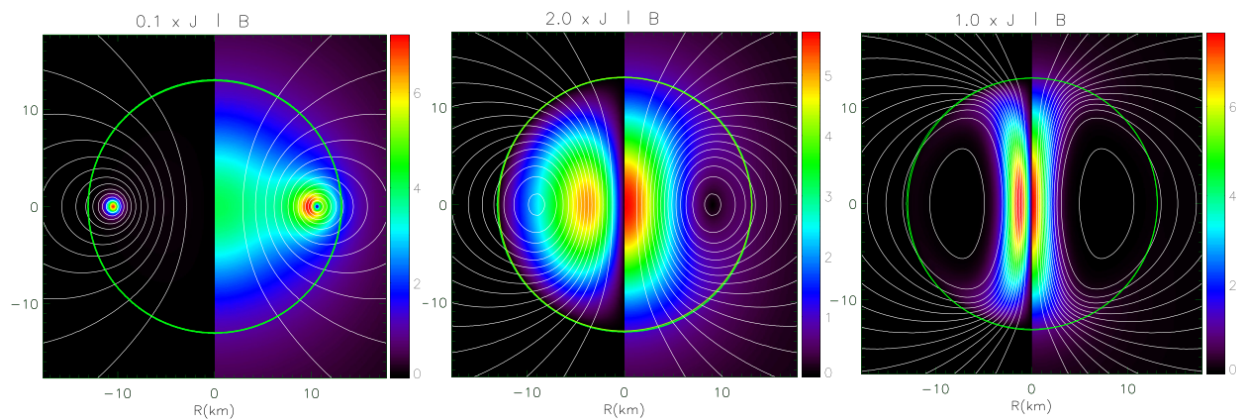


Figure 2. Neutron stars with purely poloidal field. Panels show on the right the strength of the magnetic field (units $10^{14}G$), and on the left the strength of the currents, for a star of mass $M = 1.68M_{\odot}$. The left panel shows the effect of additive non-linear currents that concentrate the field toward the surface, the right one the effect of subtractive currents that concentrate the field toward the axis. The blue line is the stellar surface.

We have computed Twisted-Torus configurations in the non-perturbative regime. These mixed configurations are favored based on stability arguments. The toroidal component can reach a strength comparable with the poloidal one but it is always energetically subdominant. The deformations are almost completely due to the poloidal field, acting on the interior. Several functional forms for the current distribution were used, but the system was always found to

saturate to configurations where the energy of the toroidal component is at most 10% of the total magnetic energy. The main reason for this is that to increase the toroidal magnetic field, one needs to rise also the toroidal currents (the two being related due to equilibrium requirement in the GS equation), which act to change the structure of the poloidal field, reducing the volume occupied by the toroidal field. It is possible to overcome this problem only by sacrificing global dynamical equilibrium in the outer layers of the star, or in the case of non-barotropic EoS. Interestingly it looks like such energy ratio depends more on the stratification of the NS than on the current distribution.

More recently [23] models were built with currents extending also outside the neutron star into a twisted magnetosphere. In the case of magnetars there is an increasing set of observational evidence pointing to the fact that their magnetosphere is endowed with a highly twisted magnetic field. This is strongly suggested by the features of their persistent X-ray spectra, which are well fitted by a blackbody-like component at $kT \sim 0.5$ keV, likely thermal emission from the neutron star surface, joined with a power-law tail that becomes dominant above 10 keV [31]. The latter can be explained in terms of resonant cyclotron scattering of the thermal photons by magnetospheric particles [32, 33]. Typically, in the standard reference model [32] the magnetosphere is described in terms of a self-similar, globally twisted, dipolar magnetic field. This model has been refined to account for higher order multipoles [34], in response to observational indications of a local, rather than global, twist in the magnetosphere [35, 36]. Recently this scenario has been strengthened also by the detection of a proton cyclotron feature in the X-ray spectrum of the “low-field” magnetar SGR 0418+5729 which is compatible with a strong, but localized, toroidal field of the order of 10^{15} G [37].

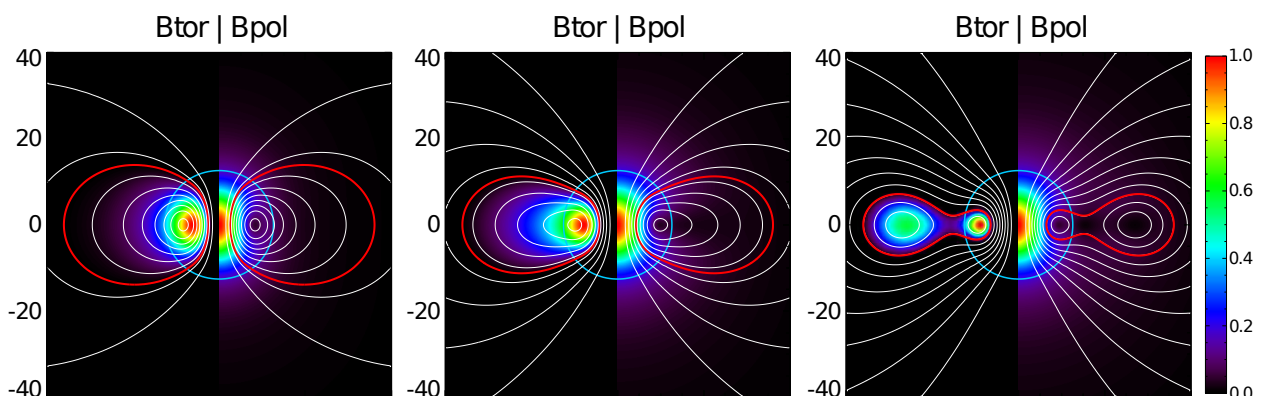


Figure 3. Neutron stars with twisted magnetospheres. Panels show on the left the strength of the toroidal component of the magnetic field, and on the right the strength of the poloidal component (normalized to the maxima). From left to right models have progressively higher level of twist, showing the transition from a configuration of topologically connected magnetic regions to a configuration where a detached magnetospheric rope is realized. The blue line is the stellar surface.

All the equilibrium models we obtained are energetically dominated by the poloidal component of the magnetic field, the energy of the external toroidal magnetic field is, at most, 25% of the total magnetic energy of the magnetosphere. This result is similar to what is found when the twisted field is fully confined within the star. The amount of twist in the magnetosphere can be regulated essentially by the amount of poloidal non-linear currents that are imposed to the system. When the non-linear current terms are weak, the magnetic field lines are inflated outward by the toroidal magnetic field pressure and the twist of the field lines extends also to higher latitudes. The result is a single magnetically connected region, where all field lines have

footpoints attached to the stellar surface. As the currents increase the effects of the non-linearity get stronger. This not only increases the twist of the near-surface magnetic field but also leads to the formation of a disconnected magnetic island, reminiscent of the so-called plasmoids often found in simulations of the solar corona. This regime and these topologies are very likely to be unstable. Only magnetic ropes confined close to the stellar surface satisfy the Kruskal-Shafranov condition for stability against the development of kink. For all the configurations computed, the internal linear current is always greater than the external one reaching similar values only for configurations where the energy ratio reaches a maximum. Apparently, as one tries to rise the external currents, the system self-regulates inducing a change in the topology of the distribution of the magnetic field and the associated external current. As a consequence there is a maximum twist that can be imposed to the magnetosphere, before reconnection and plasmoid formation sets in. We found moreover that external currents contribute to the net dipole without affecting too much the strength of the magnetic field at the surface.

Magnetized rapidly rotating neutron stars have been invoked as a promising engine for both long duration GRBs [38, 39], and for short duration GRBs [40]. The energy losses due to the emission of a relativistic magnetically driven wind can explain the bulk of known events, but requires in general a high efficiency to convert the rotational energy of the proto-neutron star into wind kinetic energy. The presence of a strong magnetic field $\geq 10^{15}\text{G}$, is however expected to induce deformations in the neutron star, that can lead to copious emission of gravitational waves for rapid rotators [41, 13]. The energy loss via gravitational waves will then compete with the electromagnetic emission of the wind [14]. It is thus crucial to evaluate the level of quadrupolar deformation induced by the magnetic field. We have estimated the magnitude of this quadrupolar deformation for various cases, both for poloidal and toroidal magnetic fields, and various current and magnetic field distributions.

We find that, for a NS with a typical mass of $\sim 1.5M_{\odot}$, in the case of a purely toroidal magnetic field, the quadrupolar deformation scales as $\|\epsilon_B\| \simeq 5 \times 10^{-5} B_{16}^2/m$, in term of the maximum value of the magnetic field in units of 10^{16}G . Clearly models with a large m where the magnetic field is concentrated toward the NS surface, can have deformations that are even an order of magnitude smaller than the case $m = 1$ where the field is more concentrated toward the center. For neutron stars with a purely poloidal magnetic field, the quadrupolar deformation is found to scale as $\|\epsilon_B\| \simeq (1 - 5) \times 10^{-5} B_{16}^2$, where the upper limit is for the case of additive currents, with magnetic field concentrated in the outer stellar layers, and the lower bound for subtractive currents where the field is concentrated toward the axis, and the bulk of the star is weakly magnetized. This is the opposite trend with respect to the one found for the toroidal case. In our mixed twisted torus configurations, the deformation is always oblate, and dominated by the poloidal field, which is the energetically dominant component. However, such limitation is probably due to the barotropicity assumption in the equation of state. If this assumption is relaxed, in principle systems can be build with a large fraction of magnetic energy into the toroidal component. This cannot be tested with our algorithm, where barotropicity is a key assumption. However, if we compare the deformation derived from purely toroidal field, with the one in the purely poloidal case, it is evident, that typical twisted torus configurations, where the toroidal field is confined to small regions close to the surface (reminiscent of cases with large $m > 10$), while the poloidal component threads the entire star, will likely have a quadrupolar deformation dominated by the poloidal magnetic field unless the toroidal component is at least a few times stronger than the poloidal one. Substantial quadrupolar deformation in this case will likely require a toroidal field at least an order of magnitude stronger than the poloidal one.

5. Conclusions

We have presented here some recent results in the development of numerical models for equilibrium configurations of magnetized neutron stars in the fully non-linear general relativistic

regime. This allows us to go beyond the simplified perturbative regime (where often only the fluid variables are perturbed while the metric terms are kept fixed), and to derive the correct absolute scaling that we can then extrapolate to those regimes more representative of physical situations. The algorithm we have developed has proved to be robust and efficient, also in handling extremely deformed objects, giving results that are in agreement with more sophisticated techniques. Based on this approach a publicly available software written in FORTRAN90 has been released, together with visualization and data reduction tools written in IDL, and can be downloaded at www.arcetri.astro.it/science/ahead/XNS/. Here we have shown how, by choosing different functional forms for the distribution of currents, it is possible to realize different magnetic field configurations. We have investigated how the magnetic field distribution affects the deformation of the star, in the context of possible gravitational wave emission from fast rotators. We have shown that, at least within a barotropic formalism for the equation of state, it is not possible to build configurations of mixed poloidal-toroidal field, where the toroidal component is energetically dominant, and that the equation of state itself (in particular the stratification in the outer part of the neutron star) is important. Given that toroidal dominated configurations are expected following the collapse of rapidly rotating cores, this suggests that either NSs are out of magnetic equilibrium, or the EoS cannot be described in terms of zero temperature matter at nuclear equilibrium. This might have important consequences for the magneto-thermal evolution of NS, and magnetars in particular. Finally we have presented also models where the currents extend outside the neutron star into a twisted magnetosphere. These configurations are thought to be more representative of the physical regime characterizing magnetars. The code we have developed can also model rotating systems, again both for poloidal and toroidal configurations (in the latter case it is possible to model also a differentially rotating profile) taking into account the fact that in GR rotating systems have an induced electric field that cannot be neglected, as it is usually done for non-relativistic MHD. We hope in the future to be able to evaluate the observable signatures of the magnetic field distributions that we have computed, either in the form of cyclotron absorption features, or in the polarized pattern that the emitted radiation acquires as it travels in the magnetosphere. This will allow us to check if it is possible to constrain the magnetic geometry or maybe even GR effects with future missions for X-ray polarimetry [42].

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