Magnetic Field Instabilities in Neutron Stars

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Received 2013 Dec 20, accepted 2014 Jan 14

Key words gravitational waves – magnetohydrodynamics (MHD) – relativity – stars: magnetic fields – stars: neutron

Magnetic fields represent a crucial aspect of the physics and astrophysics of neutron stars. Despite its great relevance, the internal magnetic field configuration of neutron stars is very poorly constrained by the observations, and understanding its properties is a long-standing theoretical challenge. The investigation on the subject is focused on the search for those magnetic field geometries which are stable on several Alfvèn timescales, thus constituting a viable description of neutron star interiors. Assesing the stability of a given magnetic field geometry is therefore an important part of this research. So far only simple configurations, such as the purely poloidal or purely toroidal ones, have been studied in detail in perturbation theory and, most recently, by means of nonlinear magnetohydrodynamic simulations. Here we review the basic results of the state-of-the-art general relativistic nonlinear studies, discussing the present status of the field and its future directions.

1 Introduction

Neutron stars (NSs) are endowed with extremely strong long-lived magnetic fields, reaching surface (polar) strengths of 10^{13} G for ordinary NSs (including the most common radio pulsars) and 10^{15} G for highly magnetized NSs, or *magnetars* (Duncan & Thompson 1992; Mereghetti 2008), as mainly inferred via the simple dipole formula. Internal fields might be even stronger, possibly by one order of magnitude or more. Magnetic fields of such intensity affect the physical properties of NSs and play a fundamental role in the processes through which they are currently observed, from dipole radiation to magnetar flares. Moreover, the magnetically-induced quadrupolar deformations of NSs make them an interesting source of gravitational waves (Bonazzola & Gourgoulhon 1996; Cutler 2002), potenitally detectable in the near future.

The amount of magnetic energy stored inside a NS and the internal magnetic field geometry are known to represent key elements in determining its evolutionary path and emission properties. Recent results of magneto-thermal evolution studies (Viganò et al. 2013 and references therein) confirm this idea, showing how the evolution of a magnetized NS may proceed on very different timescales and with distinct features (*e.g.* the presence or absence of a bursting activity), depending on the internal magnetic energy and distribution of electric currents. Despite many aspects of our present modelling and understanding of NSs depend directly on the internal magnetic field energy and geometry (including the gravitational wave emission mechanism mentioned above), this feature is not constrained by direct observations, which only provide information on the external magnetic field. This obviously constitutes a very strong limitation, justifying the growing effort devoted to build realistic models decribing the possible magnetic field configurations realized in a NS.

A widely accepted scenario for the evolution of a magnetized NS pictures the following stages: (i) the newly-born NS is initially a highly convective and differentially rotating hot fluid; (ii) in a very short timescale (of the order of seconds to minutes) convection and differential rotation are damped, the star cools down and rearranges towards a magnetohydrodynamic (MHD) equilibrium; temperature keeps decreasing and within few hours it reaches the critical values for the formation of a solid crust and the onset of superfluidity, both in the range $10^9 - 10^{10}$ K; (iii) the following evolution proceeds on much longer dissipative timescales ($10^3 - 10^6$ years). In the intermediate stage, while the star is still completely fluid and well described as a non-superfluid ideal (electric) conductor, the magnetic field evolves on the Alfvèn timescale, which typically lies in the range $\tau_A \sim 0.01 - 10$ s depending on the magnetic field strength. Therefore, there is ample time for the magnetized fluid to reach a stable MHD equilibrium or, alternatively, to lose almost all of its magnetic energy (*e.g.* in electromagnetic emission) before the crust and/or superfluidity appear. According to the above scenario, the observation of long-lived magnetic fields represents an evidence that, in this intermediate stage, a configuration has been reached which is stable on Alfvèn timescales. A natural apporach to constrain the properties of the internal magnetic field of NSs is then to (i) consider the widest range of possible equilibrium configurations in an ideally conducting fluid NS (*i.e.* in the conditions met during the "pre-crust" stage) which are compatible with the observations and (ii) to assess their stabilty on Alfvèn timescales. In case stable configurations are found these would represent a viable description of a magnetized NS at the time of crust formation, setting realistic initial conditions for long-term magneto-thermal evolution studies, where the dissipative

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processes are taken into account and the effects of superfluidity/superconductivity are included. Since in the long-term evolution the main features of the internal magnetic field (*e.g.* the distribution of energy in toroidal and poloidal components, the multipolar structure and the overall energy/strength) are modified very slowly, the intial configuration likely represent also a good qualitative description of the internal magnetic field in the relatively young NSs observed.

Since the early work of Chandrasekhar & Fermi (1953) a number or analytical and numerical studies have been devoted to the construction of equilibrium models of magnetized NSs, under the common assumpitions of ideal MHD and pure-fluid matter, well-suited to describe the conditions occurring before the formation of a solid crust and the onset of superfluidity. These models focused at first on the simple purely poloidal and purely toroidal magnetic field geometries. However, already from the early analytical work on nonrotating magnetized stars (Markey & Tayler 1973; Tayler 1973; Wright 1973) there has been growing evidence that these simple geometries would suffer from the so-called Tayler (or kink) instability, acting on Alfvèn timescales. The unstable nature of purely poloidal and purely toroidal geometries was confirmed more recently in Newtonian numerical simulations in the linear regime (Lander & Jones 2011a,b) and, for main-sequence stars, via nonlinear simulations (Braithwaite 2006, 2007). Only in the very last years, the same system was studied for the first time by means of nonlinear MHD simulations in general relativity (Ciolfi et al. 2011; Ciolfi & Rezzolla 2012; Kiuchi et al. 2008, 2011; Lasky et al. 2011, 2012), further verifying the presence of a hydrodynamic instability in the purely poloidal and purely toroidal cases and providing important indications on the subsequent nonlinear rearrangement of magnetic fields. In this paper (Section 2) we discuss in some detail the setup and basic results of these simulations, which represent the state-of-the-art of the nonlinear investigation on the stability of magnetic field configurations in NSs.

All the above stability studies converged to the idea that any long-lived magnetic field configuration in a NS has to consist of a mixture of poloidal and toroidal field components. Among the mixed-field configurations it is worth mentioning the *twisted-torus* geometry, which recently emerged as a good candidate for NS interiors. It consists of an axisymmetric field where the poloidal component extends throughout the entire star and to the exterior, while the toroidal one is confined inside the star, in the torus-shaped region where the poloidal field lines are closed (see *e.g.* Fig. 1,2 of Ciolfi & Rezzolla 2013). Important indications are in favour of the twisted-torus configuration (see discussion in Ciolfi & Rezzolla 2013), including the results of Newtonian simulations performed by Braithwaite & Nordlund (2006), where this geometry emerged as the final outcome of the evolution of initial random fields in a nonrotating fluid star. Those simulations where adapted to study main-sequence stars, while the equivalent evidence in a NS and in general relativity is still missing; nevertheless, the results triggered a growing interest in twisted-torus geometries, which were recently considered in several equilibrium models of magnetized NSs, both in Newtonian (Fujisawa et al. 2012; Glampedakis et al. 2012; Lander & Jones 2009, 2012; Tomimura & Eriguchi 2005; Yoshida & Eriguchi 2006) and general relativistic frameworks (Ciolfi et al. 2009, 2010). All the proposed equilibrium solutions, however, found a common limitation to poloidal-dominated geometries, with a magnetic energy in the toroidal component always $\lesssim 10\%$, which is in contrast with the general expectation of a higher toroidal field contribution (see Ciolfi & Rezzolla 2013); moreover, there are already indications that poloidal-dominated configurations are unstable on Alfvèn timescales (Braithwaite 2009; Lander & Jones 2012). A solution to this problem has been offered most recently in Ciolfi & Rezzolla (2013), where it is shown how a different prescription for the electric currents allows to expand the space of known solutions to a much higher toroidal field content (without invoking surface discontinuities in the magnetic field, as in Fujisawa & Eriguchi 2013). Twisted-torus configurations with a high toroidal magnetic energy content (*i.e.* $> 10\%$) are certainly among the most promising candidates for stability. Future nonlinear studies, so far limited to simple purely poloidal/toroidal geometries, will possibly provide the missing evidence.

Apart from the search for long-lived magnetic field configurations in NSs, there is a second main motivation for studying the nonlinear MHD evolution of a magnetized NS. The global rearrangement of magnetic fields induced by a hydromagnetic instability (as the one affecting the purely poloidal/toroidal configurations) is a violent, strongly dynamical process, and soon after the magnetar model was proposed (Duncan & Thompson 1992) it was suggested as a trigger mechanism for the giant flares of magnetars (Thompson & Duncan 1995, 2001). This “internal rearrangement scenario” still represents one of the two leading models to explain the phenomenology observed in magnetar giant flares, the other one involving a large-scale rearrangement of magnetic fields in the magnetosphere surrounding the star (Gill & Heyl 2010; Lyutikov 2003, 2006). Investigating the dynamics associated with hydromagnetic instabilities in NSs can provide important constraints on the electromagnetic and gravitational wave emissions to be expected, according to the internal rearrangement scenario, in coincidence with a giant flare event. Moreover, by comparing with the electromagnetic luminosities and emission timescales measured in the three giant flares already observed, nonlinear simulations can help establish the viability of a hydromagnetic instability as a trigger mechanism. In Section 3 we discuss the results obtained in this direction in the recent nonlinear general relativistic MHD studies of the instability of purely poloidal magnetic fields in NSs (Ciolfi et al. 2011; Ciolfi & Rezzolla 2012; Lasky et al. 2012; Zink et al. 2012). Finally, in Section 4 we give our conclusions.

2 General relativistic MHD simulations of the Tayler instability

In this Section we discuss in more detail the recent studies on the stability of magnetized NSs via nonlinear general relativis-

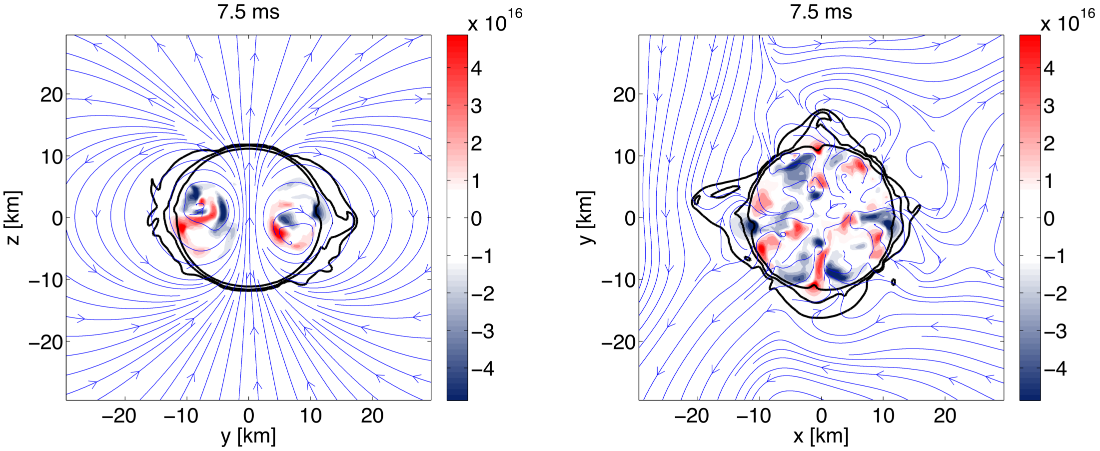

Fig. 1 Instability of a purely poloidal field in a magnetized NS with an initial polar magnetic field strength of 6.5×10^{16} G. Left and right panels show respectively the meridional and equatorial view of the system at $t = 7.5$ ms, time at which the instability has fully developed. Vector lines illustrate the (global) magnetic field lines, while the colors show the intensity (in Gauss) of the toroidal magnetic field only; also reported are three rest-mass isodensity contours near the stellar surface, corresponding to $(0.02, 0.2, 2) \times 10^{13}\,\mathrm{g/cm^3}$.

tic MHD simulations. So far, this investigation only covered the simple purely poloidal and purely toroidal configurations, confirming the presence of the Tayler instability.

The first three-dimensional general relativistic MHD simulations of the poloidal field instability in NSs were presented in two parallel works (Ciolfi et al. 2011; Lasky et al. 2011), both followed by a more extended investigation (Ciolfi & Rezzolla 2012; Lasky et al. 2012). These studies employ analogous initial data, produced with the multi-domain spectral-method code `LORENE` (Bocquet et al. 1995): an axisymmetric magnetizd NS with a purely poloidal magnetic field, composed of a barotropic fluid obeying a simple polytropic equation of state with index $n = 1$, and having a typical mass of $1.4\ \mathrm{M}_\odot$ (or slightly smaller) in the unmagnetized limit. The magnetic field strength at the pole varies by about one order of magnitude around a fiducial value of $\sim 10^{16}$ G. Such high magnetic field strength is chosen to shorten the evolution timescale of the system, making the simulations computationally feasible. Even if this exceeds by far the measured values even for magnetars, most of the results can be extrapolated back to smaller (and more realistic) magnetic field strengths. Despite the differences in the numerical codes employed, the numerical setup (*e.g.* size of the computational domain and boundary conditions) and the treatment of magnetic fields outside the star, the initial development of the instability shows perfect agreement between the findings of Ciolfi et al. (2011); Ciolfi & Rezzolla (2012) and of Lasky et al. (2011, 2012). Relevant differences emerge later in the evolution, as the nonlinear rearrangement of the magnetic field proceeds. In what follows we focus on the results of Ciolfi et al. (2011) and Ciolfi & Rezzolla (2012), pointing out similarities and differences with Lasky et al. (2011, 2012).

Fig. 1 shows two snapshots of the evolution for a representative simulation among those presented in Ciolfi & Rezzolla (2012). In this case the initial polar magnetic field strength is 6.5×10^{16} G. Left and right panels give respectively the meridional and equatorial view of the system at 7.5 ms, corresponding to the most violent phase of the evolution, shortly after the instability has fully developed and the nonlinear rearrangement of the magnetized NS has begun. As predicted by previous linear studies, the Tayler instability first occurs in the surrounding of the neutral line (in the closed-line region) and forces the field to produce there a toroidal component. In Fig. 2 we report the evolution of poloidal and toroidal magnetic energies for the same simulation and for one with a smaller initial magnetic field strength. The different stages of the evolution are clearly distinguishable: (i) initially, the field is purely poloidal, but as the instability takes place the toroidal component starts to grow exponentially; (ii) when a comparable local strength has been reached (around one Alfvèn crossing time) the instability saturates and the nonlinear evolution begins; the poloidal field energy drops violently while the toroidal energy experiences a smaller variation, resulting in a growing toroidal-to-poloidal energy ratio; (iii) after the first violent rearrangement, the system keeps evolving on a much longer timescale. It is worth stressing that the initial location of the instability, the production of a toroidal component and the saturation timescales are in full agreement with the results of Lasky et al. (2011, 2012), also meeting all the expectations from previous analytic and numerical studies.

The advantage of nonlinear simulations is that, in addition to providing a confirmation to the predictions of the linear analysis, they allow to follow the evolution of the system beyond the instability saturation, giving hints on the preferred state of the system. The end result of the (relatively long) simulations performed in Ciolfi & Rezzolla (2012) gave no evidence for a stable magnetic field configuration (although we cannot exclude that a stable condition would be reached on much longer timescales). Nevertheless, some important indications were obtained. First, the system revealed a clear tendency to migrate towards a configuration where the magnetic energy is equally distributed in the poloidal and toroidal components. This result was also reported in Lasky et al. (2012). Secondly, the total magnetic helicity of the system, which is zero by definition at the beginning, was always found to grow up to significant values (see discussion in Ciolfi & Rezzolla 2012), suggesting that this quantity might play a crucial role in stabilizing the magnetic field. The natural conclusion is that both the equipartition of magnetic energy in poloidal and toroidal fields and a significant amount of magnetic helicity are likely features of any stable configuration.

The strong loss of magnetic energy that the magnetized NS experiences at the beginning of the nonlinear phase of the evolution, right after the exponential growth of the instability has saturated, is mainly associated with the diffusion of magnetic fields outside the NS. The internal dynamics imposes a rapid change of the magnetic field at the stellar surface and, as a consequence, a reconfiguration of the external field. In a realistic scenario, this process would load the magnetosphere with magnetic energy and ultimately cause a strong electromagnetic emission. In Ciolfi et al. (2011) and Ciolfi & Rezzolla (2012), in order to mimic this external behaviour and provide more suitable boundary conditions for the internal evolution, a resistive term is added in the induction equation, which tends to dissipate the non-zero laplacian components of the magnetic field in the exterior (*i.e.* those which would be rapidly carried away in electromagnetic waves according to the Maxwell's equations in vacuum) and to restore the potential-field condition. This approach, also adopted in the simulations of Braithwaite & Nordlund (2006), results in a more realistic internal dynamics, even if it represents a too crude approximation to describe correctly the dynamics of the external fields. Moreover, it allows for an order-of-magnitude estimate of the amount of magnetic energy that the star would lose during the evolution and that would be supplied to the magnetosphere and/or to power the electromagnetic emission (Section 3.1).[1] Note that a small fraction of the energy lost is instead converted into oscillatory motions, mainly damped through the emission of gravitational waves (Section 3.2).

General relativistic nonlinear MHD simulations also confirmed the instability of NSs endowed with a purely toroidal magnetic field (Kiuchi et al. 2008, 2011), as predicted by linear studies. In this case the Tayler instability acts in an anoalogous way, but along the magnetic axis, and other instabilities may play an important role, *e.g.* the Parker instability (Parker 1955, 1966). The setup of these simulations is very similar to the one employed for the purely poloidal field case. Also in this case, the end state of the evolutions showed no evidence of stable configurations.

Rapid (uniform) rotation of the magnetized NSs has long been suggested to have a stabilizing effect, potentially able to suppress the instability of purely poloidal and purely toroidal fields. Some of the nonlinear studies discussed in the present Section included also the NS rotation, never finding it sufficient to avoid the hydromagnetic instability (Kiuchi et al. 2011; Lasky et al. 2012).

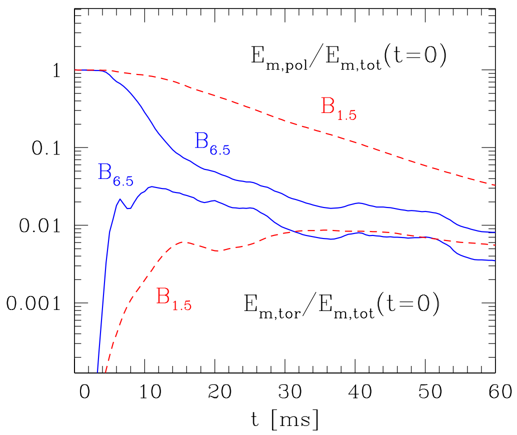

Fig. 2 Evolution of poloidal and toroidal magnetic energies normalized to the initial total magnetic energy, in log scale. The continuous blue line refers to the simulation with an initial polar field strength of 6.5×10^{16} G, the dashed red line to the one with 1.5×10^{16} G.

3 Hydromagnetic instabilities and magnetar giant flares

As discussed in Section 1, nonlinear MHD simulations of magnetized NSs subject to hydromagnetic instabilities can be used to test the internal rearrangement scenario of magnetar giant flares, according to which this kind of instabilities would be the trigger of the giant flare events (Thompson & Duncan 1995, 2001). Here we discuss the first indications provided by the recent nonlinear studies on the electromagnetic and gravitational wave emission that would be expected in coincidence with a giant flare.

3.1 Electromagnetic emission

In this Section we report on results presented in Ciolfi & Rezzolla (2012). For any of the magnetic field strengths considered, the NS always loses most of its magnetic energy at the end of the simulations, as a result of the poloidal field instability. In particular, about 90% of this energy is lost in the first few Alfvèn timescales after the instability saturation. Fig. 3 shows, as an example, the evolution of the total magnetic energy E_m for the same simulation shown in Fig. 1. The initial rapid drop in energy corresponds to a spike in its time derivative, $\dot{E}_m$. As stated in the previous Section (2), only a small fraction of this energy is converted into oscillatory motions, while most of it is lost due to the diffusion of magnetic fields outside the star. Within the approximation of the apporach adopted, these losses give an order-of-magnitude estimate of the magnetic energy that would leave the star

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[1] A different apporach is adopted in Lasky et al. (2011, 2012), where the magnetic fields are evolved according to ideal MHD also in the exterior. This does not allow to estimate the losses of the system and is at the origin of the differences in the late evolution of the system.

because of the instability-induced internal dynamics, supplying the magnetosphere and ultimately powering a strong electromagnetic emission.

The emission observed in giant flares is characterized by an initial spike in luminosity lasting $\sim 0.2-0.5$ s, in which a large fraction of the energy budget of the event is released (up to more than 99%), followed by a pulsating tail lasting hundreds of seconds and most certainly associated with the residual energy stored in the excited magnetosphere (Mereghetti 2008). We now assume that the trigger of these events is an internal hydromagnetic instability and that the spike in luminosity is the direct result of the initial violent energy release from the star, with no significant delay due to the processing of such energy in the magnetosphere. In this case, a compatibility in timescales is expected between the observed spike emission and the typical timescale of an internal rearrangement. By taking the instability of a purely poloidal field as a test case, a comparison can be attempted between the duration of the observed initial spike of giant flares and the duration of the spike in $\dot{E}_m$ produced by the instability, as estimated from numerical simulations. This was tried in Ciolfi & Rezzolla (2012). After extrapolating the results to magnetar-like field strengths the compatibility of the two timescales was confirmed, thus providing support to the proposed scenario.

For the alternative, external scenario, according to which the giant flare would be triggered by a reconfiguration of the external magnetic fields in the magnetosphere, an initial spike lasting $\sim 0.2-0.5$ s represents instead a strong challenge, because the evolution timescale outside the star is orders of magnitude shorter. The measured raise time of the spike emission, on the other hand, is way too short to be explained with the internal dynamical timescales, suggesting the following possible conclusion: the event is likely triggered by an internal rearrangement, which provides most of the energy powering the flare, but the internal dynamics immediately triggers also some rearrangement of the external magnetic fields. At this stage, however, any conclusion remains still a matter of debate and further investigation is necessary to shed light on the subject.

As a note of caution, we remark that our simulations do not account for the presence of a solid crust, most probably relevant in the dynamics of giant flares. Moreover, the instability of a purely poloidal field is likely more dramatic than in a more realistic situation, where the magnetic field would migrate from one configuration to another with a smaller jump in magnetic energy.

3.2 Gravitational wave emission

The violent reorganization of magnetic fields induced by a hydromagnetic instability is accompanied by a significant excitation of NS oscillations, in particular in the f-mode, which can then lead to a strong emission of gravitational waves (GWs). Following the argument that the instability of a purely poloidal field represents a test case for the internal rearrangement scenario of magnetar giant flares, the results of nonlinear simulations can be used to put an upper limit on the amplitude of the GW signal potentially emitted in connection to a giant flare and on its level of detectability with the next generation GW detectors. This idea was put forward in Ciolfi et al. (2011), where the first waveform produced in this way was presented. The GW emission was then studied systematically in Ciolfi & Rezzolla (2012); Lasky et al. (2012); Zink et al. (2012).

The main results on GWs of Ciolfi & Rezzolla (2012) are summarized in Fig. 4, where the (root-sum-square) amplitude of the continuous emission at the f-mode frequency is plotted against the magnetic field strength, assuming a typical source distance of 10 kpc and a GW damping time of 100 ms. A

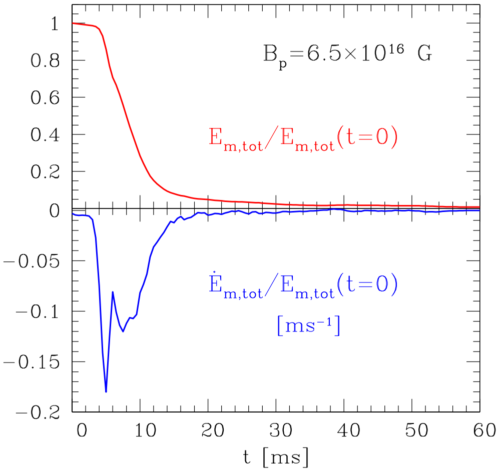

Fig. 3 Top: Evolution of the total magnetic energy normalized to its initial value, for a NS with a purely poloidal magnetic field having an initial polar strength of 6.5×10^{16} G. Bottom: Time derivative of the total magnetic energy.

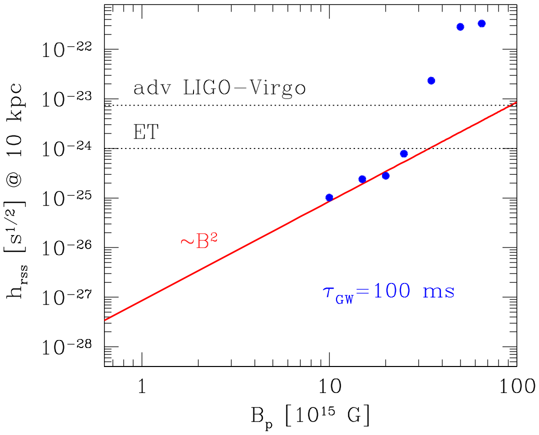

Fig. 4 Gravitational wave signal amplitude versus the initial polar magnetic field strength, assuming a distance of 10 kpc and a damping time of 100 ms. Horizontal lines mark the strain-noise amplitude of near-future GW detectors at the f-mode frequency. The red line is obtained by imposing a quadratic scaling and fitting the results for the lowest magnetic fields (first four points).

good match with the theoretical expectation that the GW amplitude scales quadratically with the magnetic field strength in the weak field limit (Levin & van Hoven 2011), allows to safely extrapolate the amplitude down to the more realistic value of 10^{15} G. By comparing with the sensitivity of the next generation GW detectors, the amplitude is found to be orders of magnitude below detectability. Since the instability of a purely poloidal field is likely to provide an upper limit to the realistic GW emission in coincidence with a giant flare (see Section 3.1), the prospects of detection result extremely small in the near future. In Zink et al. (2012) and Lasky et al. (2012) the GW amplitudes follow a different scaling law ($h \propto B^n$, with $n \sim 3$), but the prospects of detection are found to be equally pessimistic.

4 Concluding remarks

Understanding the properties of the internal magnetic field of neutron stars represents one of the most important long-standing open issues in the physics and astrophysics of these objects. An important part of the current effort is devoted to the search for equilibrium configurations of magnetized NSs which are stable on Alfvèn timescales, as these would represent a viable description of the internal magnetic field at the time of crust formation, thus setting the main properties of the magnetized NS at the beginning of its long-term dissipative evolution. So far, the state-of-the-art nonlinear simulations of magnetized NSs in general relativity, discussed in this paper, only considered the simple cases of purely poloidal and purely toroidal magnetic field geometries, confirming their unstable nature as predicted in previous linear studies. The future of this investigation is to consider mixed poloidal-toroidal configurations which currently represent good candidates for stability, as the twisted-torus one. In order to improve the realism of the simulations, various aspects need to be refined, *e.g.* the treatment of magnetic fields in the magnetosphere surrounding the star. Moreover, the present simulations only consider simple polytropic equations of state and should be extended to more realistic ones. Finally, stable stratification due to composition gradients, whose role in NSs needs to be clarified, could represent an additional necessary ingredient to be included in the simulations (Reisenegger 2009).

As discussed in Section 3, numerical simulations of the purely poloidal instability in NSs also provided indications on the electromagnetic and GW emission to be expected in association with a hydromagnetic instability, useful as a test case for the internal rearrangement scenario of magnetar giant flares. Future work in this direction will help understanding more on this exciting phenomena.

Acknowledgements. RC is supported by the Humboldt Foundation. Support comes also from CompStar, a Research Networking Programme of the European Science Foundation.

References

Bocquet, M., Bonazzola, S., Gourgoulhon, E., Novak, J.: 1995, A&A 301, 757
Bonazzola, S., Gourgoulhon, E.: 1996, A&A 312, 675
Braithwaite, J., Nordlund, Å.: 2006, A&A 450, 1077
Braithwaite, J.: 2006, A&A 453, 687
Braithwaite, J.: 2007, A&A 469, 275
Braithwaite, J.: 2009, MNRAS 397, 763
Chandrasekhar, S., Fermi, E.: 1953, ApJ 118, 116
Ciolfi, R., Ferrari, V., Gualtieri, L., Pons, J.A.: 2009, MNRAS 397, 913
Ciolfi, R., Ferrari, V., Gualtieri, L.: 2010, MNRAS 406, 2540
Ciolfi, R., Lander, S.K., Manca, G.M., Rezzolla, L.: 2011, ApJ 736, L6
Ciolfi, R., Rezzolla, L.: 2012, ApJ 760, 1
Ciolfi, R., Rezzolla, L.: 2013, MNRAS 435, L43
Cutler, C.: 2002, PRD 66, 084025
Duncan, R.C., Thompson, C.: 1992, ApJ 392, L9
Fujisawa, K., Yoshida, S., Eriguchi, Y.: 2012, MNRAS 422, 434
Fujisawa, K., Eriguchi, Y.: 2013, MNRAS 432, 1245
Gill, R., Heyl, J.S.: 2010, MNRAS 407, 1926
Glampedakis, K., Andersson, N., Lander, S.K.: 2012, MNRAS 420, 1263
Kiuchi, K., Shibata, M., Yoshida, S.: 2008, PRD 78, 024029
Kiuchi, K., Yoshida, S., Shibata, M.: 2011, A&A 532, A30
Lander, S.K., Jones, D.I.: 2009, MNRAS 395, 2162
Lander, S.K., Jones, D.I.: 2011a, MNRAS 412, 1394
Lander, S.K., Jones, D.I.: 2011b, MNRAS 412, 1730
Lander, S.K., Jones, D.I.: 2012, MNRAS 424, 482
Lasky, P.D., Zink, B., Kokkotas, K.D., Glampedakis, K.: 2011, ApJ 735, L20
Lasky, P.D., Zink, B., Kokkotas, K.D.: 2012, ArXiv e-prints arXiv:1203.3590
Levin, Y., van Hoven, M.: 2011, MNRAS 418, 659
Lyutikov, M.: 2003, MNRAS 346, 540
Lyutikov, M.: 2006, MNRAS 367, 1594
Markey, P., Tayler, R.J.: 1973, MNRAS 163, 77
Mereghetti, S.: 2008, A&AR 15, 225
Parker, E.N.: 1955, ApJ 121, 49
Parker, E.N.: 1966, ApJ 145, 811
Reisenegger, A.: 2009, A&A 499, 557
Tayler, R.J.: 1973, MNRAS 161, 365
Thompson, C., Duncan, R.C.: 1995, MNRAS 275, 255
Thompson, C., Duncan, R.C.: 2001, ApJ 561, 980
Tomimura, Y., Eriguchi, Y.: 2005, MNRAS 359, 1117
Viganò, D., Rea, N., Pons, J.A., Perna, R., Aguilera, D.N., Miralles, J.A.: 2013, MNRAS 434, 123
Wright, G.A.E.: 1973, MNRAS 162, 339
Yoshida, S., Eriguchi, Y.: 2006, ApJ Suppl. 164, 156
Zink, B., Lasky, P.D., Kokkotas, K.D.: 2012, PRD 85, 024030