

General relativistic effects of strong magnetic fields on the gravitational force: a driving engine for bursts of gamma rays in SGRs?

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Abstract. In general relativity all forms of energy contribute to gravity and not only just ordinary matter as in Newtonian Physics. This fact can be seen in the modified hydrostatic equilibrium equation for relativistic stars pervaded by magnetic (B) fields. It has an additional term coupled to the matter part as well as an anisotropic term which is purely of magnetic origin. That additional term coming from the pressure changed by the radial component of the diagonal electromagnetic field tensor, weakens the gravitational force when B is strong enough and can even produce an *unexpected* change in the *attractive* nature of the force by reversing its sign. In an extreme case, this new general relativistic (GR) effect can even trigger an instability in the star as a consequence of the *sudden* reversal of the hydrostatic pressure gradient. We suggest here that this GR effect may be the possible central engine driving the transient giant outbursts observed in Soft Gamma-ray Repeaters (SGRs). In small regions of the neutron star (NS), strong magnetic condensation can take place. Beyond a critical limit, these highly magnetised bubbles may explode releasing the trapped energy as a burst of γ -rays of $\sim 10^{36-40}$ erg.

Key words. relativity – stars: magnetic fields – stars: interiors – dense matter – gamma rays: bursts

1. Introduction

A class of neutron stars seem to have strong surface magnetic fields of the order of 10^{15} Gauss. They are referred to as the Magnetars. These highly magnetised stars have been speculated to be the progenitors of some *peculiar* gamma ray bursts events, the so-called repeaters. Two kind of (candidates) compact stars are believed to have very strong surface magnetic field: the Soft Gamma-ray Repeaters (SGRs) and the Anomalous X-ray Pulsars (AXPs: Mereghetti & Stella 1995). SGRs are objects that repeatedly emit bursts of gamma rays with energies of the order of 10^{36-40} erg, in addition to persistent X-rays. The SGRs are also a small enigmatic class of hard X-ray transient sources (Marsden et al. 2001). AXPs show persistent X-ray emission, modulated at a stable, slowly lengthening period. Contrary to the standard *binary X-ray pulsars*, they show no evidence for a companion star.

Stars with strong surface magnetic fields have still stronger field inside. Influence of strong magnetic fields on degenerate nuclear matter has been studied by Lai & Shapiro (1991). They employed the scalar virial theorem $2T + W + 3\Pi + \mathcal{M} = 0$, with T , W , Π and \mathcal{M} , being the rotational kinetic energy, the gravitational potential energy, the internal energy and the magnetic energy respectively. With this approach, they found out that a surface field of 10^{13} Gauss can readily imply that an inner magnetic field to be as high as 10^{18} Gauss. Alternately, this field limit can easily be estimated if we consider the magnetic energy approaching the gravitational energy to produce a significant deviation from the normal balance between pressure and gravity. This implies an extreme upper limit for the average field B, with $(B^2/8\pi)(4\pi R^3/3) \sim GM^2/R$ so that $B_{lim} \sim 1.3 \cdot 10^8 (M/M_\odot)/(R/R_\odot)^2$ (Mestel, 1999). For a neutron star with $R/R_\odot \sim 10^{-5}$, $B_{lim} \sim 10^{18}$ Gauss. In this work we discuss the effect on the gravitational force, of strong magnetic fields of the order of the previously quoted limit.

Unlike its Newtonian counterpart, in the GR hydrostatic equilibrium equation there appears a new term that depends not only on the pressure of the gas but also on the electromagnetic field strength in the radial direction. When the magnetic field is very strong and approaches the critical limit, it “softens” the gravitational force. In the extreme case, when the threshold strength (10^{18} Gauss) is reached, the sign of the radial pressure gradient $\frac{dp_r}{dr}$ reverses, thus indicating that the overall effect has become repulsive. An instability must then appear, and a criterion for it can readily be set. The appearance of a positive pressure gradient in the radial direction, i.e., $\frac{dp_r}{dr} \geq 0$, means that the NS is unstable. This may be interpreted as if in the interior of the magnetar the matter struggles to expand as the field reaches (locally) such large values.

The electromagnetic field can be treated as a fluid and there exists room for the occurrence of magnetic field condensation in a local volume in the NS interior. The B limit is called for here to study highly magnetised matter bearing in mind a stable stellar configuration. So, it is not surprising that in order to reach the instability one needs to be nearly at this critical field limit. The radial instability discussed here, and expected to occur in the interior of a magnetar, is actually produced by the *spatial anisotropy* of the magnetic stress-energy tensor. The *anisotropic stress tensor* (i.e., the fact that the radial component, p_r , differs from the angular components, $p_\theta = p_\phi = p_t$ or, the transverse component), introduces a *repulsive term*, purely of magnetic origin, in the hydrostatic equilibrium equation. Besides this term, the stellar *gravitational pull* is reduced because it depends directly on the radial component of the stress-energy momentum tensor which becomes smaller in the presence of a very strong magnetic field. Both effects conspire to make positive the “effective” gradient of the radial pressure as to induce the instability.

A similar effect has been discussed recently by Ray et al. (2003, 2004) with regard to the appearance of a net electric charge in a stellar structure. Therein, it is shown that there exists a critical limit to the electric field, beyond which the star is unstable. Here we make use of this novel phenomenon, the counterbalance of the gravitational pull excerpted by the compact object in critically magnetised interiors of neutron stars. The attentive reader must realize that not everywhere in the interior of such stars the field is so high as $\sim 10^{18}$ Gauss, except only in small regions (the bubble) where it can be raised by the effect of a strong magnetisation, as discussed for example by Pérez Martínez et al. (2003). This instability may trigger an abrupt release of energy similar to the giant flares of soft gamma-ray outbursts seen in SGRs.

The mechanism for the emission of gamma rays from the SGRs is still unknown. Typical energy of the emitted flares in the SGRs is 10^{36} erg/s, with special exception of a few sources emitting as high as 10^{44} erg/s. The magnetar model of Wheeler et al. (2000) makes use of the high magnetic field (10^{15} to 10^{17} Gauss) of a rapidly rotating neutron star as the possible source of cosmological Gamma-ray bursts (GRBs) releasing energy of $\sim 10^{54}$ erg.

As a manifestation of the radial instability generated by the GR effect discussed here, we also suggest a model to the emission process of the SGRs, by the concentration of the magnetic field in certain volume of the star, which we may call it as a “magnetic bubble”. It is the fast expansion (explosion) of this bubble, driven by the positive pressure gradient, which triggers the quiescent state to the super outbursts in SGRs, and as such, it may be a viable explanation of their central engine.

Magnetic field evolution in compact stars have been studied in details by Thompson & Duncan (1993, 1995, 1996 & 2001) and by Thompson, Lyutikov & Kulkarni (2002). Their main idea for the existence of high field in the neutron stars (magnetars) was, due to some dynamo mechanism (alpha - Omega), based on the fact that the neutron star convection is a transient phenomena and has extremely high Reynolds number. They showed that most of the magnetic energy of young pulsars reside in a convective cell of diameter ≤ 1 km. Lyutikov & Blandford (2002 & 2003) modeled the cosmological GRBs as explosions of electromagnetic bubbles in a force free configuration, where the bubbles expand non-relativistically inside the star, and then become highly relativistic when they break from the surface.

Here also we take such an idea as a working hypothesis of the formation of small volumes like bubbles, where the magnetic field is very high and nearly close to some *critical field* limit. The order of this critical magnetic field inside the magnetic bubble is found to be the same as that of the pressure and the mass of the inner sphere where the bubble is located. Also the *not so frequent* giant flares found in SGR 0526–66, with the famous March 5, 1979 event of energy release of 1.3×10^{44} erg, and the SGR 1900+14, of the August 27, 1998 event of energy release of 6.8×10^{43} erg, can also be caused by this relativistic effect of the strong magnetic field on the gravitational force. We argue, conversely, that what the magnetic field drives in fact is the reversal of the *gravitational force* when a critical field strength is reached.

We organise this article in the following way. In Section 2 we present the formalism to describe the stellar matter under strong magnetic fields in the light of general relativistic formulation and present the modified Tolman-Oppenheimer-Volkoff (TOV) equation. In the Section 3, we explain the instability and estimate the critical value of B field as a function of the depth of the star. In Section 4 we present the emission mechanism of the bursts in SGRs and give the estimates of the released energy and finally we draw our conclusions in Section 5.

2. General relativistic effects of magnetic fields on the structure equations

In this section we study the effect of the magnetic field in the hydrostatic equilibrium equation. The magnetic field energy-momentum tensor introduces an anisotropy in the fluid pressure in the stellar interior. In our case we have an anisotropy in the sense that the radial component

of the pressure p_r differs from the angular components $p_\theta = p_\phi = p_t$ (transverse pressure). We choose the magnetic field produced by a magnetised surface to be a radial function which guarantees that the pressure components are still a function of the radial coordinate keeping the spherical symmetry.

We proceed with the standard form of the metric

$$ds^2 = e^\nu dt^2 - e^\lambda dr^2 - r^2(d\theta^2 + \sin^2\theta d\phi^2). \quad (1)$$

The Einstein-Maxwell stress tensor T_ν^μ will have contributions coming from the matter part and the magnetic fields, and will take the form:

$$T_\nu^\mu = (p+\epsilon)u^\mu u_\nu - pg_\nu^\mu + \frac{1}{4\pi} \left(-F^{\mu\alpha} F_{\alpha\nu} + \frac{1}{4} g_\nu^\mu F_{\alpha\beta} F^{\alpha\beta} \right) \quad (2)$$

where p is the pressure, ϵ is the energy density ($=\rho c^2$) and u -s are the 4-velocity vectors. For the time component, one easily sees that $u_t = e^{\nu/2}$ and hence $u^t u_t = 1$. Consequently, the other components (radial and spherical) of the four vector are absent.

Maxwell's electromagnetic field equations can also be written as:

$$F_{\mu\nu;\alpha} = 0, \quad (3)$$

$$F^{\mu\nu}{}_{;\nu} = 4\pi j^\mu, \quad (4)$$

where $F_{\mu\nu;\alpha}$ and j^μ are the covariant derivative of the field strength tensor and the electric current 4-vector, respectively. Eq. (3) gives the form of the vector potential (A_μ) as $F_{\mu\nu} = A_{\nu,\mu} - A_{\mu,\nu}$. So, the electric and magnetic fields in the rest frame are defined as

$$E_\mu = F_{\mu\nu} u^\nu, \quad (5)$$

$$B_\mu = -\frac{1}{2} \epsilon_{\mu\nu\alpha\beta} u^\nu F^{\alpha\beta}, \quad (6)$$

$\epsilon_{\mu\nu\alpha\beta}$ being the Levi-Civita antisymmetric unit tensor with $\epsilon_{0123} = \sqrt{-g}$. Now, considering the presence of a purely magnetic field, we can write

$$E_\mu = F_{\mu\nu} u^\nu = 0. \quad (7)$$

This can also be thought of as a highly conducting medium of the star, where the term for the electrostatic charge will vanish.

The electromagnetic field strength is chosen in the form

$$F_{\theta\varphi} = -F_{\varphi\theta} = B(r) r^2 \sin\theta, \quad (8)$$

where $B(r)$ can be interpreted as the local magnetic field, the other components of $F_{\mu\nu}$ being zero.

Maxwell's equations (4) imply just one equation, the t component

$$\nabla_r F^{ti} = 4\pi J_m^t. \quad (9)$$

Thus by using Eq.(8) we have,

$$(r^2 B)' = 0, \quad (10)$$

where the prime stands for the derivative with respect to the coordinate r . Such an equation can be integrated to give

$$B(r) = q_m/r^2, \quad r > 0,$$

q_m being an integration constant.

The nonzero components of the stress-energy tensor T_ν^μ are

$$T_t^t = (\epsilon + \rho_{em}), \quad T_r^r = -(p - \rho_{em})$$

and

$$T_\theta^\theta = T_\varphi^\varphi = -(p + \rho_{em}) \quad (11)$$

where $\rho_{em} = B^2/8\pi$ is the energy density in the electromagnetic field. The relevant components of Einstein-Maxwell field equations are

$$\frac{e^{-\lambda}}{r^2} (r\lambda' - 1) + \frac{1}{r^2} = 8\pi (\epsilon + \rho_{em}), \quad (12)$$

$$\frac{e^{-\lambda}}{r^2} (r\nu' + 1) - \frac{1}{r^2} = 8\pi (p - \rho_{em}). \quad (13)$$

The first of the Einstein's equations is used to determine the metric coefficient e^λ , which is used to define the mass and charge inside a sphere of radius r . Namely,

$$e^{-\lambda} = 1 - \frac{2m(r)}{r} + \frac{q_m^2(r)}{r^2}, \quad (14)$$

where

$$m(r) = \int_0^r 4\pi r'^2 (\epsilon + \rho_{em}) dr' + \frac{q_m^2(r)}{2r}. \quad (15)$$

The mass of the star is now due to the total contribution of the energy density of the matter and the magnetic energy ($B^2/8\pi$) density. Such a definition is suitable since it coincides with the mass of a localised object as observed from infinity. So, for an observer at infinity, the mass is given by

$$\begin{aligned} m_\infty &= \int_0^R 4\pi r'^2 (\epsilon + \rho_{em}) dr' + \int_R^\infty 4\pi r'^2 (\epsilon + \rho_{em}) dr' \\ &= \int_0^R 4\pi r'^2 (\epsilon + \rho_{em}) dr' + \frac{q_m^2(R)}{2R} = m(R), \end{aligned} \quad (16)$$

where R is the radius of the star.

From Maxwell's equations we find $q_m(r) = B(r)r^2 - q_m(0)$. If there are no singularities at $r = 0$ the charge $q_m(0)$ is zero. Therefore, it follows the well known relations for radial magnetic field $B(r) = q_m/r^2$ (as above).

Exact solutions for anisotropic stars were obtained by Dev & Gleiser (2002;2003), where they considered anisotropy in the pressure component for a spherically symmetric gravitationally bound object. Taking a radial and transverse component of the stress-energy tensor (p_r and p_t respectively), they arrived at the analogous TOV equation for anisotropic stars.

$$\frac{dp_r}{dr} = -\frac{(\rho + p_r)(M(r) + 4\pi r^3 p_r)}{r^2 \left(1 - \frac{2M(r)}{r}\right)} + \frac{2}{r}(p_t - p_r). \quad (17)$$

This equation explicitly shows the repulsive term coming from the difference between the transverse and radial pressures (anisotropy effect), with the *radial pressure* changing the gravitational attraction. This is a purely relativistic effect and it is of importance because of the appearance of a radial magnetic field. To our knowledge, it has not been considered in previous studies of magnetars.

Considering that $T_i^i = -p_i$ for $i = r, \theta$ and $\dot{\phi}$ and using in the equilibrium equation, Eq. (17), the stress-energy momentum tensor from Eq. (11), and replacing the energy density ρ by the time component $T_t^t = (\epsilon + \rho_{em})$, the modified TOV for this case will be:

$$\frac{dp_r}{dr} = -\frac{(p + \epsilon) \left(M(r) + 4\pi r^3 \left(p - \frac{B^2}{8\pi} \right) \right)}{r^2 \left(1 - \frac{2M(r)}{r} \right)} + \frac{B^2}{2\pi r} \quad (18)$$

where, the mass $M(r)$ is the mass of the inner sphere, below the depth where the bubble is situated, and is integrated along the entire length, from the center of the star to the bubble. Here $M(r)$ is the mass for an observer in the star and is related to the mass at infinity $m(r)$ from Eq. (15) by $M(r) = m(r) - q_m^2(r)/2r$.

This form for the modified hydrostatic equation equation is essentially the same as has been recently done for the case of presence of charge inside a star (Ray et al. 2003) if we substitute the radial pressure gradient by the total dp/dr using the expression for $p_r = (p - \rho_{em})$ from Eq. (11).

3. A radial hydrostatic instability created by strong magnetic fields

Let's find out the order of magnitude of the magnetic field so as to produce an instability inside the star. Considering Eq. (18), the negative sign of the radial pressure gradient needs to be maintained for the entire radius of the star for a stable configuration. The reversal of the force field occurs only for a large value of the magnetic field. Now, the first term on the right hand side of Eq. (18), i.e., $(p + \epsilon)$ is positive definite. So, the term which primarily controls the 'change of sign' for dp_r/dr is $(M(r) + 4\pi r^3(p - B^2/8\pi))$. Also, the presence of the positive term $B^2/(2\pi r)$ helps in the process of making the dp_r/dr positive. So the stability criterion is

$$\frac{dp_r}{dr} \leq 0$$

or,

$$\frac{(p + \epsilon) \left(M(r) + 4\pi r^3 \left(p - \frac{B^2}{8\pi} \right) \right)}{r^2 \left(1 - \frac{2M(r)}{r} \right)} - \frac{B^2}{2\pi r} \geq 0. \quad (19)$$

This can be written in terms of the limiting magnetic field as

$$B_{crit} \leq \sqrt{2\pi(p + \epsilon) \frac{(M(r) + 4\pi r^3 p)}{r \left(1 - \frac{2M(r)}{r} \right) + \pi(p + \epsilon)r^2}}. \quad (20)$$

Magnetic field stronger than this critical field limit reverses the sign of the radial pressure gradient, as shown in the Fig. (1).

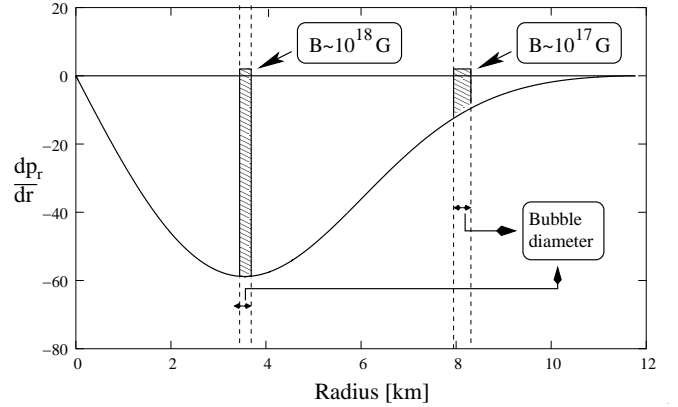


Fig. 1. The dp_r/dr of the star as a function of the radius of the star. The region of the space where it faces a strong magnetic field, the dp_r/dr becomes positive, and produces a burst. The maximum strength of the field is necessary where the depth of dp_r/dr is the maximum.

What is the order of the critical magnetic field required to equate both sides of the inequality (20)? Taking pressure (p) to be in MeV/fm^3 , relation (20) shows that the analog of B in that unit is $(MeV/fm^3)^{1/2}$. Hence,

$$\begin{aligned} 1 (MeV/fm^3)^{1/2} &\simeq (1.6 \times 10^{33})^{1/2} c.g.s. \text{ units} \\ &\simeq 4 \times 10^{16} \text{ Gauss}. \end{aligned} \quad (21)$$

Working out relation (20) we find that for the characteristic pressure inside a neutrons star $p \sim 10(MeV/fm^3) \sim 10^{35} \text{ dynes/cm}^2$ the critical field limit is $\sim 10^2 (MeV/fm^3)^{1/2}$, which gives us, from relation (21) a value of $\sim 10^{18} \text{ Gauss}$. In this extreme case, the magnetic stress $(B^2/8\pi) \sim 10^{35} \text{ dynes/cm}^2$ that is smaller but at

the same order of the matter pressure and can contribute to the stellar mass.

In normal matter, a non-potential magnetic field is held inside a conductor in the form of stresses in the lattice. There the critical stress is smaller than unity, and consequently B^2 would be much less than the pressure P . However, in a highly dense and a complicated system like a neutron star where forces are close to the strong interaction regime, the limit of the neutron matter to support steady B field is still unknown and is expected to be many orders of magnitude higher than that of normal matter.

The critical field as a function of the depth of the star is shown in Fig. (2). The choice of different EOSs will change the number coefficients, but the overall order of magnitude will remain the same. It is also shown in Fig. (1) that even for the maximum depth of the pressure gradient, the magnetic field is calculated to be still of that order of magnitude. So, the critical magnetic field depends essentially on the intrinsic scales of the neutron star parameters, such as mass, pressure, radius, etc.

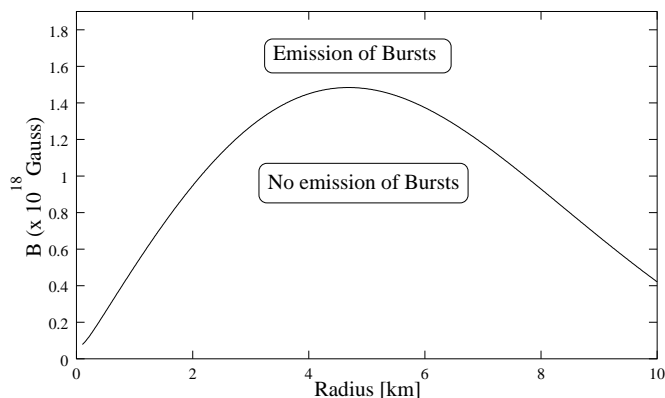


Fig. 2. Critical magnetic field (B) line defined by the condition $dp_r/dr = 0$ and given by Eq. (20).

It is worth mentioning at this point, that the strong B field on dp/dr (of Eq.(18)) at r indicates that an entire shell of volume $4\pi r^2 dr$ should have a magnetic field stronger than the critical field limit. However, alignment of the magnetic moments of the nucleons, which is the possible reason for the formation of the strong field, is not guaranteed throughout the entire shell at the same time. So, the small pockets inside the shell which gets magnetised, are referred here as the magnetic bubbles, and the dp/dr of Eq.(18) acts only on these small volume elements. The magnetic fields in these bubbles are local.

4. Gamma-Ray emission process

One possible consequence of this general relativistic effect coming from strong magnetic fields can be a mechanism for the emission of gamma-ray flares in SGRs. Energy emitted during each burst process in a SGR is of the order of 10^{36} to 10^{40} erg with some special exceptions of about 10^{44} erg (the March 5, 1979 event in SGR 0526–66 and the August 27, 1998 event in SGR 1900+14).

Fig. (2) indicates the region below the curve as the stable region, where there is no reversal of sign in the modified TOV. Thus, this is the limit of the magnetic fields in the stars having no burst. When the field limits exceeds the critical value (as shown in Fig. (2)) of the magnetic field, then we have flares of gamma-rays from the stars.

How much of the stellar matter is needed to produce a burst of the order of 10^{36} erg? Typically, if we consider a small bubble of 1 cm radius, then the volume of the bubble is 10^{-18} times than that of a neutron star of radius 10 km. For a bubble of radius 1 cm, the total energy released will be

$$\mathcal{E} = r^3 \frac{B^2}{6} \simeq (1)^3 \times (10^{18})^2 \text{erg} \simeq 10^{36} \text{erg} \quad (22)$$

where we have used the scale of the order of 10^{18} Gauss as obtained for the critical field strength.

So, to match with the energy released by the SGRs ($\sim 10^{36}$ erg/s), the bubble should have a volume of $\sim 1 \text{ cm}^3$. There is a little variation in the scale due to the position of the bubble inside the star. Another variation comes from the choice of the EOS of the matter inside the star. These collected variations however changes the numbers by maximally one order of magnitude, but the general features will be restored. **We have considered a simple model where magnetic field condense in a small sphere inside the neutron star.** So, this gives a very general picture in our model of freezing of magnetic field inside small droplets or bubbles, negligibly smaller than the volume of the star, and emission of gamma-ray flares in the SGRs, from the effect of relativistic equations. It can be equally applicable to any and every neutron/strange star model having a strong magnetic field.

5. Conclusions

We have discussed a general relativistic effect, due to strong magnetic fields, that can induce a radial instability inside magnetars, with the subsequent release of gamma rays as an outcome. We have estimated the strength of the magnetic field in order to drive such an effect. The high magnetic field that is necessary to change the chemical potential of the particles in the nuclear matter of the neutron star has been calculated to be more than 10^{18} Gauss and the maximum mass of the entire star, due to this high field, increases by a very small percentage (e.g., see Table 2 & 4 of Cardall et al., 2001). So, for our model, a field

of the order of 10^{17} to 10^{18} Gauss inside a small bubble of radius 1 cm, which is more likely to make a burst, the increase of chemical potential inside the bubble due to very strong field, will leave very little effect on the chemical potential in the rest of the matter of the star where the field is comparatively weak. It is also worth emphasising the fact that a freezing of the magnetic field in the small volumes, is more likely due to alignment of magnetic moments of the nucleons, rather than due to any convective mechanism (e.g., Table 4 of Cardall et al., 2001), and can be continuously produced. They do not need to form just during the birth of the neutron star and survived for thousands of years. Besides, a burst of this kind in the interior of a compact star may produce a starquake as those already observed in the SGRs. This relativistic effect due to the anisotropic nature of the stress-energy momentum tensor inside a strongly magnetised NSs or magnetars, as the progenitors for the central engine of the giant flares in SGRs seems to having been overlooked in previous studies.

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