Possible rotation-power nature of SGRs and AXPs

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Abstract. We investigate the possibility of some Soft Gamma-ray Repeaters (SGRs) and Anomalous X-ray Pulsars (AXPs) could be described as rotation-powered neutron stars (NSs). The analysis was carried out by computing the structure properties of NSs, and then we focus on giving estimates for the surface magnetic field using both realistic structure parameters of NSs and a general relativistic model of a rotating magnetic dipole. We show that the use of realistic parameters of rotating neutron stars obtained from numerical integration of the self-consistent axisymmetric general relativistic equations of equilibrium leads to values of the magnetic field and radiation efficiency of SGRs/AXPs very different from estimates based on fiducial parameters. This analysis leads to a precise prediction of the range of NS masses, obtained here by making use of selected up-to-date nuclear equations of state (EOS). We show that 40\% (nine) of the entire observed population of SGRs and AXPs can be described as canonical pulsars driven by the rotational energy of neutron stars, for which we give their possible range of masses. We also show that if the blackbody component in soft X-rays is due to the surface temperature of NSs, then 50\% of the sources could be explained as ordinary rotation-powered pulsars. Besides, amongst these sources we find the four SGRs/AXPs with observed radio emission and six that are possibly associated with supernova remnants (including Swift J1834.9-0846 as the first magnetar to show a surrounding wind nebula), suggesting as well a natural explanation as ordinary pulsars.

1. Introduction
SGRs and AXPs constitute a class of pulsars with the following properties [1]: periods $P \sim (2-12)\; s$, slowing down rates $\dot{P} \sim (10^{-15} - 10^{-10})\; s/s$, persistent X-ray luminosity as large as $10^{35}\;\text{erg}\; s^{-1}$ and transient activity in the form of outbursts of energies around $(10^{41}-10^{43})\;\text{erg}$. There is a current widely accepted view of SGR/AXPs as magnetars [2, 3]. Adopting NS's fiducial parameters (mass $M = 1.4M_{\odot}$, radius $R = 10\; \text{km}$, and moment of inertia $I = 10^{45}\;\text{g}\;\text{cm}^2$), one has that the rotational energy loss...
\[ \dot{E}_{\text{rot}} = -4\pi^2 I \frac{\dot{P}}{P^2} = -3.95 \times 10^{46} \frac{\dot{P}}{P^2} \text{ erg s}^{-1}. \] (1)

When the above \( P \) and \( \dot{P} \) are substituted into Eq. (1), we conclude that \( \dot{E}_{\text{rot}} \) is not enough to explain the observed X-ray luminosities from SGR/AXPs (i.e. \( L_X > \dot{E}_{\text{rot}} \)), unlike the traditional rotation-powered pulsars. Thus, SGRs and AXPs need further scrutiny of their energy reservoirs. The magnetar model hypothesizes the release of magnetic energy via the decay of an ultrastrong NS surface magnetic field, larger than the critical field for vacuum polarization \( B_c = m_e^2 c^3 / (e \hbar) = 4.4 \times 10^{13} \text{ G} \).

It is important to pointing out that there are alternative scenarios with NSs but with ordinary magnetic fields \( B \sim 10^{12} \text{ G} \) which already challenge the magnetar model (see e.g., [4, 5] and references therein). Other alternatives have been explored in terms of quark stars, i.e. accreting quark stars [6] or the quark-nova remnant model [7]. Alternatively to NSs, Malheiro et al. [8] have suggested that massive, fast rotating, highly magnetized WDs could explain as well the general properties of SGRs and AXPs. Despite the wide acceptance of the magnetar model, we have recalled and stressed that there are alternative scenarios not ruled out by the current data, motivating us to scrutinize further their predictions and evaluate their consistency [9]. Following this reasoning, the authors of [8] introduced a word of caution on labeling a source as a magnetar only because it shows a transient outburst activity. As we show below, this method of classification on which the current catalog of SGRs/AXPs has been constructed [10], is in clear contrast with the original idea underlying magnetars, which were introduced for the explanation of sources with \( L_X > \dot{E}_{\text{rot}} \).

Bearing this in mind, we examined in [8, 9, 11, 12] the possibility of some SGR/AXPs being rotation-powered pulsars (RPPs): we found at the time that, indeed, four sources (1E 1547.0–5408, SGR 1627–41, PSR J1622–4950, and XTE J1810–197) of the SGR/AXP catalog could be explained via the rotational energy loss of a NS. Once identified as RPPs, one is led to the theoretical prediction that some of the phenomena observed in ordinary pulsars could also occur in SGRs and AXPs. Indeed, the radio emission, a property common in pulsars but generally absent in SGRs and AXPs, is observed in three out of these four objects, as previously discussed in [9, 12]. It is interesting to notice that among these nine sources, we can also find six sources with possible associations with supernova remnants (SNRs). Very recently, Younes et al. [13] discovered a vast cloud of high-energy particles called a wind nebula around of Swift J1834.9-0846, for the first time. Wind nebula around other high-\( B \) sources have also been suggested. In this work, we have shown that this discovery is further evidence corroborating to the description of some SGRs/AXPs as rotation powered pulsars.

In addition, PSR J1846-0258, a source that although recognized as rotation-powered is often quoted as a magnetar-like or a transitional object due to its outburst event in June 2006, the energetics of its flaring activity is well explained from the gain of rotational energy during the accompanied glitch. Such a glitch-outburst connection is clearly not expected in a source not driven by rotational energy.

The aim of this work is to extend the analysis of [8, 9, 11, 12] on the possibility of SGRs/AXPs as rotation-powered NSs. In order to proceed with such an analysis, we first compute in section 2 the structure properties of NSs, and then in section 3 we focus on giving estimates for the surface magnetic field using both realistic structure parameters of NSs and a general relativistic model of a rotating magnetic dipole. We then show in section 4 that indeed nine of the currently confirmed twenty three SGR/AXPs can be ordinary rotation-powered pulsars. This analysis leads to a precise prediction of the range of NS masses, obtained here by making use of selected up-to-date nuclear equations of state (EOS), in both cases of local and global charge neutrality. We also show in section 5 an analysis of the glitch/outburst connection in the 9 aforementioned sources. Finally, in Section 6, we summarize the main conclusions and remarks.
2. Neutron star structure
In order to compute the rotational energy loss of a NS as a function of its structure parameters, e.g. mass and radius, we need to construct the equilibrium configurations of a uniformly rotating NS in the range of the observed periods. In the case of both static and rotating NSs, the Tolman-Oppenheimer-Volkoff (TOV) system of equations is superseded by the Einstein-Maxwell system of equations coupled to the general relativistic Thomas-Fermi equations of equilibrium, giving rise to what we have called the Einstein-Maxwell-Thomas-Fermi (EMTF) equations. In the TOV-like approach, the condition of local charge neutrality is applied to each point of the configuration, while in the EMTF equations the condition of global charge neutrality is imposed. The EMTF equations account for the weak, strong, gravitational and electromagnetic interactions within the framework of general relativity and relativistic nuclear mean field theory. In this work we shall use both global (EMTF) and local (TOV) charge neutrality to compare and contrast their results. We have recently discussed this point in [14], and for the rotational periods as the ones observed in SGR/AXPs ($P \sim 2–12$ s), the structure of the rotating NS can be accurately described by small departures from the spherically symmetric case [15, 16], for instance using Hartle’s formalism [17]. Following this method we compute rotating configurations, accurate up to second-order in $\Omega$, with the same central density as the seed static non-rotating configurations. The mass-radius relation for non-rotating configurations in the cases of global and local charge neutrality are shown in figure 1 of [14]. For the rotation periods of interest here, the mass-equatorial radius relation of the uniformly rotating NSs practically overlaps the one given by the static sequence (see figure 1 in [16]). Thus, we take here advantage of that result and consider hereafter, as masses and corresponding radii, the values of the non-rotating NSs. Although in general there is a dependence of all the structure parameters on the nuclear EOS, we use below, without loss of generality and for the sake of exemplification, only the GM1 EOS. Similar qualitatively and quantitatively results are obtained for the other EOSs.

3. Surface Magnetic Field
We have recently showed in [14, 18] that the range of $P$ for SGRs and AXPs is similar to the one concerning the high-magnetic field pulsar class, we can directly apply the results of [16], taking into account only the most relevant of the above corrections for the present range of periods, namely the finite-size correction.

Figures 1 and 2 show our theoretical prediction for the surface magnetic fields of the SGR/AXPs as a function of the NS mass, using the general relativistic formula, for the GM1 parametrization and for the global and local charge neutrality cases, respectively (see [14], for details). We find that, both in the cases of global and local neutrality, some of the sources have inferred magnetic fields lower than the critical value, $B_c$, for some range of NS masses. Clearly this set of sources includes SGR 0418+5729, Swift J1822.3-1606 and 3XMM J185246.6+003317, which are already known to show this feature even using fiducial NS parameters and the classic magnetic dipole model (see e.g., [10]).

4. Efficiency of SGRs/AXPs
Another important quantity for the identification of the nature of SGRs and AXPs is the ratio between the observed luminosity and the rotational energy loss. We know that such a ratio is a function of the NS mass, hence the NS radius, via the moment of inertia. For SGR/AXPs the dominant emission is in X-rays, thus we analyze all the possible values of the ratio $L_X/\dot{E}_{\text{rot}}$ in the entire parameter space of NSs. As we demonstrate below, some SGRs and AXPs allow a wide range of masses for which $L_X/\dot{E}_{\text{rot}} < 1$, implying a possible rotation-powered nature for those sources. Figure 3 show the X-ray luminosity to rotational energy loss ratio as a function of the NS mass, for both global and local charge neutrality configurations. We can see from these
figures that nine out of the twenty three SGR/AXPs could have masses in which \( L_X < \dot{E}_{\text{rot}} \), and therefore they could be explained as ordinary rotation-powered NSs. Such sources are: Swift J1834.9–0846, PSR J1846–0258, 1E 1547.0–5408, SGR J1745-2900, XTE J1810–197, PSR J1622–4950, SGR 1627–41, SGR 0501+4516, CXOU J171405.7–381031 (see Table 1). In view of the proximity of some of the sources to the line \( L_X / \dot{E}_{\text{rot}} = 1 \) (see e.g., SGR 1900+14, SGR 0418+5729, and Swift J1822.3–1606), and the currently poorly constrained determination of the distance to the sources, there is still the possibility of having additional sources as rotation powered NSs.

In this line, two sources are particularly interesting, namely SGR 1900+14 and SGR 1806–20, which appear very close (but above) to the limit of becoming rotation-powered NSs. The soft X-rays spectra of SGRs and AXPs are usually well fitted by a blackbody+power-law (BB+PL) spectral model. The BB temperature is usually of the order \( k_B T \sim 0.5 \text{ keV} \) and surface radii of the emitting region are \( \sim 1 \text{ km} \). In the case of a NS, one could interpret the BB component as due to the surface temperature of the NS, while the PL component necessarily has a non-thermal nature and must be due to magnetospheric processes. Within this interpretation, the request that the rotational energy loss of a NS pays also for the contribution of the BB to the luminosity is unnecessarily rigorous since the surface BB luminosity can come from the thermal reservoir of the NS. Thus, the above ratio \( L_X / \dot{E}_{\text{rot}} \) becomes an upper limit to the actual efficiency for the conversion of rotational into electromagnetic energy. We have recently applied this interpretation to the above two sources (see [14], for more details). Figure 4 shows the ratio \( L_X / \dot{E}_{\text{rot}} \) as a function of the NS mass in the case of SGR 1900+14 and SGR 1806–20, adopting the GM1 EOS. It is clear from this analysis the importance of identifying the different contributions to the emission of the object. There is no doubt that the subtraction of the surface temperature contribution to the total flux in soft X-rays can be important for the correct identification of the nature of these sources: now there is a range of masses for which the luminosity to rotational
energy loss ratio becomes smaller than unity. Again, it is worth recalling that there are still additional effects which could improve the above analysis: distances to the sources are not known accurately; the spectrum could be also fitted by a different spectral model (e.g. a double blackbody); the NS EOS is still unknown and so the moment of inertia and radius for a given mass might be different. These effects might lead to a different value of the total luminosity, contribution of the star’s surface temperature to it, and rotational energy loss. Clearly the above analysis can be extended to all the other SGRs and AXPs, and in the case of the nine sources already identified with $L_X/\dot{E}_{\text{rot}} < 1$, it will further diminish this ratio.
Table 1. The observational properties of nine sources explained as ordinary rotation-powered NSs. The parameters $P, \dot{P}$ and $L_X$ have been taken from the McGill online catalog at www.physics.mcgill.ca/pulsar/magnetar/main.html. The surface magnetic field $B_{NS}$ are calculated using fiducial neutron star model parameters.

| Source         | $P$ (s) | $\dot{P} \times 10^{-11}$ s/s | $B_{NS}^{\text{fiducial}} \times 10^{14}$ G | $L_X \times 10^{33}$ erg/s |
|----------------|---------|-------------------------------|---------------------------------|--------------------------|
| SGR 0501+4516  | 5.8     | 0.59                          | 1.9                             | 0.81                     |
| 1E 1547.0-5408 | 2.07    | 4.77                          | 3.2                             | 1.3                      |
| PSR J1622-4950 | 4.33    | 1.7                           | 2.7                             | 0.44                     |
| SGR 1627-41    | 2.59    | 1.9                           | 2.2                             | 3.6                      |
| CXOU J171405.7-381031 | 3.8 | 6.4                            | 5.0                             | 56                       |
| SGR J1745-2900 | 3.76    | 1.38                          | 2.3                             | 0.11                     |
| XTE J1810-197  | 5.54    | 0.77                          | 2.1                             | 0.043                    |
| Swift J1834.9-0846 | 2.48 | 0.79                            | 1.4                             | 0.0084                   |
| PSR J1846-0258 | 0.33    | 0.71                          | 0.49                            | 19                       |

5. Glitches and bursts

It is natural to expect that in a rotation-powered star the energetics of its bursting activity of SGRs/AXPs could be explained by the gain of rotational energy during the glitch, $\Delta E_{\text{rot}} = -2\pi^2 I \Delta P / P^3$ [8]. We have shown in the last section that nine of the twenty three SGR/AXPs can be explained as rotation-powered NSs. Thus, it is mandatory to scrutinize the outburst data of SGR/AXPs, to seek for associated glitches, and assess if the NS glitch rotational energy can explain the transient activity. It is important to start our analysis by recalling the case of PSR J1846–0258 ($L_X < \dot{E}_{\text{rot}}$ when fiducial parameters to the NS are adopted), which showed an outburst activity in 2006 [19]. In view of the possible NS rotation-power nature of PSR J1846–0258, Malheiro et al. [8] assumed that the outburst with energy $(3.8–4.8) \times 10^{41}$ erg [20] was triggered by a glitch in the NS, and found that a glitch of $|\Delta P|/P \sim (1.73–2.2) \times 10^{-6}$ could explain the outburst of 2006. This theoretical result is in full agreement with the observational analysis of [21], who showed that indeed a major glitch with $|\Delta P|/P \sim (2–4.4) \times 10^{-6}$ occurred.

Following this reasoning, we proceed to theoretically predict the values of $|\Delta P|/P$ which could explain the energetics of the bursts of those SGR/AXPs with $L_X < \dot{E}_{\text{rot}}$, obtained by assuming that $|\Delta E_{\text{rot}}|$ equals the observed energy of the burst event, $E_{\text{burst}}$, namely

$$\frac{|\Delta P|}{P} = \frac{E_{\text{burst}} P^2}{2\pi^2 I}.$$  \hspace{1cm} (2)

Figure 5 shows the value of $|\Delta P|/P$ obtained from equation (2), as a function of the NS mass. From this set of nine sources, the only glitch detected was the one of PSR J1846–0258 in June 2006 [21], whose observed value of $|\Delta P|/P$ is shown with the gray-shaded area in these plots. Indeed a minimum mass for the NS can be established for this source by requesting that 1) the entire moment of inertia is involved in the glitch and 2) that the theoretical value of $|\Delta P|/P$ coincides with the observed value: we obtain $M_{\text{min}} = 0.72 \, M_\odot$ and $M_{\text{min}} = 0.61 \, M_\odot$ for the global and local charge neutrality cases, respectively. On the other hand, if we substitute the moment of inertia $I$ in equation (2) by $I_{\text{glitch}} = \eta I$ where $\eta \leq 1$, being $I_{\text{glitch}}$ the moment of inertia powering the glitch, then we can obtain a lower limit for the parameter $\eta$: we obtain $\eta = 0.20$ and $\eta = 0.18$ for the global and local charge neutrality cases, respectively. Tables 2 and 3 show the theoretically predicted value of $|\Delta P|/P$ assuming the mass of the NS is larger than $1 \, M_\odot$ and $\eta = 1$, in the cases of global and local charge neutrality, respectively.
Figure 5. Inferred fractional change of rotation period during the glitch, $\Delta P/P$, obtained by equating the rotational energy gained during the glitch, $\Delta E_{\text{rot}}$, to the energy of the burst, for globally neutral (left panel) and locally neutral (right panel) NSs. In this example the NS obeys the GM1 EOS. The gray-shaded area corresponds to the value of $|\Delta P|/P$ in the observed glitch of PSR J1846–0258 in June 2006 [21].

Table 2. Predicted values of $|\Delta P|/P$ assuming rotation-powered NSs - Global Charge Neutrality

| Source name   | Total isotropic burst energy [erg] | Predicted $|\Delta P|/P$ for $M > 1 M_\odot$ |
|---------------|-----------------------------------|---------------------------------------------|
| PSR J1846–0258 | $4.8 \times 10^{41}$               | $(8.8 \times 10^{-7} - 2.6 \times 10^{-6})$ |
| 1E 1547.0–5408 | $1.1 \times 10^{41}$               | $(8.1 \times 10^{-6} - 2.4 \times 10^{-5})$ |
| XTE J1810–197  | $4.0 \times 10^{37}$               | $(2.1 \times 10^{-5} - 6.3 \times 10^{-8})$ |
| SGR 1627–41    | $1.0 \times 10^{41}$               | $(1.0 \times 10^{-5} - 3.8 \times 10^{-5})$ |
| SGR 0501+4516  | $1.0 \times 10^{40}$               | $(5.7 \times 10^{-6} - 1.7 \times 10^{-5})$ |
| Swift J1834.9–0846 | $1.5 \times 10^{37}$       | $(1.6 \times 10^{-9} - 4.8 \times 10^{-9})$ |
| SGR 1745–2900  | $6.7 \times 10^{37}$               | $(1.61 \times 10^{-8} - 4.9 \times 10^{-8})$ |

Table 3. Predicted values of $|\Delta P|/P$ assuming rotation-powered NSs - Local Charge Neutrality

| Source name   | Total isotropic burst energy [erg] | Predicted $|\Delta P|/P$ for $M > 1 M_\odot$ |
|---------------|-----------------------------------|---------------------------------------------|
| PSR J1846–0258 | $4.8 \times 10^{41}$               | $(7.9 \times 10^{-7} - 2.2 \times 10^{-6})$ |
| 1E 1547.0–5408 | $1.1 \times 10^{41}$               | $(7.2 \times 10^{-6} - 2.0 \times 10^{-5})$ |
| XTE J1810–197  | $4.0 \times 10^{37}$               | $(1.9 \times 10^{-8} - 5.3 \times 10^{-8})$ |
| SGR 1627–41    | $1.0 \times 10^{41}$               | $(1.1 \times 10^{-5} - 3.2 \times 10^{-5})$ |
| SGR 0501+4516  | $1.0 \times 10^{40}$               | $(5.0 \times 10^{-6} - 1.4 \times 10^{-5})$ |
| Swift J1834.9–0846 | $1.5 \times 10^{37}$       | $(1.4 \times 10^{-9} - 3.9 \times 10^{-9})$ |
| SGR 1745–2900  | $6.7 \times 10^{37}$               | $(1.4 \times 10^{-8} - 4.1 \times 10^{-8})$ |

6. Conclusions
By extending the analysis of [8, 9, 11, 12] on the possibility of some SGRs and AXPs as rotation-powered NSs, we have explored in this work the consequences of a realistic model
for NSs on the inference of the astrophysical observables of SGRs and AXPs. We showed that the X-ray luminosity of nine sources (Swift J1834.9–0846, PSR J1846–0258, SGR J1745–2000, XTE J1810–197, PSR J1622–4950, SGR 1627–41, SGR 0501+4516, CXOU J171405.7381031), which corresponds to the 40% of the entire SGR/AXP population, can be explained via the loss of rotational energy of NSs, thus falling into the family of ordinary rotation-powered pulsars. We have also given their associated lower mass limits. We have also shown that the interpretation of the blackbody component of the spectrum in soft X-rays as due to the surface temperature of the NS allow both SGR 1900+14 and SGR 1806-20 to be added to the above list, leading to ≈ 50% of the SGR/AXP population that could be explained via rotation-powered NSs. We also argued that the observational uncertainties in the determination of the distances and/or luminosities, as well as the uncertainties in the NS nuclear EOS, leave still room for a possible explanation in terms of spindown power for additional sources.

We have shown that both surface magnetic fields and the efficiencies of pulsars are overestimated, if computed with NS fiducial parameters. We estimated the surface magnetic fields of SGR/AXPs as a function of NS masses, from the self-consistent general relativistic model of the radiation of a rotating magnetic dipole in vacuum. We have explored for the nine sources with \(L_X < \dot{E}_{\text{rot}}\) the possibility that the energetics of their bursting activity, \(E_{\text{burst}}\), can be explained from the rotational energy gained in an associated glitch, \(\Delta E_{\text{rot}}\). We thus computed lower limits to the fractional change of rotation period of NSs caused by glitches, \(|\Delta P|/P\), by requesting \(\Delta E_{\text{rot}} = E_{\text{burst}}\). The fact that there exist physically plausible solutions for \(|\Delta P|/P\) reinforces the possible rotation-powered nature for these sources (e.g., the case of PSR J1846–0258).

It is interesting to notice that four of the above nine sources, namely 1E 1547.0–5408, SGR J1745–2900, XTE J1810–197, and PSR J1622–4950, are actually the only ones with detected radio emission [10, 22, 23], as expected from ordinary rotation-powered pulsars, although it has interestingly different properties from that typical of radio pulsars. We shall perform a deeper analysis of the radio emission from SGRs and AXPs in a forthcoming publication. It is worth mentioning that, among these nine sources, we can also find six sources with possible associations with supernova remnants (SNRs): Swift J1834.9–0846 associated with SNR W41 (see [13] for the recent detection of a wind nebula around this source), PSR J1846–0258 (with SNR Kes75), 1E 1547.0–5408 with SNR G327.24–0.13, PSR J1622–4950 with SNR G333.9+0.0, SGR 1627–41 with SNR G337.0–0, CXOU J171405.7–381031 with SNR CTB37B [10]. All these findings support the description of some SGRs/AXPs as belonging to the class of RPPs. If these associations are observationally confirmed, then the NS was born from the core-collapse of a massive star which triggered the SN explosion.

Theoretical predictions and observations in additional bands of the electromagnetic spectrum such as the optical, high and ultra-high gamma rays and cosmic-rays are encouraged to discriminate amongst the different models and elucidate the actual nature of SGRs and AXPs.

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