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SGRs/AXPs as Rotation-Powered Neutron Stars

Rafael C. R. de Lima

Universidade do Estado de Santa Catarina (UESC)
Av. Madre Benvenuta, 2007, 88.035901 Florianópolis, SC, Brazil
rafael.camargo@icranet.org

Jaziel G. Coelho

Instituto Nacional de Pesquisas Espaciais (INPE)
Av. dos Astronautas 1758, 12227010 São José dos Campos, SP, Brazil
jaziel.coelho@inpe.br

Manuel Malheiro

Instituto Tecnológico de Aeronáutica (ITA)
Praça Marechal Eduardo Gomes, 50, 12228900 São José dos Campos, SP, Brazil
malheiro@ita.br

Jorge A. Rueda, and Remo Ruffini

Dipartimento di Fisica and ICRA
Sapienza Universit di Roma
P.le Aldo Moro 5, I00185 Rome, Italy
International Center for Relativistic Astrophysics Network (ICRANet)
Piazza della Repubblica, 65100 Pescara, PE, Italy
jorge.rueda@icra.it, ruffini@icra.it

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We show that nine soft gamma repeaters (SGRs) and Anomalous X-ray Pulsars (AXPs) of the twenty three known sources can be described as rotation-powered canonical pulsars. To accomplish this we use realistic parameters of rotating neutron stars obtained from numerical integration of the self-consistent axisymmetric general relativistic equations of equilibrium. We present limits to the NS mass where the sources can be rotation-powered.

Keywords: Neutron Star, SGR, AXP.

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1. Introduction

Over the last decade, observational evidence has suggested that soft gamma-ray repeaters (SGRs) and anomalous X-ray pulsars (AXPs) belong to a particular class of pulsars. Observationally, they are slow rotating isolated pulsars with rotational periods in the range of $P \sim (2-12)$ s, spin-down rates $\dot{P} \sim (10^{-13}-10^{-10})$, persistent X-ray luminosity as large as $L_X \sim 10^{35}$ erg s^{-1}, and outbursts of energies $\sim (10^{41}-10^{43})$ erg and, in the case of SGRs, have giant flares of astonishing energies $\sim (10^{44}-10^{47})$ erg.

For an ordinary rotation-powered pulsar, the X-ray luminosity can be expressed as originated from the loss of rotational energy,

$$\dot{E}_{\rm rot} = -4\pi^2 I \frac{\dot{P}}{P^3}, \tag{1}$$

where I is the star's moment of inertia. One can see, using Eq. (1) with a fiducial value for the neutron star (NS) moment of inertia $I \sim 10^{45}$ erg cm^2, that SGRs/AXPs have an X-ray luminosity L_X that cannot be explained through their loss of rotational energy, i.e. $L_X > |\dot{E}_{\rm rot}| \sim (10^{32}-10^{33})$ erg. Because of this discrepancy, SGRs/AXPs have been widely depicted as magnetars, namely NSs powered by the decay of their ultrastrong surface magnetic field larger than the critical field for vacuum polarization, $B_c = m_e c^3/(e\hbar) = 4.4 \times 10^{13}$ G (see, Ref.,[1] for a review).

Despite the wide acceptance that the magnetar model finds in the scientific community, there are competing models which cannot be ruled out by the current data, and therefore the nature of SGRs and AXPs is still under continuous debate. We remind, for instance, the models of SGRs/AXPs based still on NSs but with ordinary fields, $B \sim 10^{12}$ G, powered either by the generation of drift waves in the magnetosphere,[2] or by the accretion of fallback material via a circumstellar disk.[3] There is the alternative model based on massive, fast rotating, highly magnetized white dwarfs.[4–7]

Although Ref.[4] was mainly devoted to the white dwarf model of SGRs/AXPs, it was there also analyzed the possibility that SGRs/AXPs (or at least a part of them) be rotation-powered NSs. Four candidates were there identified. In this work, we extend this latter analysis of Ref.[4] by using up-to-date nuclear matter equations of state (EOS) and the construction of NS equilibrium configurations from the solution of the general relativistic field equations, instead of introducing ad-hoc fiducial parameters. Indeed, we shall show below that at least nine SGRs/AXPs (with a possible extension to twelve), can be rotation-powered pulsars. We shall give the range of NS masses where this is possible. Following Ref.,[8] we obtain the values of magnetic field for SGRs/AXPs taking into account general relativistic corrections into the rotating magnetic-dipole model in electrovacuum. We show the results for NSs in the case when Coulomb interactions are allowed and the configuration is subjected to the constraint of global charge neutrality, where we follow previous works (see, Refs.,[9,10] and references therein) where was obtained a new set of equations, the Einstein-Maxwell-Thomas-Fermi (EMTF) equations, which accounts for the weak, strong, gravitational and electromagnetic interactions within the framework of general relativity and relativistic nuclear mean-field theory.

This work is organized as follows. We first briefly summarize the EOS, the equations of equilibrium, and the resulting NS structure from their integration in both the static and uniform rotation cases. We then analyze the estimates of the magnetic field and radiation efficiency of the SGRs/AXPs class. Finally, we summarize our results.

2. Nuclear Equation of State and Mass-Radius Relation

The NS interior is made of a core and a crust. The core of the star has densities higher than the nuclear value, $\rho_{\rm nuc} \approx 3 \times 10^{14}$ g cm^{-3}, and it is composed by a degenerate gas of baryons (e.g. neutrons, protons, hyperons) and leptons (e.g. electrons and muons). The crust, in its outer region ($\rho \leq \rho_{\rm drip} \approx 4.3 \times 10^{11}$ g cm^{-3}), is composed of ions and electrons, and in the so-called inner crust ($\rho_{\rm drip} < \rho < \rho_{\rm nuc}$), there are also free neutrons that drip out from the nuclei. For the crust, we adopt the Baym-Pethick-Sutherland (BPS) EOS[11,12] . For the core, we here adopt modern models based on relativistic mean-field (RMF) theory, which have Lorentz covariance, intrinsic inclusion of spin, a simple mechanism of saturation for nuclear matter, and they do not violate causality. We use an extension of the formulation of Ref. [13] with a massive scalar meson (σ) and two vector mesons (ω and ρ) mediators, and possible interactions between them. We adopt in this work three sets of parameterizations for these models: the NL3[14] , TM1[15] , and GM1[16] EOS.

With the knowledge of the EOS of the NS interior, we are in the position of computing the structure parameters (e.g. mass, radius, and moment of inertia) of the NS, which are needed for computing the loss of rotational energy of the star. The latter requires, in particular, the knowledge of the moment of inertia, which is a function of the star's mass. In order to compute the function $I(M)$ for a given source, we need to construct the equilibrium configurations of uniformly rotating NSs, at the observed rotation periods.

We have shown[9,10,17,18] that the Tolman-Oppenheimer-Volkoff (TOV) system of equations,[19,20] in which the condition of local charge neutrality is implicitly applied to each point of the configuration, are superseded by the Einstein-Maxwell system of equations coupled to the general relativistic Thomas-Fermi equations of equilibrium, giving raise to the what we have called the Einstein-Maxwell-Thomas-Fermi (EMTF) equations. The EMTF equations request only the condition of global charge neutrality, accounting for the weak, strong, gravitational and electromagnetic interactions within the framework of general relativity and relativistic nuclear mean-field theory. For the sake of comparison, we shall show below our results in both the global (EMTF) and local (TOV) charge neutrality cases.

For rotation 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, for instance using the Hartle's formalism.[21] Following this method we calculate rotating configurations, accurate up to the second-order in Ω, with the same central density as the seed static (i.e. non-rotating) configurations. For the rotation periods of interest here, deviations from spherical symmetry are extremely low, leading to an equatorial radius that is practically the same as the radius of the spherical configuration with the same central density. Therefore, the mass-equatorial radius relation of these uniformly rotating NSs almost overlaps the one given by the static sequence (see Fig. 1 of Ref.[10]). We take advantage of this result and consider hereafter the mass and corresponding radius of the non-rotating NSs.

The moment of inertia of the star is given by

$$I = \frac{J}{\Omega}, \tag{2}$$

where Ω is the angular velocity, and J is the angular momentum. The moment of inertia calculated in this way does not account for deviations from spherical symmetry up to the second order series expansion in the angular velocity Ω because J is an even function of Ω, given by

$$J = \frac{1}{6} R^4 \left(\frac{\bar{\omega}}{dr}\right)_{r=R}, \tag{3}$$

where R is the local radius of the non-rotating star and $\bar{\omega} = \Omega - \omega(r)$ is the angular velocity of the fluid relative to the local inertial frame, and ω is the angular velocity local frame. The angular velocity Ω is related the angular momentum J by

$$\Omega = \bar{\omega}(R) + \frac{2J}{R^3}. \tag{4}$$

We shall use below, without loss of generality and for the sake of simplification, only the GM1 EOS. Similar qualitatively and quantitatively results are obtained for the other EOS.

3. Implications on the Pulsar Properties

We turn now to the consequences of using realistic general relativistic structure parameters on the inference of the magnetic field and efficiency of a pulsar to convert rotational energy into electromagnetic radiation. We apply here, to SGR/AXPs, a similar analysis to the one of Ref.[8] for the high-magnetic field pulsar class.

The simplified picture of a point-like magnetic dipole has been traditionally applied as a model for pulsars of any rotation period and assuming fiducial values for the neutron star structure parameters. Following Ref.,[8] we take here into account the corrections measured by the compactness parameter $GM/(c^2R)$, introduced by the finiteness of the mass and size of the star, namely the general relativistic finite-size effects on the magnetic-dipole model. The first exact solution in general relativity of the exterior electromagnetic fields of a (slowly) rotating magnetic-dipole in vacuum, and aligned with the rotation axis, was first found in Refs.[22,23] (see, also, Ref.[24]), whom solved the Einstein-Maxwell equations of this system in the

Schwarzschild background. The generalization of the above works to the case of higher multipoles in the electromagnetic structure in a Schwarzschild metric was found in Ref.[24] The general relativistic analog of the Deutsch's solution in the slow rotation regime of a misaligned magnetic-dipole, was obtained in analytic form in the *near zone* ($r \ll c/\Omega = 1/k = \lambda/2\pi$) in Refs.[25,26] and, for the wave zone in Ref.[27] In the latter, the radiation power of the dipole was computed as

$$P_{\rm dip}^{\rm G.R.} = -\frac{2}{3}\frac{\mu_\perp^2 \Omega^4}{c^3}\left(\frac{f}{N^2}\right)^2 , \tag{5}$$

where f and N are the general relativistic corrections

$$f = -\frac{3}{8}\left(\frac{R}{M}\right)^3\left[\ln(N^2) + \frac{2M}{R}\left(1+\frac{M}{R}\right)\right] , \tag{6}$$

$$N = \sqrt{1-\frac{2M}{R}} , \tag{7}$$

with M the mass of the non-rotating configuration. Now, equating the rotational energy loss, Eq. (1), to the above electromagnetic radiation power, Eq. (5), one obtains the formula to infer the surface magnetic field with general relativistic corrections:

$$B \sin\chi = \frac{N^2}{f}\left(\frac{3c^3}{8\pi^2}\frac{I}{R^6}P\dot{P}\right)^{1/2} , \tag{8}$$

where we have introduced the subscript 'GR' to indicate the general relativistic character of the formula.

One of the key physical quantities for the identification of the nature of SGRs and AXPs is the ratio between the observed luminosity and the rotational energy loss (1). For SGRs/AXPs the dominant emission is in X-rays, thus we shall analyze all the possible values of the ratio $L_X/\dot{E}_{rot}$ in the entire parameter space of NSs. We will show that some SGRs/AXPs allow a wide range of masses for which $L_X/\dot{E}_{rot} \lesssim 1$, implying a possible rotation-powered nature for those sources.

The left panel of Fig. 1 shows our theoretical prediction for magnetic fields of the SGRs/AXPs as a function of the NS mass, using Eq. (8), for the GM1 parametrization for the global charge neutrality cases. We find that, both in global and local neutrality cases, some sources have inferred magnetic fields lower than the critical value B_c in a particular range of NS masses. This set includes SGR 0418+5729, SWIFT J1822.3-1606 and 3XMM J1855246.6+003317, which are already known to show this feature even using fiducial NS parameters and the classic magnetic-dipole model (see, e.g., Ref.[28]). As we have mentioned above, Eq. (8) is derived for a rotating magnetic-dipole in electrovacuum, thus neglecting the extra (negative) torque from magnetospheric plasma. This additional torque certainly leads to an inferred magnetic field still lower than the ones shown here.

Concerning the efficiency of SGRs/AXPs in converting rotational energy into electromagnetic radiation, we show in the right panel of Fig. 1 the ratio $L_X/\dot{E}_{\rm rot}$,

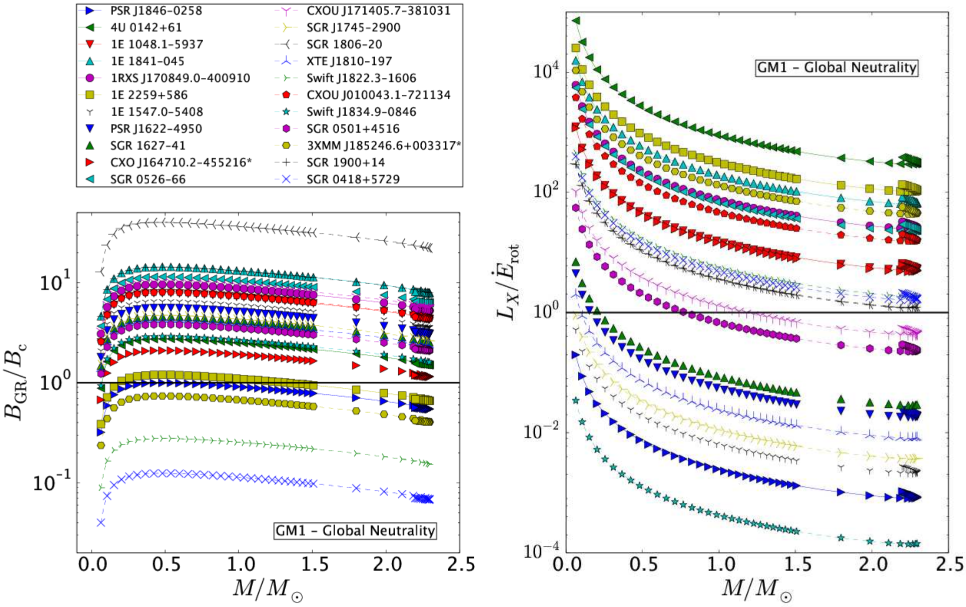

Fig. 1. (Color online) The left panel shows the magnetic field $B_{\rm G.R}$ obtained from the general relativistic magneto-dipole formula, Eq. (8), in units of critical field B_c. The right panel shows the ratio between the observed X-ray luminosity L_X and the loss of rotational energy $\dot{E}_{\rm rot}$. Both are showed as functions of the mass (in solar masses) in the case of global charge neutrality..

X-ray luminosity to rotation energy loss, as a function of the NS mass, for global charge neutrality. We find in these figures that nine of the twenty three sources have possible range of masses in which $L_X < \dot{E}_{\rm rot}$, and therefore they could be explained as ordinary rotation-powered NSs. These nine 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 71405.7-381031. In view of the proximity of some of the sources to the line $L_X/\dot{E}_{\rm rot} = 1$ (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 possibility of additional rotation powered NSs sources.

4. Conclusions

In this work we explored the consequences of a realistic model for NSs on the inference of the astrophysical observables of SGRs/AXPs. We showed that the X-ray luminosity of nine sources, which corresponds to 40% of the known SGR/AXP, can be well explained via the loss of rotational energy of the NS, and therefore they fit into the family of ordinary rotation-powered pulsars. The nine 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 71405.7-381031. We argued that observational uncertainties in the determination of the distances and/or luminosities leave still ample room for a possible explanation in terms of spin-down power.

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