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Particle acceleration and radio emission for SGRs/AXPs as white dwarf pulsars

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Abstract. Recently, an alternative model based on white dwarfs pulsars has been proposed to explain a class of pulsars known as Soft Gamma Repeaters (SGR) and Anomalus X-Ray Pulsars (AXP) [6][4], usually named as magnetars. In this model the magnetized white dwarfs can have surface magnetic field $B \sim 10^7 - 10^{10}$G and rotate very fast with frequencies $\omega \sim 1$ rad/s, allowing them to produce large electromagnetic (EM) potentials and generate electron-positron pairs. These EM potentials are comparable with the ones of neutron stars pulsars with strong magnetic fields. In our study we consider two possible processes associated with the particle acceleration: in one we have the pair production near to the star polar caps i.e., inside the light cylinder where magnetic-field lines are closed, on the other the creation of pair is in the Outer Magnetosphere i.e., far away of the star surface where magnetic field are open [1]. This analysis of the possibility of radio emission was done for all the 23 SGRs/AXPs of the McGill Online Magnetar Catalog [7] that contains the current information available on these sources. Our work is a first attempted to find an explanation for the puzzle why for all the SGRs/AXPs was expected radio emission, but it was observed in only four of them.

1. Introduction

Pulsars are neutrons stars with a large magnetic field, since their discovery, many kinds of pulsars are found. There is one class named as Soft Gamma Repeaters (SGRs) and Anomalus X-Ray Pulsars (AXPs) that have been intensively studied. They are known as neutron stars with large period of rotation $P \sim (2-12)$s and large spin-down $\dot{P} \sim (10^{-13} - 10^{-10})$s/s.

1.1. Canonical Spin-Powered Pulsar Model

In the framework of pulsars there is one class known as rotation-powered pulsars, a neutron star rotating uniformly with a frequency Ω, where the conversion of rotational energy into electromagnetic energy occur, i.e, the loss of rotational energy of the star provides the power.
In this model we consider a dipole moment μ with a orientation α in the rotation axis. On the surface of star the magnetic field at equator is $B_s \sim \mu/R^3$ and at the poles $B_p = 2\mu/R^3$, where R is the radius of the star. The rotational energy is given by [9]:

$$E_{\rm rot} = \frac{1}{2} I \Omega^2, \tag{1}$$

where I is the moment of inertia, and the loss of rotational energy of the pulsar:

$$\dot{E}_{\rm rot} = I\Omega\dot{\Omega} + \frac{1}{2}\dot{I}\Omega^2 \approx I\Omega\dot{\Omega}. \tag{2}$$

Such configuration has time-varying dipole moment, in an infinity referential, and radiates energy with a rate

$$\dot{E}_{\rm rot} = \frac{2\mu^2\Omega^4\sin^2\alpha}{3c^3}, \tag{3}$$

where c is the speed of light. Combining (2) and (3) we obtain the surface magnetic field at the equator as [5]:

$$B_s = B_p/2 = \left(\frac{3c^3 I}{8\pi^2 R^6} P\dot{P}\right)^{1/2}, \tag{4}$$

with $P = 2\pi/\Omega$.

2. SGRs/AXPs as White Dwarf Pulsars

Neutron stars pulsars with an extremely magnetic field $B_p \sim (10^{12} - 10^{14}\mathrm{G})$ are known as magnetars. Currently there are 23 SRGs/AXPs [7] that are classified as magnetars or candidates. An alternative model has explained them as white dwarfs, because the magnetars modeled as neutron stars have some characteristics that are not understood very well, i.e., SRGs/AXPs are very slow rotating pulsars comparing to ordinary pulsars $P \sim (0.001 - 1)$s, spin-down rates larger than normal pulsars $\dot{P} \sim (10^{-15} - 10^{-14})$s/s, strong outburts of energies per weeks or months (for more details see [6, 4]). As show by [10], the process of release energy in a white dwarf can be explained in terms of a canonical spin-powered pulsars model, because in several aspects they are similar.
For example, if we consider a star with $M = 1.4M_\odot$ and $R = 10^6$ cm, from (4) the magnetic field at poles is:

$$B_p = 3.2 \times 10^{19}(P\dot{P})^{1/2}G, \tag{5}$$

now, in the case of a white dwarf with $M = 1.4M_\odot$ and $R = 3 \times 10^8$ cm, there is a new scale for the magnetic field at poles:

$$B_p = 4.21 \times 10^{14}(P\dot{P})^{1/2}G, \tag{6}$$

following the last consideration there are new values for the: mass density, moment of inertia, dipole moment and rotation energy. It explains a large class of problems related in considering this SGRs/AXPs as neutron stars. Furthermore, we cannot ignore that the recent astronomical observations of old SGRs (characteristic age $\sim (10^6 - 10^7)$ Myr) with low surface magnetic field, as well as the four SGRs/AXPs showing radio emission recently discussed by [3][2].

3. Models of Electromagnetic Emission

There are two models associate the pair $e^\pm$ production and emission of radiation in compact stars.

3.1. Polar Cap Model

The first process is the polar-cap model, where electrons are accelerated on the stellar surface emitting γ-rays by curvature radiation. In this model we consider a polar cap region. Since the corotating speed field lines cannot exceed the speed of light, the magnetic lines cannot be closed outside of the light cylinder $R_{lc} = c/\Omega$. This fact leads to the open magnetic field lines in the polar region. The potential difference along an open magnetic line given by [8]:

$$\Delta V_{\max} = \frac{B_p \Omega^2 R^3}{2c^2}, \tag{7}$$

and for any potential the pairs of $e^{\pm}$ are accelerated by the Lorentz factor

$$\gamma = e\Delta V/mc^2, \tag{8}$$

where m is the mass of electron. Following [1], we determine the condition to pairs $e^{\pm}$ production in the polar cap regions of pulsars:

$$\left(\frac{e\Delta V}{mc^2}\right)\frac{\hbar}{2mcr_c}\frac{h}{r_c}\frac{B_s}{B_g} \approx \frac{1}{15}, \tag{9}$$

where h is the distance (gap) above the pulsar surface, r_c is the curvature radius of the magnetic field lines, $B_g = m^2c^3/e\hbar = 4.4 \times 10^{13}$ G and B_s the magnetic field on the surface.

3.2. Outer Gap Model

The second model of emission consider the production of the photons far away from the stellar surface, where the magnetic field lines are open. In this model, the energy is limited by a combination of curvature radiation and inverse Compton scattering. The initial inverse Compton scattering limits the energy of the primary $e^{\pm}$ to $\gamma mc^2 \sim (mc^2)^2/\hbar\omega_s$. Because the maximum energy of secondary $e^{\pm}$ is γmc^2, the highest frequency synchrotron radiation from secondary $e^{\pm}$ becomes:

$$\omega_{\max} \sim \gamma \sin\theta \omega_B, \tag{10}$$

where $\omega_B = eB/mc$ and θ the angle between $e^{\pm}$ and local B. There is a critical value, where the energy spectrum can be cut [1],

$$\omega_c \sim \gamma\gamma_{\perp,c}\omega_B = \frac{\gamma_{\parallel}^3}{\omega_B^3}\left(\frac{mc^3\omega}{e^2}\right)^2. \tag{11}$$

The typical frequency of the tertiary photons is

$$\omega_s \sim \frac{1}{\omega_B^3}\left(\frac{mc^3\Omega}{e^2}\right)^2 \quad \text{valid only for } \omega_s \geq \omega_B. \tag{12}$$

From (10), (11) and (12), we can obtain the critical frequency:

$$\omega_c \approx \gamma_{\parallel}^3 \frac{m^5c^9}{e^7}\Omega^2 B^{-3}, \tag{13}$$

and the maximum synchrotron emission frequency:

$$\omega_{\max} \approx \frac{e^{15}}{\gamma_{\parallel}\hbar^2 m^9 c^{15}}\Omega^{-4}B^7. \tag{14}$$

4. Results

4.1. Polar Cap Model Applied to SGRs and AXps as White Dwarfs

From equation (9) for white dwarf with a mass $M = 1.26M_\odot$ and $R = 3 \times 10^8$ cm we obtain the theoretical death line:

m1 - Pure dipole:

$$4 \log B_p - 7.5 \log P = 25.84, \tag{15}$$

with $B_s = B_p$ and $r_c = (Rc/\Omega)^{1/2}$.

m2 - Magnetic field lines very curved:

$$4 \log B_p - 6.5 \log P = 19.68, \tag{16}$$

with $B_s = B_p$ and $r_c \sim R^9$ cm.

m3 - Magnetic field lines very curved on the polar cap:

$$7 \log B_p - 13 \log P = 26.06, \tag{17}$$

with $B_s = 2 \times 10^9$ G, $r_c \sim R^9$ cm and $h \sim (B_p/B_s)^{1/2} R(R\Omega/c)^{1/2}$.

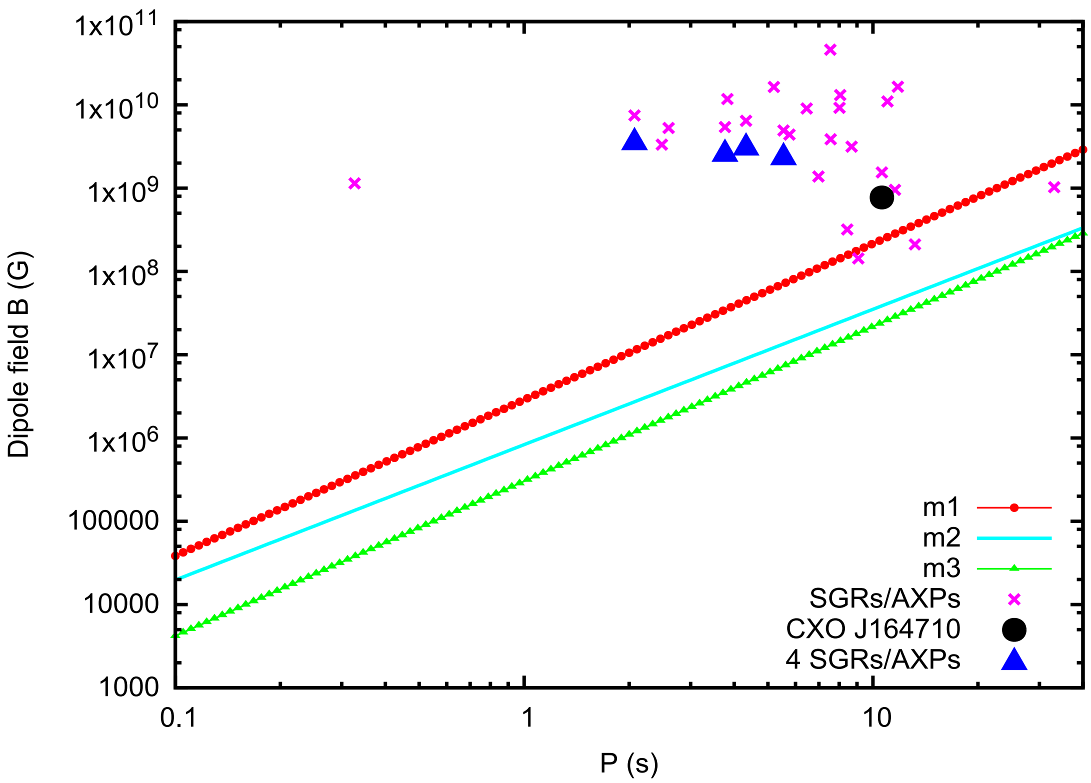

Figure 1. Polar Cap Model applied to white dwarfs stars with $M = 1.26M_\odot$ and $R = 3\times10^8$cm. The dots-cross are all SGRs/AXPs, the dots-triangle are the four sources that emit in radio, the dot-circle is a star very old.

4.2. Outer Gap Model Applied to SGRs and AXps as White Dwarfs

From (13) if we assumes that magnetic field is the B at the light cylinder

$$B = B_p R^3/r^3 = B_p(\Omega R/c)^3, \tag{18}$$

for white dwarf with a mass $M = 1.4M_\odot$ and $R = 3 \times 10^8$cm we construct:
o1:

$$5 \log B_p - 12 \log P = 34.38, \tag{19}$$

o2:

$$2 \log B_p - 5 \log P = 16.54, \tag{20}$$

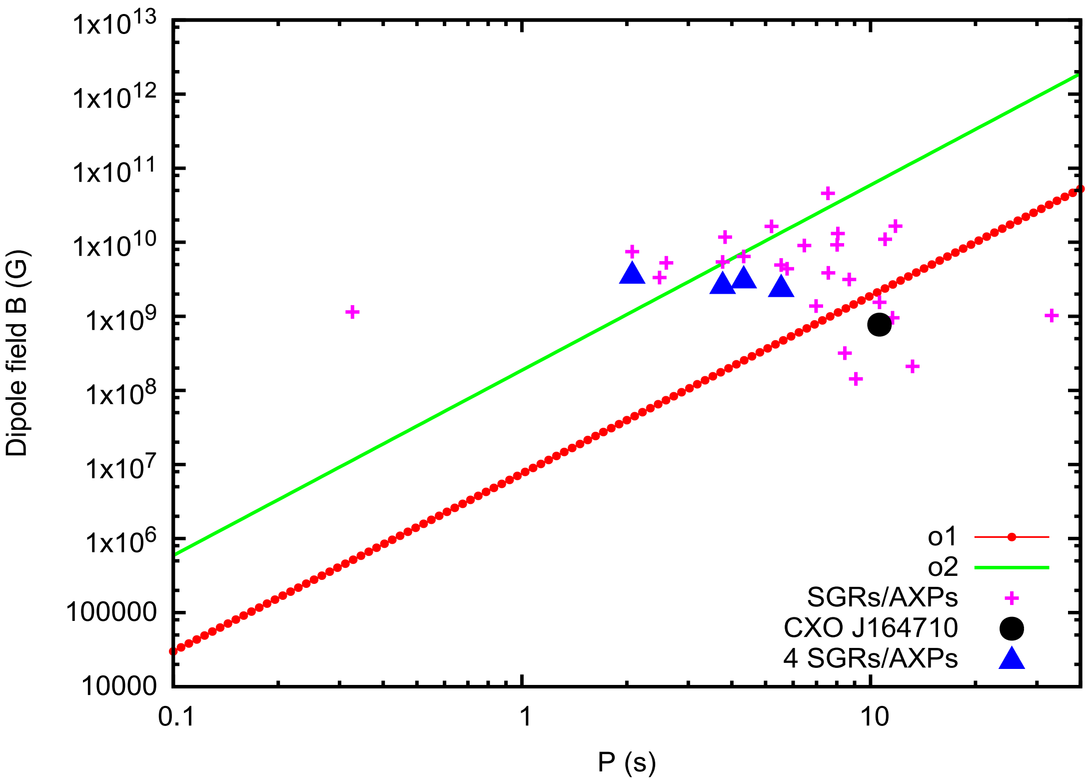

Figure 2. Outer Gap Model applied to white dwarfs stars with with $M = 1.26M_\odot$ and $R = 3 \times 10^8$cm. The dots-plus are all SGRs/AXPs, the dots-triangle are the four sources that emit in radio, the dot-circle is a star very old.

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5. Conclusions

Our work is a first attempted to find an explanation for the puzzle why for all the SGRs/AXPs was expected radio emission, but it was observed only four of them.
In the polar Cap Model (figure 4.1) almost all stars should emit, however, only in four of then was observed radio emission. So there is a difference in nature of this sources, we suppose that ones (which emit) are neutron stars and others white dwarfs. For emission far from the WD star surface, using the Outer Gap Model, may explains why some of the SGRS and AXPs emit in radio and others no. As we can see in figure (4.2) all sources are very near the dead-line or below. This could explain the absence of radio emission observed in these sources.

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