Strong magnetic fields and SGRs/AXPs as white dwarf pulsar: a source of ultra-high energy cosmic rays

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Abstract. The origin of highest energy cosmic rays still remains a mystery in Astrophysics. In this work we consider the Soft Gamma Repeaters (SGRs) and Anomalous X-ray Pulsars (AXPs) as possible sources of ultra-high cosmic rays. These stars described as white dwarfs pulsars can achieved large electric potential differences in their surface and accelerate particles up to Lorentz factors $\gamma \sim 10^{10}$. Pulsars offer favorable sites for the injection of electrons and heavy nuclei, and accelerate them to ultrahigh energies. Once accelerated in the pulsar this particles can escape from the magnetosphere and produce the radiation observed. Here, we discuss the possibility of SGRs/AXPs as white dwarf pulsars to be possible sources of ultra-high energetic photons with $E \sim 10^{21}$ eV.

1. Introduction
Following and updating ours previous [1] work, we study the influence of large magnetic fields in white dwarfs (WD), their role at the magnetosphere, where the electron-positron pair and electromagnetic radiation occurs. For neutron stars there are many evidences of photons from radio to $\gamma$-rays energies, produced by electric potentials in neutron star magnetosphere that are able to accelerate particles to high energies. To explain it, a number of models were proposed: polar cap model [2, 3], slot gap model and outer gap model [4, 5]. There are some works exploring the possibility that the enhance of positron fraction observed by PAMELA could be explained by local pulsars [6, 7] and others considering white dwarfs pulsars [8]. We extend this idea considering the possibility of SGRs/AXPs being white dwarfs. We will see that fast and highly magnetized white dwarfs are also able to have large electric fields in their surface induced by their magnetic field and accelerate particles producing ultra-high energy cosmic rays. White dwarfs with large magnetic fields of $10^6$ to $10^9$G and very massive have been discovered in the last years [9]. This fact opens the possibility to have white dwarfs pulsars [10], the theoretical possibility already was considered in [11] and it is shown that generation of hard X-ray and gamma rays are possible by fast rotating magnetic white dwarfs. The first fast white dwarf pulsar founded in the observations was AE Aquarii with a short period $P = 33.08$ s [12]. It shows high energy emission in X that can be explained in terms of a rotation powered pulsar. Furthermore, 10 years ago already a candidate to a white dwarf pulsar has been proposed in [13] where high energy has been observed in a source in the Galactic center with a period $P = 77.13$ minutes.
1.1. Soft Gamma Repeaters and Anomalous X-ray Pulsars SGRs/AXPs

Soft Gamma Repeaters (SGRs) and Anomalous X-Ray Pulsars (AXPs) are very slow rotating pulsars $P \sim (2 - 12)\text{s}$, have huge magnetic fields (100-1000) times larger than radio pulsars, and are understood as neutron star (known as Magnetars [14]). Their spin-down rates $\dot{P} \sim (10^{-15} - 10^{-14})\text{s/s}$ are larger than the ones of normal pulsars $\dot{P} \sim (10^{-15} - 10^{-14})\text{s/s}$ [15]. To explain their luminosity is considered a reservoir of high magnetic energy liberated by the decay of their huge magnetic field. They cannot be understood as neutron star rotating-powered pulsars, since their rotational energy is smaller than their luminosity in X-rays. Currently there are 23 SRGs/AXPs [16] that are classified as magnetars and 5 until now only candidates.

2. SGRs/AXPs as White Dwarf Pulsars

In the last years, white dwarfs (WD) very massive, fast and with large magnetic field ($10^6 - 10^9\text{G}$) observed for this type of star ($10^4\text{G}$) were discovered [17, 9]. They share some characteristics with low $B$ SGRs/AXPs recently detected, when understood as white dwarf pulsars [10]. Two more known fast WD are AE Aquarii [19, 20, 21] with a period $P = 33.078$ and RXJ 0648.0-4418 with a period $P = 13.2$ [22, 23, 24].

An alternative model has been proposed considering SGRs/AXPs as white dwarf pulsars [25, 10]. The magnetars model to SGRs/AXPs cannot explain some observation (for more details see [10]). As show in [26], the process of release energy by dipole radiation 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 $R = 10^6\text{ cm}$, the magnetic field at poles is:

$$B_{p}^{NS} = 3.2 \times 10^{19}(P\dot{P})^{1/2}\text{G},$$

(1)

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

$$B_{p}^{WD} = 4.21 \times 10^{14}(P\dot{P})^{1/2}\text{G}.$$ 

(2)

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 when SGRs/AXPs are considered as neutron stars.

2.1. White dwarfs under presence of a high magnetic field

Magnetic fields has a important role in the structure of the WD, because the pressure not depend only on $\rho$ but on magnetic field also [27],

$$\frac{\partial P}{\partial \rho} |_{B}\nabla \rho + \frac{\partial P}{\partial B} |_{\rho} \nabla B = -\rho \nabla \Phi + \frac{1}{4\pi} \nabla \times B \times B.$$ 

(3)

Several works explore this importance [28, 29, 30, 31] showing that white dwarfs with strong interior magnetic fields are more massive [29, 32]. In [33, 34, 35] self-consistent computations shown that the minimum period for white dwarfs are for example $\sim 0.3s$ to star made of $^4\text{He}$. To white dwarfs this is a high frequency, near of the Kepler frequency where the balance between gravity and centrifugal forces is equal. A star in this frequency losses mass, and become unstable.
3. Rotation Powered Pulsars and emission mechanism

There is a class of pulsars known as rotation-powered pulsars (RPPs), where we have rotating magnets, that emit dipole radiation with a rate

\[ \dot{E}_{\text{rot}} = \frac{2\mu^2 \Omega^4 \sin^2 \alpha}{3c^3}, \]  

(4)

where \( c \) is the speed of light. A dominant effect as to increase of their period \( P \), by the breaking in the rotation star frequency by the conversion of rotational energy

\[ \dot{E}_{\text{rot}} = I \Omega \dot{\Omega} + \frac{1}{2} I \dot{\Omega}^2 \approx I \Omega \dot{\Omega}. \]  

(5)

into electromagnetic energy [27].

A conducting magnetized sphere rotating in vacuum will induce in the surrounded space an electric field \( \vec{E} \) with a component along \( B \),

\[ E_\parallel = \vec{E} \cdot \frac{\vec{B}}{|\vec{B}|} \neq 0. \]  

(6)

Near the surface this electric field produce a force that surpass the gravitational attraction and put off particles from the surface and eject into magnetosphere. This particle will co-rotate with the star until the distance where the linear velocity reaches the speed of light, \( v = c \). This region is the light cylinder with radius

\[ R_L = \frac{c}{\Omega}. \]  

(7)

and much more particles achieve this region more relativistic they are. Magnetic field lines beyond the light cylinder are open and delimit a region at surface called polar cap.

The plasma in the magnetosphere is governed by electric forces and flowed. If we assume the electric conductivity as infinity, the version of Ohm’s law \( J = \sigma (E + vB/c) \) implies [36],

\[ \vec{E} + \frac{1}{c} (\vec{\Omega} \times \vec{r}) \times \vec{B} = 0. \]  

(8)

This parallel electric field determines a charge distribution, known as Goldreich-Julian charge density [37]

\[ \rho_c = \frac{1}{4\pi} \vec{\nabla} \cdot \vec{E} = -\frac{1}{2\pi c} \vec{\Omega} \cdot \vec{B}. \]  

(9)

For a magnetic dipole field pointing along \( \theta = 0 \),

\[ B(r) = \frac{B_0 R^3}{r^3} (2e_r \cos \theta + e_\theta \sin \theta), \]  

(10)

the typical length where the particle are accelerated is essentially the same of the radius of polar cap, so the potential difference follow as [38]

\[ \nabla \Phi \sim \frac{\Omega^2 R^3 B_0}{2c^2}. \]  

(11)

This potential would be available to accelerate particles from the surface of the star along the open magnetic fields lines that leave the magnetosphere with high energy.

There are some sites in the magnetosphere where occurs the particle acceleration, one of this is the polar cap region, just above the magnetic pole. Electrons and ions emerge with ultra-relativistic energies, moving along the magnetic field lines. The perpendicular energy is rapidly
dissipated by synchrotron radiation, but the longitudinal energy acquired could radiates far way of the star by curvature radiation,

\[ E_\gamma = \frac{3}{2} \frac{\hbar c \gamma^3}{r_c} \]  

(12)

where

\[ r_c \sim (Rc/\Omega)^{1/2}, \]  

(13)

is the curvature radius of the field lines. This curvature radiation interact with the magnetic field and produce secondary \( e^\pm \) pairs, \( \gamma + B \rightarrow e^- + e^+ \) leading to a pair creation avalanche. The value of \( \gamma \) is given by the potential difference in the polar cap region,

\[ \gamma = \frac{e\Delta V}{mc^2}, \]  

(14)

that in neutron stars pulsars is able to produce electrons that achieve Lorentz factors \( \gamma \gtrsim 10^7 \). In the polar cap model, there is a gap \( h \) [2] above the polar region, and the potential difference becomes

\[ \Delta V = \frac{B_\theta \Omega h^2}{2c}, \]  

(15)

where \( h \) is given by

\[ h \approx \left( \frac{R^3 \Omega}{c} \right)^{1/2}. \]  

(16)

4. Discussion

As we discuss the previous sections, the magnetic field of a white dwarfs can be calculated by the dipole expression. Thus, for SGRs/AXPs with \( P \) and \( \dot{P} \) from [16], the magnetic fields are

\[ B_{WD}^p \sim 10^{9} \text{G}. \]  

(17)

This allow us to estimate the charge density in the magnetosphere, i.e., the Goldreich-Julian density given by equation (9)

\[ \rho_{WD}^c \sim 10^{-2} \text{cm}^{-3}, \]  

(18)

this value is \( 10^5 \) smaller than the one when SGRs/AXPs are considered as neutron star which has a magnetic field \( B \sim 10^{14} \text{G} \). So, in the magnetosphere of SGRs/AXPs as white dwarfs there are less charge particles than in the neutron star magnetosphere.

We can calculate the maximum potential difference achieved on the surface of SGRs/AXPs as white dwarfs by equation (15) with \( \Omega \sim 1 \text{Hz}, R \sim 3 \times 10^3 \text{km}, \) and obtain,

\[ \Delta V \sim 10^{16} \text{V}. \]  

(19)

This difference is achieved for length \( h \sim 10^3 \text{cm} \) and allows the particles accelerated to reach ultra-relativistic energies more than neutron stars pulsars, i.e.. White dwarfs can accelerate electrons, following equation (14), with a Lorentz factor at least \( \gamma \sim 10^{10} \), one thousand large than neutron star pulsars, which can produce curvature photons with an energy up to \( \sim 10^{21} \text{eV} \) (ions iron can be also accelerated up to high energy). Since the photon is emitted in a cone with a angular aperture \( 1/\gamma \) and there is a low charged particle density, some photons or another low mass particle produced by \( \gamma + \gamma \) with this energy can escape far away from the star and through the space to the Earth. SGRs/AXPs are within the GZK limit [39] (\( \approx 10\text{Mpc} \) for protons with a energy of \( 10^{19} \text{eV} \)) and the particles accelerated in this sources could be a fraction of ultra-high cosmic ray observed in our planet.
5. Acknowledgments
This work was financially supported by CAPES (Coordenação de Aperfeiçoamento de Pessoal de Nível Superior), CNPq (Conselho Nacional de Desenvolvimento Científico e Tecnológico) and FAPESP thematic project 2015/26258-4. The authors acknowledgements also to McGill Pulsar Group.

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