

Ultra-high energy cosmic rays from white dwarf pulsars and the Hillas criterion

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Abstract. The origins of ultra-high-energy cosmic rays ($E \gtrsim 10^{19}$ eV) are a mystery and still under debate in astroparticle physics. In recent years some efforts were made to understand their nature. In this contribution we consider the possibility of Some Soft Gamma Repeaters (SGRs) and Anomalous X-ray Pulsars (AXPs) being white dwarf pulsars, and show that these sources can achieve large electromagnetic potentials on their surface that accelerate particle almost at the speed of light, with energies $E \sim 10^{20-21}$ eV. The sources SGRs/AXPs considered as highly magnetized white dwarfs are well described in the Hillas diagram, lying close to the AR Scorpii and AE Aquarii which are understood as white dwarf pulsars.

1. Introduction

In our previous work we have raised some issues concerning the origin of ultra-high-cosmic rays (UHECR) [1]. We pointed out that some soft Gamma Repeaters (SGRs) and Anomalous X-ray pulsars (AXPs) could be considered white dwarf pulsars. The idea of SGRs/AXPs as possible sources of the highest energy cosmic rays was investigated by Arons [2], that have considered these sources as neutron stars with ultrastrong magnetic field ($B \sim 10^{15}$ G) on their surface, the so-called magnetars. Rotation and strong magnetic fields can induce large potential differences [3, 4] on the star's surface, accelerating particles with high energy and fulfilling the magnetosphere with pairs of electron and positrons, which turns into a cascade of photons. More recently Kashiyama et al. [5] have done an important work in this perspective, suggesting that the excess of cosmic ray electron and positrons observed in PAMELA is produced in magnetized White Dwarfs (WDs), by the same mechanism as the one of neutron star pulsars.

In fact, highly magnetized white dwarfs are able to have a large electric field on their surface. Recently, a great number of massive and magnetic white dwarfs (10^6 - 10^9 G) have been observed [6], and in 2016 a white dwarf pulsar known as AR Scorpii has been discovered with some minutes of period, showing radiation in a broad range of frequencies [7, 8]. Thus, these fast and magnetized WDs can be in principle a potential source for ultra-high-energy-cosmic rays, and in this contribution we will investigate this possibility.



2. The sources

SGRs/AXPs are typically identified with very slow rotating pulsars $P \sim (2 - 12)$ s, with intense magnetic fields $\sim 10^{15}$ G [9]. Their spin-down rates $\dot{P} \sim (10^{-13} - 10^{-10})$ s/s are larger than the ones of normal pulsars $\dot{P} \sim (10^{-15} - 10^{-14})$ s/s [10]. The magnetar's X-ray luminosity L_X is explained by the decay of their enormous magnetic field. These sources do not can be understood as rotation powered neutron stars, because their rotational energy is much smaller than X-ray luminosity. Currently there are 23 SGRs/AXPs¹ that are classified as magnetars and 6 until now only candidates [11].

2.1. SGRs/AXPs as white dwarf pulsars

It has been proposed by Malheiro, Rueda and Ruffini an alternative model considering SGRs/AXPs as white dwarf pulsars [12]. As discussed in [13], the process of release energy for dipole radiation in a white dwarf can be explained in terms of a canonical spin-powered pulsars model, since in certain aspects they are similar (see e.g., [14, 15, 16]).

For example, if we consider a star with $M = 1.4M_\odot$ and $R = 10^6$ cm, the magnetic field at poles is given by,

$$B_p^{\text{NS}} = 3.2 \times 10^{19} (P\dot{P})^{1/2} \text{G}. \quad (1)$$

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,

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

Following the last consideration there are new values for the mass density, moment of inertia, dipole moment and rotation energy [16, 17]. This description is supported by the observational growth of fast, massive and highly magnetized WDs [6, 18, 19, 20].

2.2. White dwarf pulsars

This description was raised by Ostriker [21, 22]. Later, the seminal works of Usov [23, 24] have discussed the generation of gamma rays by magnetic white dwarfs, showing that WD can produce pairs of electron-positron e^\pm . Zhang and Gil [25] interpreted the transient radio source, GCRT J1745-3009, as a white dwarf pulsar with a period of 77.13 minutes. In this situation the production of e^\pm due curvature radiation is below of the pair-production threshold, still if the star is assumed with a field $B_p^{\text{WD}} = 10^9$ G. We highlight the recent discovery, AR Scorpii (AR Sco's), as a pulsating white dwarf in a binary system confirming the hypothesis of white dwarf pulsar [7]. AR Sco's has a range of mass $0.81M_\odot < M_1 < 1.29M_\odot$ and pulses with a period of 1.97 minutes. These pulses reflect the spin of a WD, slowing down on a 10^7 yr timescale. The AR Sco's broadband spectrum is characteristic of synchrotron radiation, requiring relativistic electrons, possibly originate from near the white dwarf and accelerated to almost the speed of light. These particles produce radiation from X-ray to radio wavelengths, typically of neutron star pulsars. This rapidly rotating magnetized WD would simulate the neutron star pulsars as pointed out by Geng et al. [26]. Another specific example is AE Aquarii, the first white dwarf pulsar, with a short period $P = 33$ s and spinning down at a rate $\dot{P} = 5.64 \times 10^{-14}$ s/s. The rapid braking of the white dwarf and the nature of hard X-ray pulses detected with SUZAKU space telescope [27] can be explained in terms of spin-powered pulsar mechanism [28]. Although AE Aquarii is a binary system with orbital period 9.88 hr, pretty likely the matters' accretion is inhibited by the fast rotation of the white dwarf.

¹ <http://www.physics.mcgill.ca/~pulsar/magnetar/main.html>

3. General constrains from geometry and radiation to UHECR

There are some constrains that UHECR particles should satisfy, as shown by [29]:

- geometry - the accelerated particle should need be kept inside the source while being accelerated;
- power - the source should posses the required amount of energy to give it to accelerated particles;
- radiation losses - the energy lost by a particle for radiation in the accelerating field should not exceed the energy gain;
- interaction losses - the energy lost by a particle in interactions with other particles should not exceed the energy gain;
- emissivity - the total number (density) and power of sources should be able to provide the observed UHECR flux;
- accompanying radiation of photons, neutrinos and low-energy cosmic rays should not exceed the observed fluxes, both for a given source and for the diffuse background.

4. Hillas criterion

If a particle escapes from the region where it was being accelerated, it will not be unable to gain more energy. The one in question establish a limit on maximum energy E_{\max} acquired by a particle passing in a medium with magnetic field B ,

$$E_{\max} = ZqBR_s, \quad (3)$$

where q is the electric charge of the particle, B is the magnetic field, R_s is the size of the accelerator and Z the atomic number of the particle (for the case of iron, $Z = 26$). This equation considers the Larmour radius of the particle, $R_L = E_{\max}/(ZqB) \leq R_s$. This is a general geometrical criterion known as the *Hillas criterion* for all types of cosmic ray sources [30]. Neglecting energy losses, i.e., the accelerator is 100% efficient, we see that only the parameters R_s and B can describe the source, showing a relationship between the sources' magnetic field strength and its size.

5. Particle acceleration

As we discussed above, there are a great number of magnetic white dwarfs and according Usov [24] if the surface temperature is less than 10^4 K (see [31], for the thermal emission in fast rotating, highly magnetized white dwarfs), a scale height of its atmosphere is essentially smaller than the radius of white dwarf R and the WD will have a strong electric field E in its magnetosphere,

$$E_{\parallel} = \vec{E} \cdot \vec{B}/|\vec{B}| \neq 0. \quad (4)$$

This parallel electric field determines a charge distribution, known as Goldreich-Julian charge density [32],

$$\rho_c = \frac{1}{4\pi} \vec{\nabla} \cdot \vec{E} = -\frac{1}{2\pi c} \vec{\Omega} \cdot \vec{B}. \quad (5)$$

Particles in that charge distribution co-rotate with the star until the distance where the linear velocity reaches the speed of light. This region is commonly known as light cylinder, with a radius $R_l = c/\Omega$. Near the surface of the star, the intense electric field tear away particles. Ultra relativistic particles flowing out, move along the open magnetic field lines producing curvature radiation,

$$E_{\gamma} = \frac{3}{2} \frac{\hbar \gamma^3 c}{r_c}, \quad (6)$$

where

$$r_c \sim (Rc/\Omega)^{1/2} \quad (7)$$

is the curvature radius of the field lines. The perpendicular energy of the particle is rapidly dissipated by synchrotron radiation. 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 the Lorentz γ factor of the e^\pm pairs produced, is given by the potential difference in the polar cap region,

$$\gamma = \frac{e\Delta V}{mc^2}. \quad (8)$$

Neutron star pulsars are able to produce electrons with Lorentz factors $\gamma \gtrsim 10^7$. There is a gap h above the polar region, and the potential difference becomes [33]

$$\Delta V = \frac{B_p \Omega h^2}{2c}, \quad (9)$$

where h is given by

$$h \approx \left(\frac{R^3 \Omega}{c} \right)^{1/2}. \quad (10)$$

6. Discussions

Using the dipole formula given in Ref. [34] to calculate the magnetic field, we have shown that the magnetic fields for SGRs/AXPs as highly magnetized white dwarf are at the order of [17, 35, 36, 37, 38],

$$B_p^{\text{WD}} \sim 10^9 \text{ G}. \quad (11)$$

This allows us to estimate the charge density in the magnetosphere, i.e., the Goldreich-Julian density given by equation 5,

$$\rho_c^{\text{WD}} \sim 10^{-2} \text{ cm}^{-3}, \quad (12)$$

this value is 10^5 smaller than the ones when SGRs/AXPs are considered as neutron stars, which have a magnetic field $B \sim 10^{14-15}$ G. Thus, in the magnetosphere of SGRs/AXPs being white dwarfs, there are less charged particles than the neutron stars ones.

From equation 9, we can calculate the maximum potential difference achieved on the surface of SGRs/AXPs as white dwarfs, using $\Omega \sim 1$ Hz, $R \sim 3 \times 10^3$ km,

$$\Delta V \sim 10^{16} \text{ V}. \quad (13)$$

This difference is achieved in a length of $h \sim 10^3$ cm, and allows the particles accelerated to reach ultra relativistic energies, larger than that of neutron star pulsars. Therefore, white dwarfs can accelerate electrons with Lorentz factors at least $\gamma \sim 10^{10}$, one thousand times larger than those accelerated by neutron star pulsars, being capable to produce curvature photons with an energy up to $\sim 10^{21}$ eV.

Figure 1 show the Hillas plot for a maximum energy of $E_{\text{max}} = 10^{20-21}$ eV for protons and $E_{\text{max}} = 10^{20-21}$ eV for iron. The sources above the green and black lines are able to accelerate atoms of iron up to 10^{20} eV and 10^{21} eV, respectively. Similarly, the sources above the blue and orange lines are able to accelerate protons up to 10^{20} eV and 10^{21} eV, respectively. This figure shows that SGRs/AXPs described as WDs and the two known white dwarf pulsars are all on the line of the Hillas plot obtained by Hillas criterion, and consistent with all the others cosmic ray sources known in the universe. Moreover, SGRs/AXPs as magnetars (neutron star pulsars) are out and much above this line, which is not the case for ordinary neutron star pulsars as

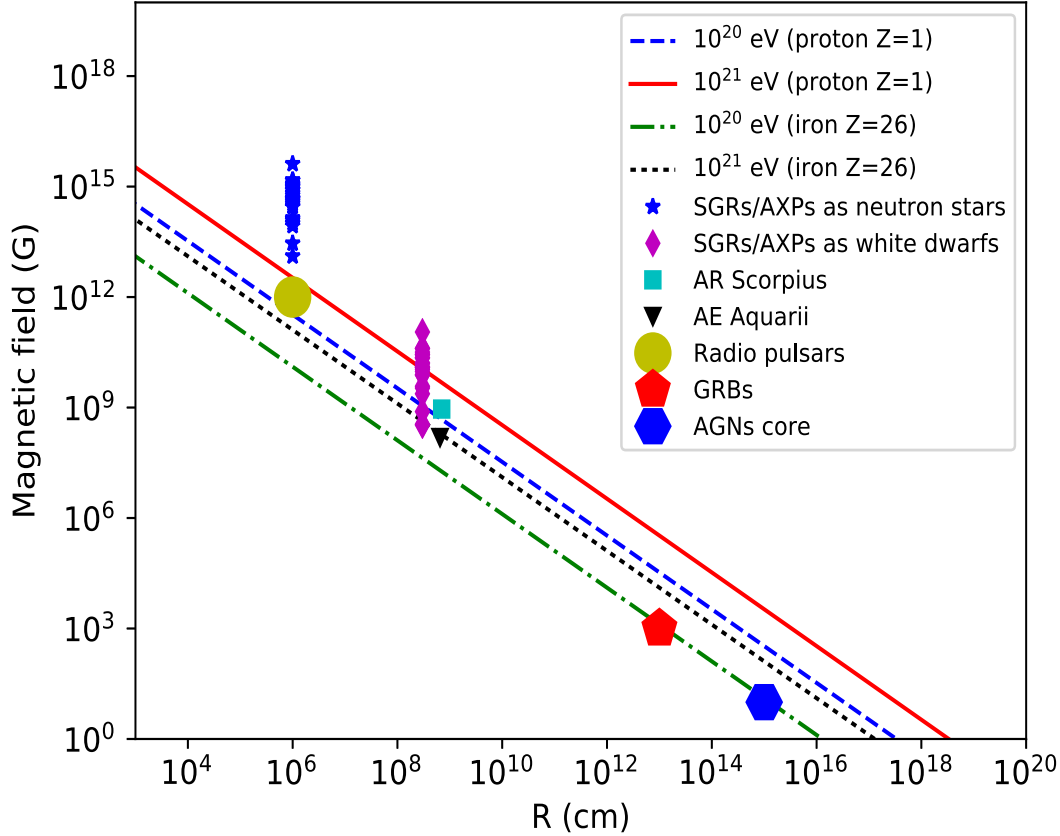


Figure 1. Hillas plot showing the magnetic field strength versus size of SGRs/AXPs as NSs (magnetic field $\sim 10^{13-15}$ G and radius of 10^6 cm) and WDs (magnetic field $\sim 10^8-10$ G and radius of 3×10^8 cm). The blue-stars and magenta-diamonds describe the SGRs/AXPs as neutron stars and white dwarfs, respectively. Here, we are considering these cosmic ray sources for a maximum energy of $E_{\max} = 10^{20-21}$ eV for protons (blue and orange lines) and $E_{\max} = 10^{20-21}$ eV for iron (green and black lines). The cyan-square and black-triangles represent AR Scorpius with magnetic field of $\approx 9 \times 10^8$ G and radius of 7×10^8 cm, and AE Aquarii with magnetic field of $\approx 1.5 \times 10^8$ G and radius of 6.5×10^8 cm, respectively. As we see these two sources are able to accelerate ultra-high energy cosmic rays. It's worth mentioning other possible sources of cosmic rays pointed in the literature: the yellow-circle, red-pentagon and blue-hexagon are the known radio pulsars, gamma rays-bursts (GRBs) and active Galaxy nuclei (AGNs), respectively.

we also show in Figure 1. Thus, it is quite important to obtain precision measurements of the radius and surface magnetic field of SGRs/AXPs with the new telescopes.

The interaction losses are minimum in the stars' magnetosphere, considering the photon is emitted in a cone with an angular aperture $1/\gamma$ and there is a low charged particle density. Among all SGRs/AXPs, CXOU J010043.1 is the most distant source, located ~ 62.4 kpc, thus all sources are within the GZK limit, which is a theoretical upper limit on the energy of cosmic rays coming from outside of our Galaxy (≈ 10 Mpc for protons with energy of 10^{19} eV) [39, 40]. Particles accelerated in these sources could be a fraction of ultra-high cosmic ray

observed in our planet. All these findings support the plausibility of ultra-high energy cosmic rays from SGRs/AXPs (fast and magnetic massive white dwarfs), in line with important and recent astronomical observations of white dwarf pulsars. We encourage future observational campaigns to verify the radius and the magnetic field of these sources.

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