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Compact central object as a source of high-energy cosmic rays

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Abstract. The production of energetic particles in the Universe is one of the great mysteries of modern science. In recent years, some efforts have been made to identify Galactic sources capable of accelerating particles to 1 PeV, known as PeVatrons. The different morphology of Galactic supernova remnants (SNRs) is directly correlated with the nature of the star's explosion and the existence of a possible Compact Central Object (CCO). CCOs have small radii and intense gravitational fields on their surfaces. Due to these strong fields and interactions with magnetized clouds (MCs) around them, they are considered possible candidates for the production of cosmic rays. In August 2002, the XMM-Newton spacecraft dedicated two of its orbits to the compact object 1E 1207.4-5209, with a total observation time of 257,303 s. The compact X-ray source 1E 1207.4-5209 is located very close to the remnant center G296.5+10.0. In this work, we obtain the contribution of high-energy gamma-ray emission (E > 100 GeV) from the acceleration and propagation of cosmic rays from the Central Compact Object 1E 1207.4-5209 and its host SNR G296.5+10.0. We also calculate the contribution of this association to the total observed Galactic cosmic-ray flux, considering the cosmic-ray propagation within the Galaxy with all energy losses and particle interactions. We propose that the above configuration can provide a rich scenario for the generation of GeV-TeV and cosmic ray to PeV ranges within the Galaxy. The new version of the GALPROP software was used and explored in order to obtain good results.

Resumo. A produção de partículas energéticas no Universo é um dos grandes mistérios da ciência moderna. Nos últimos anos, alguns esforços têm sido feitos para identificar fontes Galácticas capazes de acelerar partículas até 1 PeV, conhecidas como PeVatrons. A diferente morfologia dos remanescentes de supernovas Galácticas está correlacionado diretamente com a natureza da explosão da estrela e a existência de um possível Objeto Central Compacto (CCO). CCOs apresentam raios pequenos e intensos campos gravitacionais em suas superfícies. Devido a estes fortes campos e interações com nuvens magnetizadas ao seu redor, são considerados possíveis candidatos à produção de raios cósmicos. Em agosto de 2002, a espaçonave XMM-Newton dedicou duas de suas órbitas para o objeto compacto 1E 1207.4-5209, com um tempo total de observação de 257.303 s. A fonte compacta de raios-X 1E 1207.4-5209, está localizada muito próxima ao centro remanescente G296.5+10.0. Neste trabalho, obtemos a contribuição da emissão de raios gama de altas energias (E > 100 GeV) proveniente da aceleração e propagação dos raios cósmicos do Objeto Compacto Central 1E 1207.4-5209 e sua hospedeira SNR G296.5+10.0. Também calculamos a contribuição desta associação para o fluxo total de raios cósmicos Galácticos observado, considerando a propagação de raios cósmicos dentro da Galáxia com todas as perdas de energia e interações de partículas. Propomos que a configuração acima pode fornecer um rico cenário para a geração de gamas GeV-TeV e de raios cósmicos até PeV dentro da Galáxia. A nova versão do software GALPROP, foi utilizada e explorada a fim de obter bons resultados.

Keywords. Cosmic Rays. Gamma Radiation. Compact Central Object

1. Introduction

The generation of energetic particles in the universe is one of the great puzzles of contemporary astrophysics. Another mystery is the mechanisms of acceleration of such particles in astrophysical sources. These particles are known as cosmic rays (CRs). Cosmic rays are charged particles with velocities close to the speed of light that are produced by phenomena of cosmic scale or by astronomical objects that may be galactic or extragalactic. When accelerated from the sources, these high-energy particles travel through the interstellar medium at $E > 10^{20}$ eV and enter the atmosphere of our planet, producing a continuous stream. In their composition, we find ions made of several atomic nuclei such as protons, helium, carbon, oxygen, iron, and others. They can also consist of stable leptons, e^+, e^-, antiprotons and gamma rays Anjos (2014).

There are numerous candidates for galactic or extragalactic sources of cosmic rays. For such an origin analysis, we first use a very coarse criterion, namely the energy of the particles that make up the cosmic rays. Through direct and indirect observations, we can describe a particle flux by the energy obeying a power law $\frac{dN}{dE} \sim E^{-\alpha}$, where the particle flux is approximately equal to the energy of the particle raised to a spectral index α Bandeira & Mackedanz (2019). Such an energy spectrum classifies particles with $E < 10^9$ eV originating from the solar region and having the largest flux within the spectrum. The energy range from 10^9 to 10^{15} eV in the *Pev* region, where the flux is one particle per $\frac{m^2}{s}$, includes particles of Galactic origin, since there are no objects in our solar system that can accelerate particles to these energies. At the end of the spectrum, the particle flux is expected to drop dramatically to one particle per $\frac{metre^2}{year}$, which would allow the capture of extragalactic particles Kulikov & Khrisriansen (1959) Batista (2019). In addition to the analysis of the energy spectrum, other methods help in the classification and detection of possible sources of cosmic rays, such as the Pierre Auger Observatory anisotropy studies Anjos et. al. (2018) and the so-called Hillas criterion, which classifies possible sources of cosmic rays and deals with minimum requirements for the size of the accelerating region of the object with respect to its respective magnetic field.

After analyzing the origin of CRs, we investigated the spatial and energetic processes that involve the transport of particles until their discovery. The equation governing this transport is as follows:

$$\frac{\partial N}{\partial t} + [\nabla.(K(E,\boldsymbol{r})) + \nabla \boldsymbol{v_c}(\boldsymbol{r})N(E,\boldsymbol{r},t) + \frac{\partial}{\partial E}b(E)N-$$

$$-C(E)\frac{\partial N}{\partial E}] + (\tau_{inel} + \tau_{rad})N \equiv Q(E,\boldsymbol{r}), \quad (1)$$

where $\frac{\partial N}{\partial t}$ is the flux of particles, $\nabla.(K(E,\boldsymbol{r})$ the spatial diffusion, and $\nabla \boldsymbol{v_c}(\boldsymbol{r})$ the convection. The term $\frac{\partial}{\partial E}b(E)N$ reflects all energy losses, plus the term $C(E)\frac{\partial N}{\partial E}$ for the energy gain during particle propagation in the interstellar medium. The term $(\tau_{inel} + \tau_{rad})N$ governs the processes of nuclear destruction of particles by radioactive decay and inelastic interactions. The term $Q(E,\boldsymbol{r})$ governs the distribution of the source and is one of the main focuses of current studies.

For the construction of the model we used as source an already classified pulsar, chosen for its strong properties. Pulsars are magnetized neutron stars that appear to emit short periodic pulses of radio radiation with periods between 1.4 *ms* and 8.5 *s*. Their pulses are extremely accurate and stable, with a deviation of 10^{-16}, and are called astronomical clocks. These astronomical objects are great physics laboratories because of their extreme environments. We will see a more detailed description of the object that serves as the source and the simulation model later.

2. High-energy gamma-ray emission from CCO 1E 1207.4-5209 and its host SNR G296.5+10.0

Compact Central Objects (CCOs) are astronomical objects found at the geometric center of supernova remnants (SNR), with thermal emissions (hundreds of eV) in the X-ray range and luminosity in the range of $(10^{33} - 10^{34})$ erg s^{-1}. The interesting thing about CCOs is that they show negligible emission in other Harding (2013) energy bands. Measurements of the period (P) and deceleration rate ($\dot{P}$) suggest that these objects are "anti-magnetic", because they have low magnetic fields in the range $10^{10} - 10^{11}$ G. These weak magnetic fields are thought to be due to magnetic dipole braking.

The compact central object 1E 1207.4-5209, classified as a strongly spinning silent neutron star, lies at the center of the supernova remnant G296.5+10.0, also called PKS 1209-51, as shown in Fig.1. In August 2002, the XMM-Newton spacecraft devoted two of its orbits to 1E 1207.4-5209 with a total observation time of $\sim$ 36 *hours*, one of the longest observations with the EPIC 12.13 instrument of a galactic font Luca (2004). It is located in the constellation Centaurus, at a distance of ~ 2 kpc.

Source 1E 1207.4-5209 is the only isolated neutron star whose magnetic field is measured rather than inferred, as with other objects. XMM-Newton discovered the presence of X-ray absorption lines in its spectrum. The lines can be interpreted as electron cyclotron resonance near the surface of the central object. These found cyclotron lines (0.7 keV) correspond to a magnetic field of $\sim 8 \times 10^{10}$ G or $\sim 1.6 \times 10^{14}$ G Ankay & Ercan (2007). Other important features of this source include a pulsar period of 0.42413076 s, and a light curve for the entire energy range of $(0.2 - 4)$ keV. The upper limit of the period derivative is $\dot{P} < 2.5 \times 10^{-16}$ ss^{-1} (in 2θ), giving a characteristic age $t > 27$ Myr, which exceeds the age of the SNR Luca (2004) by 3 orders of magnitude.

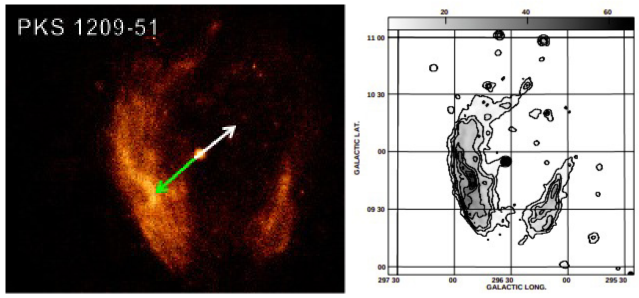

Figure 1. *(left)*: Observations by ROSAT of CCO 1E 1207.4-5209 and its SNR. The green arrow shows the explosion location in the direction of the dipole moment and the white arrow represents the direction of motion of the neutron star. Adapted from Lopez & Fesen (2018). *(Right)*: X-ray observation of the same object in Galactic coordinates in the energy range 0.1 - 2.4, with the dark spot in the center belonging to CCO 1E 1207.4-5209. Adapted from Giacani et al. (2000).

3. Simulations

To extract the information contained in cosmic ray and particle flux data, models of particle production and propagation in the Galaxy must be developed. With the goal of reproducing realistic and consistent astrophysical processes and, at the same time, all processes involved in the 1 equation, we have developed a simulation model using GALPROP software (version 57).

Given an initial distribution and given boundary conditions, GALPROP solves the transport equation in 3D simulations, taking into account all the processes mentioned earlier in this work in Section 1. At the end of the simulation, the software provides us with the corresponding spectrum of gamma rays likely to be detected on Earth. Based on the abundances of the source CR implemented at the beginning, GALPROP calculates the production of isotopes. For the numerical solution of the equation 1, the software uses the second-order Crank-Nicholson method. The diffusion coefficient is calculated using the boron/carbon ratio and considering a stiffness, and dispersion parameter Johannesson & Porter & Moskalenko (2018); Strong & Moskalenko (1998).

The model assumes that the acceleration of particles injected into the ISM follows a power law $dq(p)/dp \propto p^{-\alpha}$. The modeling is performed with a total power of Coelho & et. al. (2022)

$$L(t) = \eta L_0 \left(1 + \frac{t}{\tau_0}\right)^{-2}, \quad (2)$$

where $L_0 = 1.0 \times 10^{33}$ erg s^{-1} is the initial spin-down power of the CCO, η is the efficiency factor, $\tau_0 = 3.63 \times 10^5$ yr is the pulsar time scale Malyshev & Cholis & Gelfand (2009), defined as the ratio of the initial rotational energy to the initial rotational luminosity, and $t = 3.02 \times 10^8$ yr for the age of the pulsar.

In this work, we use inhomogeneous diffusion in space near the source of CRs, known as the two-zone diffusion model Johannesson & Porter & Moskalenko (2019). Gamma rays are produced by the propagation and interaction of particles, including primary and secondary protons. As for the energy losses, the inverse Compton scattering is calculated taking into account the interstellar radiation field. The pion photoproduction and bremsstrahlung are calculated using the gas density H in the interstellar medium. The synchrotron radiation originates from the interaction of particles with the galactic magnetic field Coelho & et. al. (2022). The γ radiation is calculated and compared with measurements of gamma radiation from the OCC, whether they are model data Zeng & et. al. (2021) or direct measurements Araya, (2013).

4. Discussions

The interaction of cosmic rays, whether hadronic or leptonic in origin, with the interstellar medium, produces gamma rays. We simulate the injection of particles from CCO E 1207.4-5209 into its environment and the contribution of gamma-ray emission from its SNR G296.5+10.0, assuming a diffusion of $2.5 \times 10^{28} cm^2 s^{-}1$ with a slope of $\delta = 0.6$ and an Alfvén velocity of 28.0 km.$s^{-}1$ Coelho & et. al. (2022). The results are shown in Figure 2.

The models shown in Figure 2 result from the sum of gamma rays produced by pion decay, the inverse Compton effect, and Bremstralung emission. The so-called "spin-down model" is the injection of particles from the rotational properties of the source. The so-called "quiescent model" is the injection of particles from natural interactions of the source with its environment, normalized with respect to an upper limit on the integral gamma-ray flux Zeng & et. al. (2021). The total model is the sum of the spin-down and quiescent models.

Our results suggest that gamma rays from CCO E 1207.4-5209 and its host SNR G296.5+10.0 (data) can be also produced by cosmic rays injected from the source, in special between 10^3 - 10^5 MeV, see the Figure 2. Another result from our simulations is that the particle injection resulting from the rotation of the object accounts for a large fraction of the total injection potential of the source.

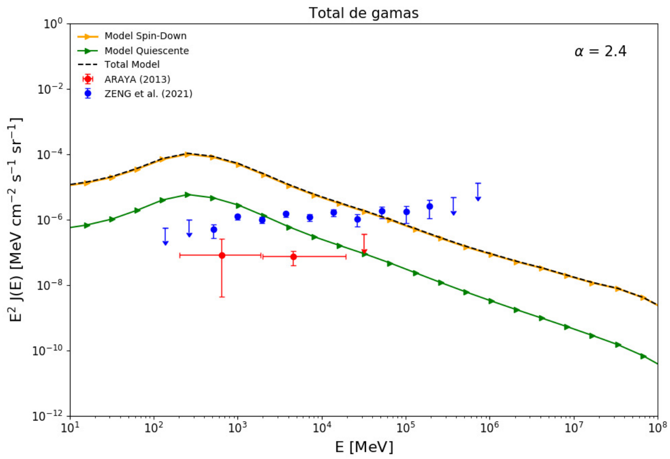

Figure 2. Spectral energy distribution of the total gamma-ray emission from CCO E 1207.4-5209 and its host SNR G296.5+10.0, for a spectral index of 2.4.

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