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Reconstructing the gamma-ray emission from the central molecular zone

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Abstract. The Galactic Center (GC) is one of the most complex and richest regions of the sky, harboring a plethora of cosmic-ray accelerators and non-thermal high-energy emitters. Among these, we highlight the recent discovery of a cosmic Pevatron, associated to the central suppemassive black hole Sagittarius A*. The Central Molecular Zone (CMZ) is a large region in the inner 600 parsecs of our Galaxy, surrounding the GC, comprised of high density giant molecular clouds. The interaction of the high-energy cosmic rays accelerated by this Pevatron with the surrounding molecular clouds can give rise to a sizeable gamma-ray emission from pion production and decay. There are different models for the CMZ density distribution along the line of sight, and properly understanding this geometry is crucial to interpret the observed GC gamma-ray emission. In this work we reconstruct the radiative models that can explain the gamma-ray emission from the GC as seen by gamma-ray telescopes. We simulate the gamma-ray flux on earth for different models of the cosmic-ray source and propagation, several models of CMZ 3D geometry.

Resumo. O Centro Galáctico (GC) é uma das regiões mais complexas e ricas do céu, abrigando uma infinidade de aceleradores de raios cósmicos e emissores de alta energia não térmica. Dentre esses, destacamos a recente descoberta de um Pevatron cósmico, associado ao buraco negro supermassivo central Sagitário A*. A Zona Molecular Central (CMZ) é uma extensa região nos 600 parsecs internos de nossa Galáxia, circundando o GC, composta por grandes nuvens moleculares de alta densidade. A interação dos raios cósmicos de alta energia acelerados por esse Pevatron com as nuvens moleculares circundantes pode gerar uma considerável emissão de raios gama decorrente da produção e decaimento de píons. Existem diferentes modelos para a distribuição de densidade da CMZ ao longo da linha de visada, e compreender adequadamente essa geometria é crucial para interpretar a emissão observada de raios gama no GC. Neste trabalho, reconstruímos os modelos radiativos que podem explicar a emissão de raios gama do GC conforme observado por telescópios de raios gama. Simulamos o fluxo de raios gama na Terra para diferentes modelos da fonte e propagação de raios cósmicos, bem como vários modelos de geometria 3D da CMZ.

Keywords. Astroparticle Physics – Galaxy: center – Gamma-rays: galaxies

1. Introduction

The Central Molecular Zone (CMZ), a region of giant molecular clouds and intense star formation near the Galactic Center, is a prolific source of gamma-ray emission. To comprehend the mechanisms at play, we employ several models that capture the physical conditions of the CMZ. Our study focuses on elucidating the gamma-ray flux and its dependence on the assumed density distribution and source properties. We assume that the gamma-ray radiation we observe is due to the π^0-decay, produced after proton-proton interactions of the CMZ nuclei with cosmic-rays emitted from a source near Sgr A*.

2. Propagation and emission model

In our analysis, we utilize the model emissivity of gamma rays originating from proton-proton collisions described by Aharonian (1996). The gamma-ray emissivity is intricately linked to the emissivity of pions, which, in turn, relies on the cosmic ray (CR) flux at the location of the molecular clouds. To calculate the CR flux, the standard diffusion approximation is solved analytically, resulting in the CR density found in equations 1 and 2,

$$f(E,R,t) = \frac{N_0 E^{-\alpha}}{\pi^{3/2} R_{dif}^3} exp\left(\frac{1-\alpha}{\tau_{pp}} t - \frac{R^2}{R_{dif}^2}\right), \tag{1}$$

$$f(E,R,t) = \frac{Q_0 E^{-\alpha}}{4\pi D(E) R} erfc\left(\frac{R}{R_{dif}}\right), \tag{2}$$

for impulsive and continuous sources, respectively. Here $f(E,R,t)$ is the cosmic-ray density by energy, R is the radial distance, t is the source age, E is the CR energy, α is the source power-law index, τ_{pp} is the average interaction time for the $p-p$ interaction, $D(E) = D_{10}\left(\frac{E}{10\ GeV}\right)^{\delta}$ is the energy-dependent diffusion coeficient, and $R_{dif} \approx 2\sqrt{D(E)t}$ is the diffusion radius.

The acceleration of protons by astrophysical sources initiates collisions between these protons and other protons in the interstellar medium (p-p collisions). From these collisions, if the center-of-mass energies is sufficiently high, neutral pions (π^0) are created. A fraction f_π of the kinetic energy of the proton is transferred to the π^0, which subsequently decays into two gamma-ray photons (γ). The explicit forms of these dependencies are captured by integral equations, where σ_{pp} denotes the proton-proton cross-section, a function of energy,

$$q_\pi(E_\pi) = \frac{1}{f_\pi}\sigma_{pp}\left(M_p c^2 + \frac{E_\pi}{f_\pi}\right) + J\left(M_p c^2 + \frac{E_\pi}{f_\pi}\right), \tag{3}$$

$$q_\gamma(E_\gamma) = 2\int_{E_{min}}^{\infty} dE_\pi \frac{q_\pi(E_\pi)}{\sqrt{E_\pi^2 - m_\pi^2 c^4}}, \text{ and} \tag{4}$$

$$F_\gamma(E_\gamma) = \frac{\int q_\gamma(\mathbf{r}) n(\mathbf{r}) dV}{4\pi d^2}. \tag{5}$$

These equations are numerically integrated in the energy using a logarithmic scale, crucial for capturing the rapid variations in q_π and q_γ. The resulting gamma-ray emissivity is then integrated in the molecular clouds with density distribution $n(\mathbf{r})$, resulting in gamma-ray maps for diverse geometric configurations of the CMZ.

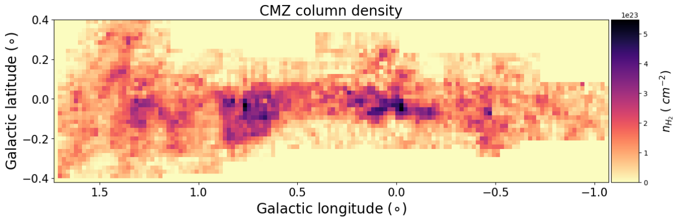

Figure 1. CMZ column density calculated through CS emission lines and by fixing the total mass at $M_{CMZ} = 2 \times 10^7 M_\odot$
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3. Modeling the CMZ

In our investigation, we explore different geometric models for the CMZ. We use molecular line-maps to calculate the front view columns density of the CMZ as shown in figure 1, and then use different schemes to model the column density distribution along the line of sight. First, we use the elliptical disk or annulus distributions of the CMZ along the line of sight suggested by Scherer (2022). This model provides a flexible framework and allows for straightforward implementation. Another approach involves the Armillota (2019) model, derived from a magneto-hydrodynamic simulation of the Milky Way's evolution. We use the simulation for a 505 Myr evolution time, after which it is assumed the CMZ enters in hidrodynamical equilibrium. We also use the data from Yan et. al. (2017) of the CMZ 3-D density distribution.

4. Results and Discussion

For our CR source we considered a continuous source with a proton luminosity $L_P(10\ TeV \leq E \leq 4\ PeV) = 8 \times 10^{37} erg/s$, aged $t = 6 \times 10^3$ years, with a power-law index $\alpha = 2.2$, and we consider an energy-dependent diffusion coefficient of $D(E) = 6 \times 10^{29} \left(\frac{E}{10\ TeV}\right)^{0.3}$ as suggested by H.E.S.S. (2016). Our investigation into gamma-ray emissions from the CMZ revealed a noteworthy consistency across diverse spatial models, as seen in figure 2. Despite variations in the proposed shapes of the CMZ—ranging from ellipses to rings and intricate magnetic field simulations—the resulting gamma-ray total fluxes exhibited the same order of magnitude with $F_\gamma(E_\gamma \geq 1\ TeV) \approx 10^{-12}\ s^{-1} cm^{-2}$. Such convergence in total gamma-ray flux output across distinct models can be attributed to a common underlying factor: the consistent utilization of the same total mass of $3 \times 10^7 M_\odot$ for the CMZ. This observation underscores the significance of overarching factors, such as total mass, in determining the gamma-ray emissions. It implies that the macroscopic characteristics exert a more pronounced influence on the outcomes than the specific nuances and shapes embedded in the models. This finding not only instills confidence in the reliability of our gamma-ray predictions but also signifies a crucial step toward understanding the fundamental dynamics of the CMZ.

5. Conclusion

Our study employs diverse models to simulate gamma-ray emission from the CMZ, providing a comprehensive analysis of the astrophysical processes at play. The discrepancies between models and observations underscore the need for refined density distributions and a deeper understanding of the CMZ's structure. Future work will involve refining models and comparing results with observational data to unravel the mysteries of gamma-ray emission in the CMZ.

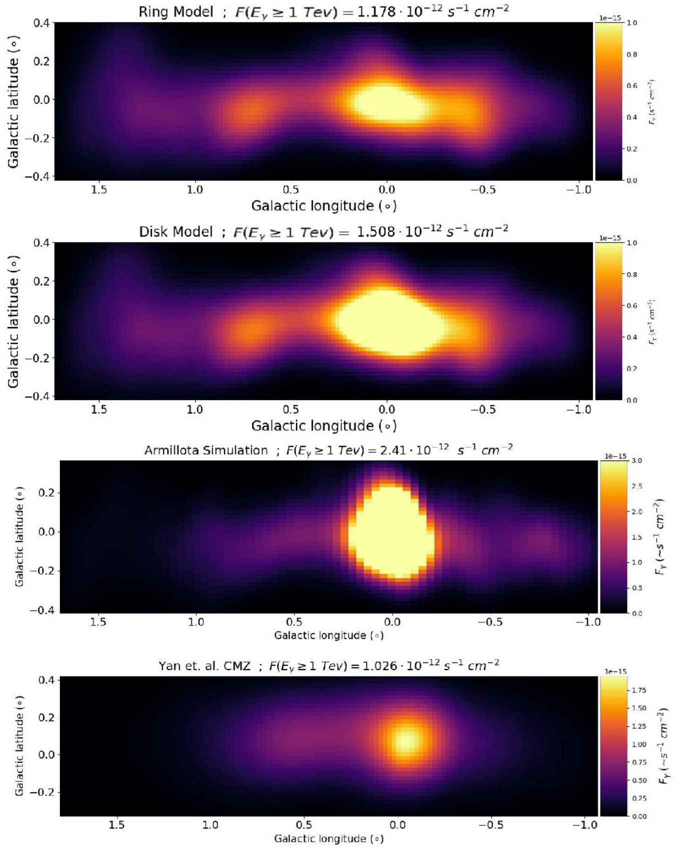

Figure 2. Gamma-ray fluxes for photons energies above 1 TeV in different CMZ models.

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