Boletim da Sociedade Astronômica Brasileira, **34**, no. 1, 34-35
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Radiative model reconstruction of gamma rays sources in the Galactic Center region

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Abstract. Among all the high-energy environments of our Galaxy, the Galactic Center region is the richest, with HESS J1745-290 being its brightest γ-ray source. However, its origin is still unknown, in view of this, this work aims to investigate whether the central source of γ-rays would be linked to cosmic particle accelerators, discovered in this region, capable of accelerating particles to PeV energies, called Pevatron.

With the elaboration of a computational code, the expected γ-ray flux was calculated in two different scenarios, from a source with an impulsive or a continuous injection of cosmic ray particles. In each case, a 2D image of the gamma-ray emissivity was made. It can be inferred from these results that future gamma-ray telescopes, such as CTA, when observing the Galactic Center, will be able to differentiate which of the two γ-ray emissivity scenarios is occurring in this region.

Resumo. Entre todos os ambientes de alta energia de nossa Galáxia, a região do Centro Galáctico é a mais rica, sendo HESS J1745-290 a sua fonte de raios-γ mais brilhante. No entanto sua origem ainda é desconhecida, em vista disso, esse trabalho almeja investigar se a fonte central de raios-γ estaria ligada a aceleradores cósmicos de partículas, descobertos nessa região, capazes de acelerar partículas até energias de PeV, chamados de Pevatron.

Com a elaboração de um código computacional o fluxo de raios-γ foi calculado em dois cenários distintos, de uma fonte de raios cósmicos de injeção impulsiva e de injeção contínua. Em cada caso foi feito uma imagem 2D desses fluxos. Já se pode inferir com esses resultados que telescópios futuros de raios gama, como o CTA, ao observar o Centro Galáctico, conseguirá diferenciar qual dos dois cenários de emissividade de raios-γ está ocorrendo nesta região.

Keywords. Acceleration of particles – Gamma rays: ISM – Cosmic rays

1. Introduction

The origin of the brightest central source of γ-ray HESS J1745-290 remains unknown. In this research we investigate the possibility that this source is linked to a PeVatron discovered in this region by the HESS Collaboration (2016). In this scenario, the stochastic acceleration of protons (up to PeV energies) interacting with the magnetic field in the vicinity of Sgr A^* could produce an outflow of relativistic protons that diffuse outward interacting with the molecular clouds that surround this region and through from the $p+p$ collision one of the generated by products is π^0 which decays into photons by the $\pi^0 \rightarrow \gamma + \gamma$ reaction It is through these γ-ray that we are studying this region The energy of the γ-ray compared to the accelerated proton is $E_\gamma \approx E_p/10$ so we need γ-ray in the TeV range to be able to identify protons with energy in PeV

2. Methods

In the standard diffusion approximation, the propagation of cosmic rays in the interstellar medium (ISM) can be described in the spherically symmetric case as Aharonian, F.A, & Atoyan, A.M. (1996)

$$\frac{\partial f}{\partial t} = \frac{D}{R}\frac{\partial}{\partial R}\left(R^2 \frac{\partial f}{\partial R}\right) + \frac{\partial (Pf)}{\partial E} + Q \tag{1}$$

In this equation $f = f(E, R, t)$ is the distribution function of particles at time t with energy E at a radial distance R from the source, $P = -\left(\frac{\partial E}{\partial t}\right)$ is the rate of continuous energy loss, $Q = Q(E, R, t)$ is the function that characterizes the emitting source of the particles, being proportional to a power law ($Q \propto E^{-\alpha}$) with spectral index $\alpha = 2.2$ and $D = D(E)$ denotes the diffusion coefficient that continues to be assumed to be independent of R or t, or in other words, a quasi-stationary and homogeneous medium around the source is assumed.

The equation 1 admits two possible scenarios for the injection regime of cosmic rays in the interstellar medium, being the impulsive case and the continuous case.

2.1. Impulsive Case

The impulsive scenario corresponds to the case where most relativistic particles are accelerated during times Δt much smaller than the age t of the accelerator. In this case, the source term can be modeled as $Q(E, R, t) = N_0 E^{-\alpha} \delta(R)\, \delta(t)$ and the solution of equation 1 is

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

where N_0 is a normalization constant, τ_{pp} is the proton lifetime and R_{dif} is the diffusion radius that corresponds to the radius of the sphere to which particles of energy E effectively propagate during the time t after their injection into the interstellar medium.

2.2. Continuous Case

In the continuous case, the accelerator continually injects relativistic particles into the ISM. In the case of continuous acceleration of particles by a single source with time-dependent evolution given by the expression $Q(E, t) = Q_0 E^{-\alpha} q(t)$ to obtain the particle distribution function $f(E, R, t)$ the Eq.2 must be convolved with the function $q\,(t-t')$ in the time interval $0 \le t' \le t$. With this, it is obtained that

$$f\,(E,R,t) = \frac{Q_0 E^{-\alpha}}{4\pi D\,(E)\,R}\,\mathrm{erfc}\left(\frac{R}{R_{dif}}\right) \tag{3}$$

where Q_0 is a normalization constant.

2.3. Modeling the Molecular Clouds of the Galactic Center

One of the hypotheses for the origin of the central source of γ-ray is that it originates from the diffusion of cosmic rays that leave the galactic center and interact with the molecular clouds in the central $10\,pc$. In this scenario, the protons relativistically accelerated by the particle accelerators, whether impulsive or continuous, will propagate in the ISM and given the large concentration of molecular clouds in the region of the central $10\,pc$ of the Sgr A^* black hole they will collide with other protons that constitute most of those clouds. As a result of the proton-proton collision there is the production of π^0, which subsequently decays into a photon in gamma energy. It is through these photons that this region can be studied.

In the article by Ferrière, K. (2012) the author proposed a 3D model of the interstellar gas inside $\sim 10\,pc$ of Sgr A^* as shown in the Fig.1

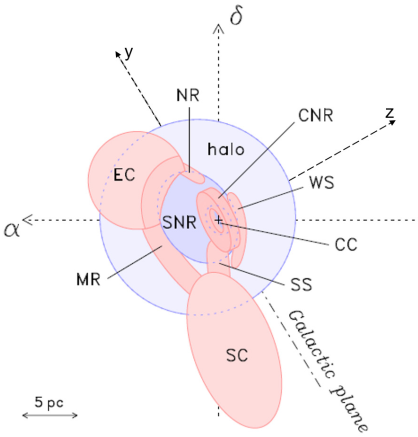

Figure 1. Diagram of the spatial arrangement of molecular clouds within $\sim 10\,pc$ of Sgr A^*

3. Results and Discussion

The masses of molecular clouds provided by Ferrière, K. (2012) are shown in Tab.1. For simplicity, the clouds that are constituted by more than one component, were considered as having a mass calculated by means of a weighted average of the volume of each constituent.

Some simplifications regarding the morphology of the clouds were also done, the main one being the treatment as curved cylinder shaped clouds as straight cylinders. Using the 3D distribution of clouds and masses given in Tab.1, a 2D image of the expected γ-ray emissivity was produced, as shown in Fig. 2 and Fig. 3, in the impulsive and continuous scenarios, respectively.

Given these first results it can be inferred that in the impulsive case the emissivity tends to be proportional to the clouds mass, while in the continuous case the flow decays with $1/R$. These two scenarios seem sufficiently different to be tested by gamma-ray telescopes, but further analysis is necessary.

Clouds	$M_H\,[M_\odot]$
Central Cavity (CC)	364
M-0.02-0.07 (EC)	2.0×10^5
Circumnuclear Ring (CNR)	9.8×10^4
Bridge	3.5×10^4
Sgr A East (SNR)	21
Southern Streamer (SS)	3.2×10^4
Radio Halo	1.6×10^4
Western Streamer (WS)	4.4×10^3
M-0.13-0.08 (SC)	2.2×10^5
Northern Ridge (NR)	2.2×10^3

Table 1. Hydrogen mass of clouds in the inner 10 pc of the Galaxy

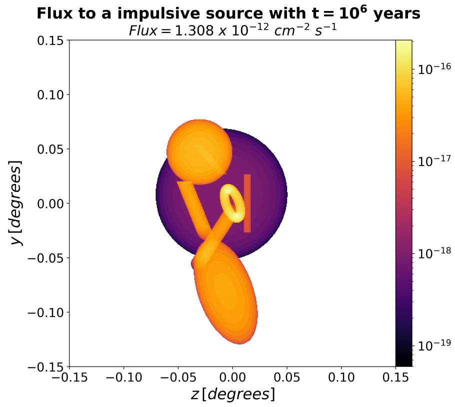

Figure 2. 2D image of the γ-ray flux from an impulsive source

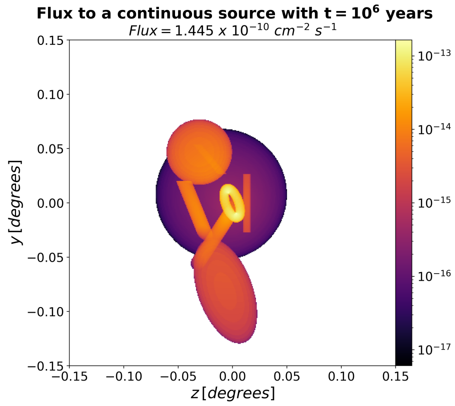

Figure 3. 2D image of the γ-ray flux from an Continuous source

4. Conclusion

Different behaviors were obtained for the different types of sources (impulsive and continuous), and it is possible to infer that future gamma-ray telescopes, such as CTA, observing the Galactic Center will probably be able to differentiate which of the gamma ray emissivity scenarios is occurring in this region.

Acknowledgements. I would like to thank São Paulo Research Foundation (FAPESP) for funding this research project number 2022/04510-2 and Professor Dr. Aion for his advsing. AV and DCM were sponsored by the São Paulo Research Foundation (FAPESP) through Grant No 2019/14893-3. AV is supported by CNPq grant 314955/2021-6

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