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Radiative model reconstruction of the Galactic Center central gamma-ray source

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Abstract. Among all the high-energy environments in our Galaxy, the Galactic Center region stands out as the richest, with HESS J1745-290 being its brightest gamma-ray source. However, its origin is still unknown; therefore, this study aims to investigate whether the central γ-ray source is connected to cosmic particle accelerators discovered in this region, capable of accelerating particles to PeV energies, known as Pevatrons. By developing a computational code, the gamma-ray flux was simulated and calculated in two distinct scenarios: from a source of impulsive cosmic ray injection and continuous injection. A 2D image of these emissions was created, yielding different morphologies. Through spatial analyses, information such as the position and extention of the source was extracted.

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 simulado e 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, obtendo diferentes morfologias das quais por meio de análises espaciais extraímos informações como a posição e extensão da fonte.

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. For instance, high pointing precision observations by the H.E.S.S. telescope led to the exclusion of Sgr A East supernova remnant as the main counterpart of the observed VHE emission HESS Collaboration (2009), and left Sgr A* (Aharonian & Neronov 2005; Liu et al. 2006) and the plerion G359.95-0.04 (discovered a lightyear of Sgr A*) (**?**) as plausible contributing sources for the observed emission. 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 generate γ-rays through $p + p$ collisions. 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 & Atoyan (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 injecting source of particles, which is proportional to a power law ($Q \propto E^{-\alpha}$) with spectral index $\alpha = 2.2$. $D = D(E)$ denotes the diffusion coefficient, independent of R or t, or in other words, a quasi-stationary and homogeneous medium around the source is assumed.

Equation 1 admits two possible scenarios for the injection regime of cosmic rays in the interstellar medium: impulsive and continuous.

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

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

where Q_0 is a normalization constant.

2.3. Emissivity of π^0-decay gamma-rays

One hypothesis for the origin of the central gamma-ray source is that it originates from the diffusion of cosmic rays emanating from the galactic center and interacting with molecular clouds within the central 10 parsecs of Sgr A*. To implement such a hypothesis, the article Ferrière (2012) was employed, where the author proposes a 3D model of the interstellar gas, as illustrated in Figure 1.

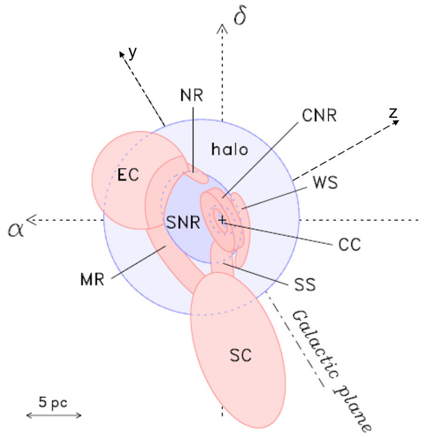


Figure 1. Diagram of the spatial arrangement of molecular clouds within ~ 10 pc of Sgr A^*. From Ferrière (2012).

In this scenario, the protons relativistically accelerated by the particle accelerator, 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, according to the reaction $\pi^0 \rightarrow \gamma + \gamma$. It is through these photons that this region can be studied.

Having the proton distribution with energy E at a radial distance R at a specific time t, as provided by equations 2 and 3, it is possible to define the differential flux of protons using the expression 4

$$J_p(E,R,t) = \frac{c}{4\pi} f(E,R,t) \quad (4)$$

Once the differential proton flux is defined, we can calculate the emissivity of gamma rays resulting from the decay of π^0 using the equation 5

$$q_\gamma\left(E_\gamma\right) = 2\int_{E_{min}}^{\infty} \frac{q_\pi(E_\pi)}{\sqrt{E_\pi^2 - m_\pi^2 c^4}} dE_\pi \quad (5)$$

With $E_{min} = E_\gamma + m_\pi^2 c^4 / 4E_\gamma$ being the minimum energy required that π^0, with mass m_π, must possess to decay into gamma rays and

$$q_\pi(E_\pi) = \frac{1}{f_\pi} \sigma\left(m_p c^2 + \frac{E_\pi}{f_\pi}\right) J_p\left(m_p c^2 + \frac{E_\pi}{f_\pi}\right) \quad (6)$$

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

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

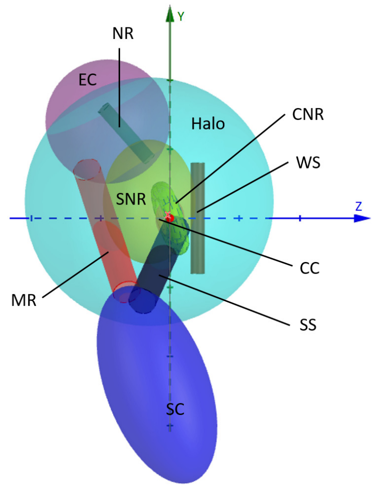


Figure 2. Remodeling of the spatial diagram of molecular clouds, considering some simplifications.

Where σ is total inelastic proton-proton cross-section given by $\sigma(E) \approx 30\,(0.95 + 0.06 Log\,(E_{GeV}))\,mb$, m_p is the mass of the proton and $f_\pi = 0.17$ is the fraction of kinetic energy that the primary proton transfers to the secondary π^0 meson at the time of its formation Aharonian & Atoyan (1996).

With the expression for emissivity, the expected gamma-ray flux is given by equation 7,

$$F_\gamma = \frac{\int_V n(r) q_\gamma(r)\, d^3 r}{4\pi d^2}, \quad (7)$$

where $n(r)$ is the gas number density, V is the volume of cloud and d is the distance of the cloud to the Earth.

3. Results and Discussion

The masses of molecular clouds provided by Ferrière (2012) are shown in Tab.1. For simplicity, the clouds constituted by more than one component were considered as having a mass calculated using a weighted average of the volume of each constituent. Some simplifications regarding the morphology of the clouds were also made, the main one being the treatment of curved cylindrical clouds as straight cylinders. By incorporating these simplifications, the three-dimensional model of molecular clouds presented in Fig.1 resulted in the adapted model shown in Fig. 2.

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. 3 and Fig. 4, in the impulsive and continuous scenarios, respectively.

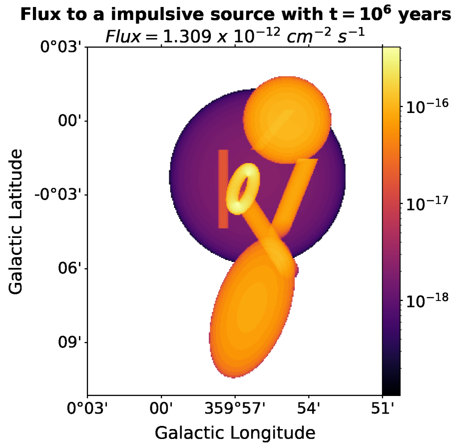


FIGURE 3. 2D image of the γ-ray flux from an impulsive source

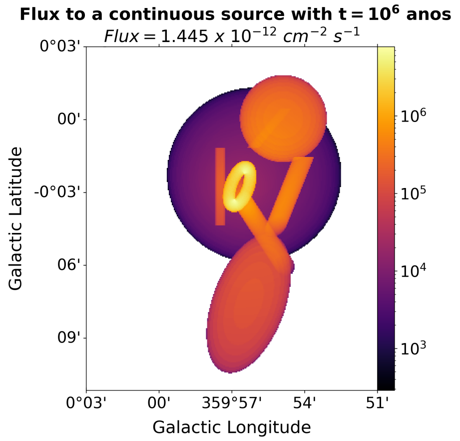


FIGURE 4. 2D image of the γ-ray flux from an continuous source

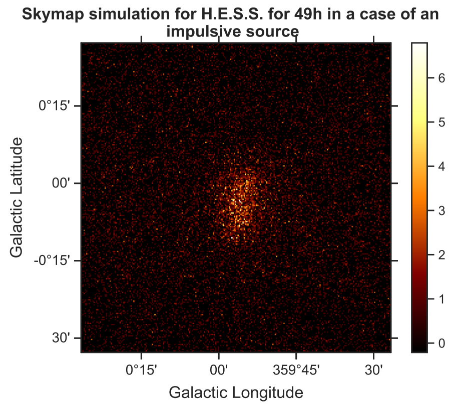


FIGURE 5. Simulation of the gamma-ray excess skymap in a $(1°, 1°)$ window for the H.E.S.S. telescope, considering 49 hours of observation in an impulsive source scenario.

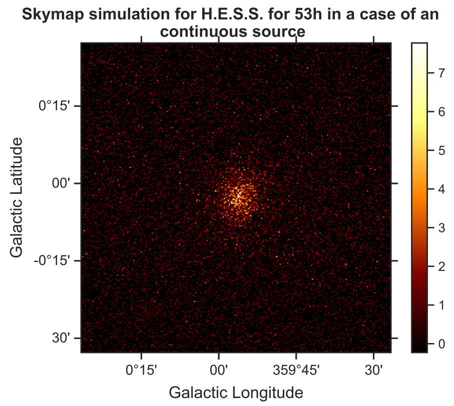


FIGURE 6. Simulation of the gamma-ray excess skymap in a $(1°, 1°)$ window for the H.E.S.S. telescope, considering 53 hours of observation in a continuous source scenario.

From the figures 3 and 4 we can conclude that in the impulsive case, the flux tends to be proportional to the mass of the cloud, due to the almost isotropic density of the cosmic rays. In contrast, in the continuous case, the gamma-ray flux is modulated by the 1/R decrease in the cosmic ray density.

Having obtained the geometry of molecular clouds and the gamma-ray emissivity resulting from the simulated decay of π^0, it was possible to simulate skymaps in a $(1°, 1°)$ window centered on Sgr A* to depict what would be observed by the H.E.S.S. telescope when pointing towards this region. To perform this sampling of the excess gamma rays observed by the H.E.S.S. telescope, the Gammapy library was employed Donath et al. (2023). In addition to incorporating the spatial geometry of the clouds and emissivity, the energy spectrum of HESS J1745-290, as obtained in the article HESS Collaboration (2016), was also included, represented by a power-law with an exponential cutoff, given by $dN/dE = \Phi_0 (E/TeV)^{-\Gamma_0} \exp(-E/E_{cut})$, where $\Phi_0 = 2.55 \times 10^{-12}\, TeV^{-1} cm^{-2} s^{-1}$ is the flux normalization, $\Gamma_0 = 2.14$ is the spectral index and $E_{cut} = 10.7 TeV$ is the cut-off energy.

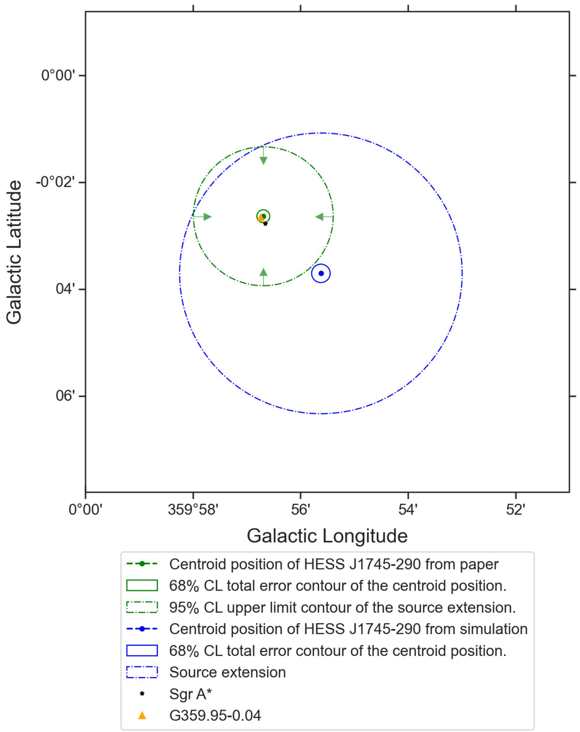
Alongside the central source, the diffuse interstellar gamma-ray emission from the Ridge was also included in the simulations, as described in the article HESS Collaboration (2016), characterized by a power-law with normalization $\Phi_0 = 6.0 \times 10^{-11}\, TeV^{-1} cm^{-2} s^{-1}$ and index $\Gamma_0 = 2.4$.

With these parameters, the simulated skymaps were produced, resulting in Figs. 5 and 6, for the case of an impulsive and continuous source, respectively.

Upon obtaining the skymaps for both scenarios, a spatial analysis was conducted by fitting a two-dimensional symmetric Gaussian centered on Sgr A* to identify the centroid and extension of the source. The results were compared with data from the article HESS Collaboration (2009), in which the H.E.S.S. collaboration determines the centroid position of the emission source HESS J1745-290 to be coincident with the position of the central black hole Sgr A* and also with a pulsar wind nebula, G359.95-0.04. In their analysis, the collaboration established an upper limit for the source extension of $1.3'$ with 95% CL (confidence level). In other words, according to observations from the H.E.S.S. telescope, the HESS J1745-290 source is considered point-like.

Our results, along with the comparison to the data from the previously mentioned article, are presented in Figs. 7a and 7b. The fitted results on the centroid coordinates and source extension can be found in the Tables 2 and 3.

Based on the results obtained in this research so far, it is concluded that, in both the continuous and impulsive scenarios, the centroid position differs from that observed by the H.E.S.S. telescope. In the impulsive case, the source extension is greater than the upper limit established by the HESS collaboration. Therefore, if this scenario could explain the nature of the gamma-ray flux, the H.E.S.S. telescope should have already detected a non-zero extension. In the continuous scenario, the extension is statistically equivalent to the upper limit.



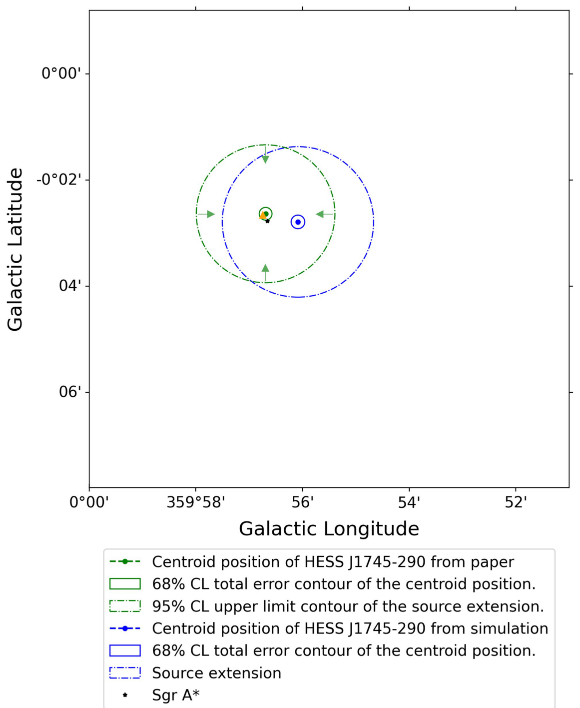


Figure 7. The centroid position and extent of the source found in this research are shown in blue for the case of a continuous source, while the results from article HESS Collaboration (2009) are presented in green. In the latter case, no extent was determined, only an upper limit. The top and bottom panels give, respectively, the Impulsive and continuous case.

Thus, considering both the centroid position and extension information and comparing it with the data from the article, the results indicate that both source models can be excluded as possible candidates to explain the phenomena producing the gamma rays from HESS J1745-290, through proton-proton collisions in the molecular clouds within the central 10 parsecs of Sgr A*, producing π^0 and decaying into gamma rays.

Table 2. Table containing the position of the centroid measured in the article HESS Collaboration (2009) and obtained in the simulation of a continuous and impulsive source.

	Centroide Position
Obtained by collaboration H.E.S.S.	lon = 359°56′41.5″ ± 0.6″ lat = −0°2′38″ ± 8″
Continuous source simulation	lon = 359°56′5″ ± 5″ lat = −0°2′47″ ± 6″
Impulsive source simulation	lon = 359°55′37″ ± 7″ lat = −0°3′42″ ± 8″

Table 3. Table containing the source extension measured in the article HESS Collaboration (2009) and obtained in the simulation of a continuous and impulsive source.

	Source Extension
Obtained by collaboration H.E.S.S.	Upper limit of 1.3′ with 95% CL
Continuous source simulation	1.4′ ± 0.1′
Impulsive source simulation	2.63′ ± 0.09′

4. Conclusion and next steps

Different morphologies were obtained for different types of sources (impulsive and continuous) in a scenario where the gamma-ray emissivity of HESS J1745-290 is coming through the decay of π^0 created in p-p collisions. By conducting spatial analysis on simulated skymaps of both sources and comparing it with the data disclosed in article HESS Collaboration (2009), we can conclude so far that the adopted model is not compatible with the phenomenology occurring in this region.

Next, we will test different sources of background and foreground emission and simulate the observed morphology of these two scenarios as observed by a future gamma-ray telescope, such as the CTA, by convolving with its instrument response function. We hope to be able to infer whether the CTA will be able to differentiate which of the gamma-ray emissivity scenarios is occurring in this region.

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