Boletim da Sociedade Astronômica Brasileira, **34**, no. 1, 161-162

Reconstruction of neutral pion-decay gamma-ray emission in the Central Molecular Zone

Lucca Radicce Justino & Aion Viana

[1] Instituto de Física de São Carlos, Universidade de São Paulo. e-mail: lradicce@usp.br, aion.viana@ifsc.usp.br

Abstract. The gamma-ray astronomy has evolved very fast over the last years. Gamma-ray radiation is an important messenger in the study of high energy astrophysical process, particularly the production of very high energy cosmic rays. The discovery of the first PeVatron in our Galaxy, localized in the Galactic Center region, was possible due to interactions of relativistic protons with the giant molecular clouds of the Central Molecular Zone. These proton-proton interactions produce neutral pions that subsequently decay generating a gamma-ray emission. Due to the possible link between this PeVatron and the central supermassive black hole Sgr A*, and the potential of this source to explain the entirety of PeV cosmic-rays in our Galaxy, this discovery is among the most important results in high energy astrophysics of the past decade. In this work, we review the solution of the diffusive propagation of CR protons for impulsive and continuous sources. Next, we reconstruct numerically the pion-decay gamma-ray emission map of the Central Molecular Zone by a new approach that uses a simplified model of the 3D distribution of the interstellar gas. In the end, we test different types of source to reproduce the expected results and suggest others advances that can be made.

Resumo. A astronomia de raios gama evoluiu rapidamente nos últimos anos. Os raios gama são mensageiros importantes no estudo de processos astrofísicos de alta energia, particularmente a produção de raios cósmicos de muito altas energias. A descoberta do primeiro PeVatron galáctico, localizado na região do Centro Galáctico, foi possível através das interações de prótons relativísticos com as gigantescas nuvens moleculares da Zona Molecular Central. Essas interações próton-próton produzem píons neutros que decaem gerando uma emissão de raios gama. Devido à possível ligação entre este PeVatron e o buraco negro supermassivo central Sgr A*, e o potencial desta fonte para explicar a totalidade dos raios cósmicos PeV em nossa Galáxia, esta descoberta está entre os resultados mais importantes em astrofísica de altas energias da última década. Neste trabalho, nós revisamos a solução da propagação difusiva de prótons de RC para fontes impulsivas e contínuas. Em seguida, reconstruímos numericamente o mapa de emissão de raios gama devido ao decaimento do pion na Zona Molecular Central por uma nova abordagem que usa um modelo simplificado da distribuição 3D do gás interestelar. Ao final, testamos diferentes tipos de fonte para reproduzir os resultados esperados e sugerimos outros avanços que podem ser implementados.

Keywords. Galaxy: center – Cosmic rays – Gamma rays: ISM

1. Introduction

Cosmic-rays are energetic charged particles coming from space, like nuclei, protons and electrons. The origin and the propagation of CR remains among the most important questions of modern astrophysics.The differential energy spectra of primary cosmic-rays are modeled by a power-law of the form $N(E)dE = KE^{-\alpha}dE$, a model that describes very well the observations. However, the sources that are responsible by the injection of the high energy particles and the process of acceleration are still controversy. Moreover, there is a strange feature in the observed spectra: an excess at $1\,PeV = 10^{15}\,eV$, usually known as a 'knee', that is not totally understood yet. It is usually believed that the majority of sources of CR are supernova remnants (SNRs) of shell-type, but this hypothesis has difficulties to explain the excess (knee) at PeV energies cited before. Currently, the best way to study the acceleration and the propagation of galactic CRs along the interstellar medium (ISM) is to analyse the γ-ray emission produced by the interaction between the CRs and the interstellar gas. In fact, giant molecular clouds (MC) can be studied to identify features in the CR distribution Aharonian & Atoyan (1996).

Irregularities in interstellar magnetic field leads to a diffusive propagation of CRs, so it necessary the search for a neutral cosmic messengers to identify their origin: γ-rays from pp-collision between CRs and the interstellar gas nuclei. This process is given by $p + p \to p + p + \pi^0$ followed by $\pi^0 \to \gamma + \gamma$. The evolution of the differential energy spectrum $N(E)$ of CRs is described by the diffusion-loss equation

$$\frac{\partial N}{\partial t} = D\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial}{\partial r}N\right) + \frac{\partial}{\partial E}(b\,N) + Q \quad (1)$$

where the effect of the magnetic field is represented by a diffusion coefficient $D(E)$, $b(E) = -dE/dt$ is the pp energy-loss term and $Q(E,t) \sim E^{-\alpha}$ is the injection. Its solution is given, for an impulsive $Q = N_0E^{-\alpha}\delta(\mathbf{r})\delta(t)$ and a continuous injection $Q = Q_oE^{-\alpha}H(t)$, respectively, by

$$N(E,r,t) = \frac{N_0E^{-\alpha}}{\pi^{3/2}R_{dif}^3}\exp\left(-\frac{(\alpha-1)t}{\tau_{pp}} - \frac{r^2}{R_{dif}^2}\right), \quad (2)$$

and

$$N(E,r,t) = \frac{Q_oE^{-\alpha}}{4\pi D(E)r}\,\mathrm{erfc}\left(\frac{r}{R_{dif}(E,t)}\right). \quad (3)$$

where R_{dif} is the diffusion radius.

Over the past 20 years some discoveries in very high energy (VHE, i.e., $E > 100\,GeV$) γ-rays at the Galactic Center ridge have showed important suggestions to the CR origin and propagation in this region. In 2006 the emission of VHE γ-ray was reported in the GC ridge in the complex of giant molecular clouds (a region known as the Central Molecular Zone, or CMZ). The close similarity between the molecular gas distribution and the γ-ray emission was first interpreted as a roughly uniform CR density, what suggests an impulsive-type source Aharonian et al. (2006). Another paper, published in 2016 by the H.E.S.S. collaboration, has reported observations of the γ-ray emission in GC region that are in agreement with the acceleration of *PeV* protons indicating the presence of a galactic PeVatron. The researchers have also discovered a gradient in the CR density in the form $1/r$ that indicates to a continuous source instead of an impulsive one H.E.S.S. et al. (2016). In the end, these studies have a difficulty: they use a 2D-model, which is very imprecise in the sense of not taking into account the depth distribution of the gas. In this work, we implement a simplified 3D gas distribution model for obtain more realistic simulations.

2. Methods

In this work, we reconstruct, at least the main component of, the γ-ray diffusive emission in the CMZ at the GC region in a new approach: by using a 3D toy-model for the density of interstellar gas by K. Ferrière, W. Gillard and P. Jean Ferriere, Gillard & Jean (2007). To achieve this goal, we follow the following steps: we 1) implement computationally in *Python* 3 the methods presented by Aharonian and Atoyan to obtain the γ-ray emissivity from the spectrum of protons injected by a continuous or an impulsive source; 2) use the *Python* functions obtained in the last step to generate the expected images in γ-ray of a MC near the GC, giving us a first intuition of how to interpret the next generated images and 3) use the 3D model by Ferrièri et al. of gas distribution for obtain a simplified 3D distribution gas -based image of the γ-ray emission in the GC region, and then test sources of different types and ages and compare it with the actual data. Finally, we give the conclusions of this work and suggest possible next steps to be follow.

Ferrière et al. have presented a simplified model that considers the CMZ as an ellipsoid with axes of 250 pc and 100 pc of size and with a major axis inclined by 70^o to the line of observation from Earth. Considering the CMZ centered at the point $(x_c, y_c) = (-50\,pc, 50\,pc)$ in the rectangular Galactic coordinates, it is more convenient using a rectangular CMZ centered system: $X = (x - x_c)\cos\theta_c + (y - y_c)\sin\theta_c$, $Y = -(x - x_c)\sin\theta_c + (y - y_c)\cos\theta_c$. In this model, the number density of molecular and atomic hydrogen in the CMZ is described by exponential terms:

$$n_{H_2} = (150\,\mathrm{cm}^{-3})\exp\left[-\left(\frac{\sqrt{X^2 + (2.5Y)^2} - X_c}{L_c}\right)^4\right]\exp\left[-\left(\frac{z}{H_c}\right)^2\right], \quad (4)$$

$$n_{H_I} = (8.8\,\mathrm{cm}^{-3})\exp\left[-\left(\frac{\sqrt{X^2 + (2.5Y)^2} - X_c}{L_c}\right)^4\right]\exp\left[-\left(\frac{z}{H_c'}\right)^2\right]. \quad (5)$$

3. Result and discussions

After generating images of a molecular cloud near the GC and comparing it with the results expected from literature, we were able to make sure of the robustness of the method. The results for the numerical reconstruction of the γ-ray emission map of the CMZ by this method is shown in figure (1). In the temporal evolution of the simulated impulsive injection, the CMZ is illuminated by γ-ray emission at $t \approx 10^5\,yr$, moreover, this γ-ray map resembles the gas distribution given by the model , as is expected by the uniform CR density inside the diffusion radius. In the case of the continuous injection, it is possible to see a bright central region, what is direct explained by the $1/r$ gradient of CRs in a continuous injection. Due this decreasing, only at advanced ages ($t \sim 10^6$) a significant emission along all the CMZ is noticeable. Therefore, a source in continuous regime at the GC must be older than that of the impulsive hypothesis, $t \gtrapprox 10^6\,yr$ instead of $t \gtrapprox 10^5\,yr$. All these results are in agreement with the cited papers.

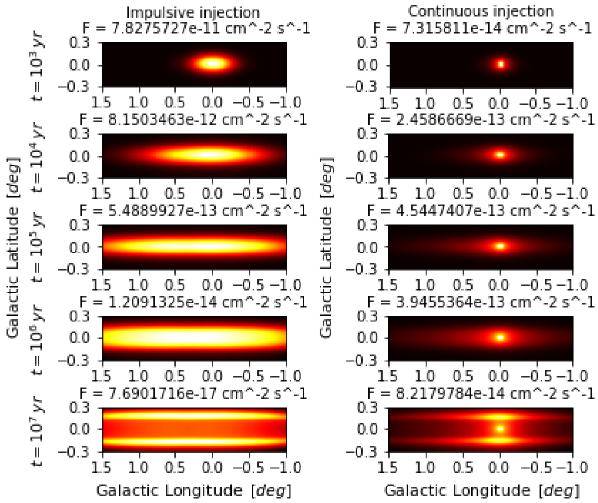

FIGURE 1. Simulation of CMZ map in γ-ray. By the author

Images with stranger behavior were generated at $t = 10^7\,yr$. This peculiar morphology is presumably explained by the fact that in the central region the particle number density n is greater then in the more distant latitudes, which implies in a larger proton lifetime τ_{pp} in the center and, therefore, a faster decay that attenuates the γ-ray emission in this region. The reason for this might be the fact that, actually, the diffusive propagation in a irregular magnetic field is just a calculation for the mean path of the charged particles. A more realistic calculation for the trajectories of particles could be performed in the future via the Monte Carlo method, which would reflects the random movement of the particles through the irregular magnetic field.

4. Conclusions

The main aim of this work was the simulation of the expected image of gamma-ray emission from the CMZ. This new approach has generated results that are in agreement with the current knowledge about the expected characteristics of the potential sources. Nevertheless, an unexpected morphology was found in the simulation for the continuous source at $t = 10^7\,yr$. This could be corrected in the future by actually simulating the path of particles in their random movements, using for instance a Monte Carlo method.

Acknowledgements. I would like to give my thanks to Prof. Dr. Aion Viana for his worth advising an help. AV and LRJ were sponsored by the São Paulo Research Foundation (FAPESP) through Grant No 2019/14893-3 and No 2022/01962-0. AV is supported by CNPq grant 314955/2021-6.

References

Aharonian, F. & Atoyan, A. 1996, Astronomy and Astrophysics, v. 309, p. 917–928.
Aharonian, F. A. et al. 2006, Nature, Nature Publishing Group, v. 439, n. 7077, p. 695–698.
Ferriere, K., Gillard, W. & Jean, P. 2007, Astronomy & Astrophysics, EDP Sciences, v. 467, n. 2, p. 611–627.
H.E.S.S. et al. 2016, Nature, v. 531, p. 24.