

# Diffuse gamma-ray emission from the Galactic center and implications of its past activities

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**Abstract.** It has been indicated that low-luminosity active galactic nuclei (LLAGNs) are accelerating high-energy cosmic-ray (CR) protons in their radiatively inefficient accretion flows (RIAFs). If this is the case, Sagittarius A\* (Sgr A\*) should also be generating CR protons, because Sgr A\* is a LLAGN. Based on this scenario, we calculate a production rate of CR protons in Sgr A\* and their diffusion in the central molecular zone (CMZ) around Sgr A\*. The CR protons diffusing in the CMZ create gamma-rays through  $pp$  interaction. We show that the gamma-ray luminosity and spectrum are consistent with observations if Sgr A\* was active in the past.

**Keywords.** cosmic rays, galaxies: active, gamma rays: theory

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## 1. Introduction

The IceCube Collaboration reported the detection of extraterrestrial neutrinos (Aartsen *et al.* 2013; Aartsen *et al.* 2014; Aartsen *et al.* 2015). Although their origin is not understood, the uniform arrival directions of the neutrinos indicate their extragalactic origin. Recently, Kimura *et al.* (2015) proposed that the neutrinos are coming from low-luminosity active galactic nuclei (LLAGNs). Those AGNs are thought to have radiatively inefficient accretion flows (RIAFs), in which gas is hot and tenuous. In this environment, thermalization of gas particles is inefficient and some of them can be stochastically accelerated. The cosmic ray (CR) protons accelerated in this process interact with photons ( $p\gamma$  interaction) and other protons ( $pp$  interaction), and produce gamma-rays and neutrinos.

Sagittarius A\* (Sgr A\*) is the AGN of the Galaxy, and it is known as a LLAGN. This means that CR protons may be accelerated in the RIAF of Sgr A\* and they may be injected in the interstellar space. Sgr A\* is surrounded by a huge amount of dense molecular gas called the central molecular zone (CMZ). The mass and size of the CMZ is  $M_{\text{CMZ}} \sim 10^7 M_{\odot}$  and  $R_{\text{CMZ}} \sim 100$  pc, respectively (e.g. Morris & Serabyn 1996). If Sgr A\* is actually producing CR protons, some of them should enter the CMZ, and generate gamma-rays and neutrinos through  $pp$  interaction with protons in the CMZ. In fact, gamma-rays have been observed from the CMZ with the High Energy Stereoscopic System (HESS; Aharonian *et al.* 2006; H.E.S.S. collaboration 2016). In this study, we consider the CR acceleration in the RIAF of Sgr A\* and the diffusion of the accelerated

protons in the CMZ. We investigate the gamma-ray and neutrino production in the CMZ. We compare the predicted gamma-ray emission with observations. The details of this study has been published in Fujita *et al.* (2015).

### 2. CR proton acceleration in Sgr A\*

Since we expect that the CRs are accelerated in a small region around the supermassive black hole (SMBH) in Sgr A\*, we adopt an one-zone model for the acceleration (Kimura *et al.* 2015). The typical energy of the CR protons can be estimated by equating their acceleration time to their escape time from the RIAF. The result is

$$\frac{E_{p,\text{eq}}}{m_p c^2} \sim 1.4 \times 10^5 \left(\frac{\dot{m}}{0.01}\right)^{1/2} \left(\frac{M_{\text{BH}}}{1 \times 10^7 M_\odot}\right)^{1/2} \times \left(\frac{\alpha}{0.1}\right)^{1/2} \left(\frac{\zeta}{0.1}\right)^3 \left(\frac{\beta}{3}\right)^{-2} \left(\frac{R_{\text{acc}}}{10 R_S}\right)^{-7/4}, \tag{2.1}$$

where  $m_p$  is the proton mass,  $\dot{m}$  is the normalized accretion rate  $\dot{m} = \dot{M}/\dot{M}_{\text{Edd}}$ ,  $\dot{M}_{\text{Edd}}$  is the Eddington accretion rate,  $\alpha$  is the alpha parameter of the accretion flow,  $\zeta$  is the ratio of the strength of turbulent fields to that of the non-turbulent fields,  $\beta$  is the plasma beta parameter,  $R_{\text{acc}}$  is the typical radius where particles are accelerated, and  $R_S$  is the Schwarzschild radius of the SMBH. As fiducial parameters, we adopt  $\alpha = 0.1$ ,  $\zeta = 0.05$ ,  $\beta = 3$ , and  $R_{\text{acc}} = 10 R_S$  to be consistent with the IceCube observations (Kimura *et al.* 2015). The proton luminosity of the RIAF is given by  $L_{p,\text{tot}} = \eta_{\text{cr}} \dot{M} c^2$ , where  $\eta_{\text{cr}}$  is the parameter and we take  $\eta_{\text{cr}} = 0.015$  as the fiducial value. Assuming that the particles are accelerated stochastically, the functional form of the CR spectrum is

$$\dot{N}(x)dx \propto x^{(7-3q)/2} K_{(b-1)/2}(x^{2-q})dx, \tag{2.2}$$

where  $x = p/p_{\text{cut}}$ ,  $K_\nu$  is the Bessel function, and  $b = 3/(2 - q)$  (Becker *et al.* 2006). The cut-off momentum is given by  $p_{\text{cut}} = (2 - q)^{1/(2-q)} p_{\text{eq}} = p_{\text{eq}}/27$ , where  $p_{\text{eq}} = E_{p,\text{eq}}/c$  and  $q = 5/3$  (Kolmogorov type turbulence). Normalization of Eq. (2.2) can be obtained by setting that the total proton luminosity is  $L_{p,\text{tot}}$ .

### 3. Diffusion of Protons in the CMZ

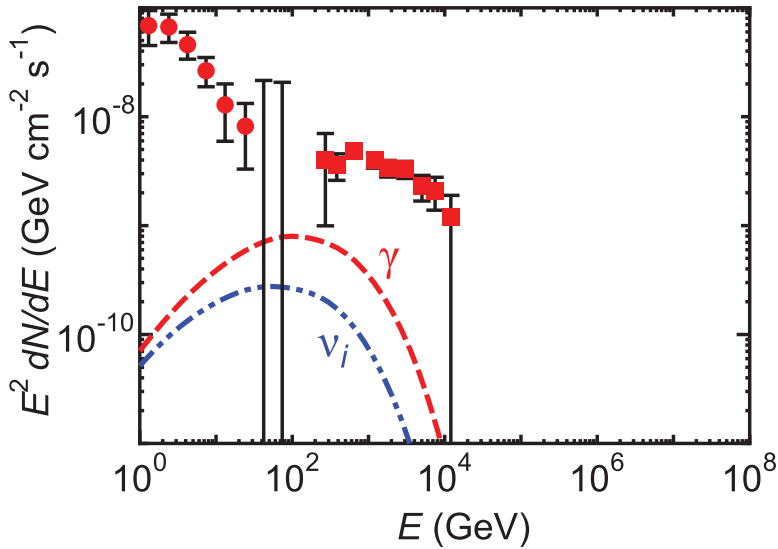
Since we are only interested in the diffusion of CRs in the direction of the CMZ or the Galactic plane, we solve a spherically symmetric diffusion equation for the sake of simplicity:

$$\frac{\partial f}{\partial t} = \frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 \kappa \frac{\partial f}{\partial r} \right) + Q. \tag{3.1}$$

We only consider the diffusion inside the CMZ ( $r < R_{\text{CMZ}}$ ) and steady state solutions ( $\partial f/\partial t = 0$ ). The source term is written as  $\int 4\pi cp^3 Q dp = \lambda L_{p,\text{tot}} = \lambda \eta_{\text{cr}} \dot{M} c^2$ , where  $\lambda$  is the effective covering factor, which is expected to be  $\lambda \ll 1$ . The diffusion coefficient is

$$\kappa = 10^{28} \left(\frac{E_p}{10 \text{ GeV}}\right)^{0.5} \left(\frac{B}{3 \mu\text{G}}\right)^{-0.5} \text{ cm}^2\text{s}^{-1}, \tag{3.2}$$

where  $E_p$  is the particle energy (Gabici *et al.* 2009). We assume that the magnetic field in the CMZ is  $B = 1 \text{ mG}$  (Morris & Serabyn 1996). The CR protons interact with protons in the CMZ and generate gamma-ray photons and neutrinos. We calculate their



**Figure 1.** Predicated gamma-ray flux (dashed line) and neutrino flux (two-dot dashed line) from the CMZ when  $\dot{m} = 4.2 \times 10^{-6}$  and  $\lambda = 0.01$ . Filled circles and squares are the Fermi and HESS observations, respectively (Yusef-Zadeh *et al.* 2013; Aharonian *et al.* 2006). This figure is cited from Fujita *et al.* (2015).

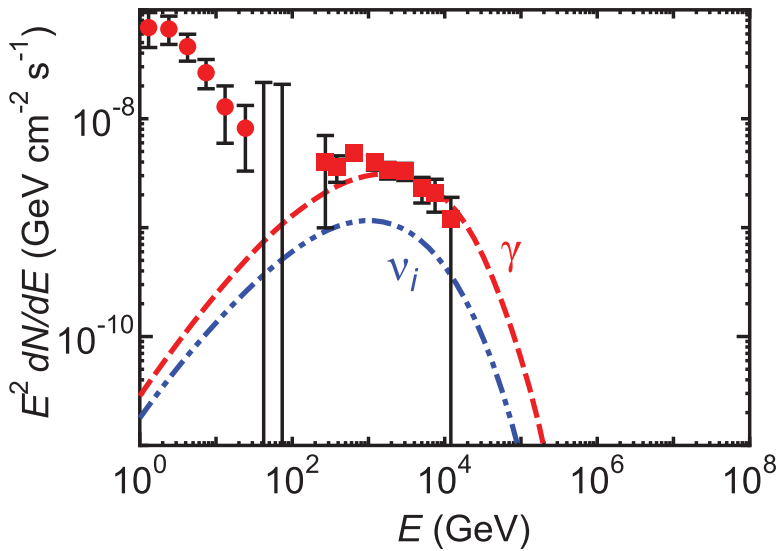
production rates using the models of Karlsson & Kamae (2008) and Kelner, Clayton & Bugayov (2006).

#### 4. Results

We assume that the typical size of the CMZ is  $R_{\text{CMZ}} = 130$  pc, and the density is  $\rho_{\text{CMZ}} = 1.4 \times 10^{-22}$  g cm $^{-3}$ . The mass of the SMBH is  $M_{\text{BH}} = 4.3 \times 10^6 M_{\odot}$  (Gillessen *et al.* 2009). Fig. 1 shows the gamma-ray and neutrino fluxes from the CMZ when the accretion rate is the currently observed one or  $\dot{m} = 4.2 \times 10^{-6}$  (Yuan *et al.* 2003), and when the effective covering factor is  $\lambda = 0.01$ . Apparently, the predicated gamma-ray flux underestimates the Fermi and HESS observations.

However, observations of X-ray echos have shown that Sgr A\* was much more active  $\gtrsim 100$  yrs ago and the accretion rate was  $10^3$ – $10^4$  times as much as the current one (Koyama *et al.* 1996; Ryu *et al.* 2013). Thus, we calculate the gamma-ray and neutrino fluxes when  $\dot{m} = 10^{-3}$  and  $\lambda = 5 \times 10^{-4}$ , and show the results in Fig. 2. The decline of  $\dot{m}$  for the recent  $\sim 100$  yrs does not affect the results. Fig 2 indicates that our prediction is consistent with TeV gamma-ray observations with HESS. However, our model cannot explain the GeV gamma-ray observations with Fermi. This may mean that the origin of the GeV emission is different from that of the TeV emission. The neutrinos could be observed with KM3Net in the future.

In summary, we have shown that the TeV gamma-ray emission from the CMZ can be explained if Sgr A\* accelerates CR protons in the RIAF and if it was more active in the past. In fact, recent HESS observations have suggested that the source of CRs responsible for the gamma-rays from the CMZ is located at the Galactic center (H.E.S.S. collaboration 2016). It is worth noting that Sgr A\* can accelerate PeV CRs in our model. Thus, Sgr A\* can also be a candidate of PeVatron in the Galaxy.



**Figure 2.** Same as Fig. 1 but for  $\dot{m} = 0.001$ , and  $\lambda = 5 \times 10^{-4}$ . This figure is cited from Fujita *et al.* (2015).

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