PHYSICAL REVIEW D **92,** 023001 (2015)

Hadronic origin of multi-TeV gamma rays and neutrinos from low-luminosity active galactic nuclei: Implications of past activities of the Galactic center

Yutaka Fujita

Department of Earth and Space Science, Graduate School of Science, Osaka University, Toyonaka, Osaka 560-0043, Japan

Shigeo S. Kimura

Frontier Research Institute for Interdisciplinary Sciences, Tohoku University, Sendai 980-8578, Japan and Astronomical Institute, Tohoku University, Sendai 980-8578, Japan

Kohta Murase

Center for Particle and Gravitational Astrophysics, Department of Physics, Department of Astronomy and Astrophysics, The Pennsylvania State University, University Park, Pennsylvania 16802, USA and Institute for Advanced Study, Princeton, New Jersey 08540, USA

(Received 1 April 2015; published 6 July 2015)

Radiatively inefficient accretion flows (RIAFs) in low-luminosity active galactic nuclei (LLAGNs) have been suggested as cosmic-ray and neutrino sources that may largely contribute to the observed diffuse neutrino intensity. We show that this scenario naturally predicts hadronic multi-TeV gamma-ray excesses around Galactic centers. The protons accelerated in the RIAF in Sagittarius A* (Sgr A*) escape and interact with dense molecular gas surrounding Sgr A*, which is known as the central molecular zone (CMZ), and produce gamma rays as well as neutrinos. Based on a theoretical model that is compatible with the IceCube data, we calculate gamma-ray spectra of the CMZ and find that the gamma rays with $\gtrsim$1 TeV may have already been detected with the High Energy Stereoscopic System if Sgr A* was more active in the past than it is today, as indicated by various observations. Our model predicts that neutrinos should come from the CMZ with a spectrum similar to the gamma-ray spectrum. We also show that such a gamma-ray excess is expected for some nearby galaxies hosting LLAGNs.

DOI: 10.1103/PhysRevD.92.023001 PACS numbers: 98.54.Cm, 95.85.Pw, 95.85.Ry, 98.38.−j

I. INTRODUCTION

Recently, the IceCube Collaboration reported the discovery of extraterrestrial neutrinos [1–3]. The origin of the neutrinos is a matter of debate ([4–19]; for reviews, see [20,21]). The data so far are compatible with an isotropic distribution, which suggests that neutrinos are of extragalactic origin. Diffuse gamma-ray data also support this idea [6,10]. However, the sources have not been identified because of poor angular information and statistics for the neutrinos. One way of improving this situation may be detection of counterparts through electromagnetic waves.

Low-luminosity active galactic nuclei (LLAGNs) are a candidate for the source of the neutrinos. The LLAGNs are expected to have radiatively inefficient accretion flows (RIAFs), which are realized when the mass accretion rate into the supermassive black hole (SMBH) is relatively small ($\dot{M}/\dot{M}_{\rm Edd} \lesssim 0.01 - 0.1$), where $\dot{M}_{\rm Edd} = L_{\rm Edd}/c^2$ is the Eddington accretion rate, and $L_{\rm Edd}$ is the Eddington luminosity [22]. In the tenuous and turbulent plasma in the RIAFs, cosmic ray (CR) protons may be accelerated via stochastic acceleration or magnetic reconnection [19]. These CR protons interact with other nucleons (pp interaction) and photons ($p\gamma$ interaction) in the flow and generate neutrinos. Although the production rate of the neutrinos per an LLAGN is not large compared with other more energetic sources such as quasistellar objects (QSOs), the abundance of LLAGNs can reproduce observed neutrino flux on the Earth [19]. Even if it is difficult to resolve LLAGNs as point neutrino sources, gamma rays from them could be used to test this model. In particular, the gamma rays that are a byproduct of the pp interactions have energies comparable to those of the neutrinos, which means that the gamma-ray spectrum should reflect the neutrino spectrum unless the gamma rays are not absorbed.

Sagittarius A* (Sgr A*) is the SMBH at the center of the Galaxy and it is known as an LLAGN. The current mass accretion rate of Sgr A* is very small and the accretion flow is thought to be a RIAF [23]. The current production rate of CR protons in the RIAF is expected to be small because of the small accretion rate [24]. Thus, the gamma-ray luminosity of the RIAF in the TeV band is also expected to be small because of inefficient pion production [19]. However, it has been indicated that Sgr A* was much more active in the past [25–28]. During those activities, a large amount of protons could have been accelerated and escaped from the RIAF. Moreover, observations have revealed that there is a huge amount of molecular gas surrounding Sgr A*. This gas concentration is known as the central molecular zone (CMZ) with the size of $R_{\rm CMZ} \sim 100$ pc and the mass of $M_{\rm CMZ} \sim 10^7\ M_\odot$ [29]. Strong turbulence and magnetic fields in the CMZ may delay the diffusion of the CR protons that have plunged into the CMZ, and those protons may stay in the CMZ for a long time. In this paper, we calculate the diffusion of the protons in the CMZ that have accelerated and escaped from the RIAF in Sgr A*. We estimate gamma-ray and neutrino emissions created through pp interactions between the CR protons and protons in the CMZ. We show that TeV gamma rays from the CMZ around Sgr A* and nearby LLAGNs observed with the High Energy Stereoscopic System (HESS) may be produced by this mechanism. Previous studies have shown that the gamma-ray excess observed in those objects at $\gtrsim 1$ TeV cannot be explained by one-zone leptonic models [30–32]. Our model can resolve this issue, although there are also studies trying to explain the HESS observations by pp interactions in the CMZ by different approaches [32–34].

II. COSMIC-RAY PROTON ACCELERATION IN RADIATIVELY INEFFICIENT ACCRETION FLOWS OF SGR A*

In our model, protons are accelerated in the RIAF of Sgr A*. Since the acceleration is confined in a small region on a scale of a few tens of the Schwarzschild radius of the SMBH, we consider the acceleration based on a one-zone model as in previous studies [19,35,36]. According to the model of Ref. [19], the typical energy of the accelerated protons is determined by the balance between the acceleration time of the protons in a RIAF ($t_{\rm acc,R}$) and their escape time from the RIAF. The escape time is comparable to the diffusion time of the protons in the RIAF ($t_{\rm diff,R}$). Thus, the Lorentz factor corresponding to the typical energy is obtained by solving the equation of $t_{\rm acc,R} = t_{\rm diff,R}$ and the result is

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

where m_p is the proton mass, $\dot{m}$ is the normalized accretion rate $\dot{m} = \dot{M}/\dot{M}_{\rm Edd}$, α is the alpha parameter of the accretion flow [37], ζ is the ratio of the strength of turbulent fields to that of the nonturbulent fields, β is the plasma beta parameter, $R_{\rm acc}$ is the typical radius where particles are accelerated, and R_S is the Schwarzschild radius of the black hole [19]. For the parameters of the RIAF, we take $\alpha = 0.1$, $\zeta = 0.05$, $\beta = 3$, and $R_{\rm acc} = 10 R_S$ as fiducial parameters, because the neutrino flux at $\sim 10-100$ TeV obtained with IceCube is well reproduced by them [19].

We assume that the luminosity of the protons accelerated in the RIAF is $L_{p,\rm tot} = \eta_{\rm cr}\dot{M}c^2$, where $\eta_{\rm cr}$ is the parameter, and we take $\eta_{\rm cr} = 0.015$ as the fiducial value following Ref. [19]. When only stochastic acceleration is effective, the production rate of protons in the momentum range p to $p + dp$ is

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

where $x = p/p_{\rm cut}$, K_ν is the Bessel function, and $b = 3/(2-q)$ [38]. The power-law index of turbulence responsible for the acceleration is assumed to be $q = 5/3$ (Kolmogorov type). The cutoff momentum is defined as $p_{\rm cut} = (2-q)^{1/(2-q)} p_{\rm eq} = p_{\rm eq}/27$, where $p_{\rm eq} = E_{p,\rm eq}/c$ [19,38]. We determine the normalization of Eq. (2) so that the total power of the protons is $L_{p,\rm tot}$.

III. DIFFUSION OF PROTONS IN THE CMZ

Protons accelerated in Sgr A* leave the acceleration site (RIAF) and disperse into the interstellar space. Some of them would enter the CMZ surrounding Sgr A*. We solve a diffusion-convection equation for the CR protons in the CMZ. For the sake of simplicity, we solve a spherically symmetric equation,

$$\frac{\partial f}{\partial t} = \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 \kappa \frac{\partial f}{\partial r}\right) - u\frac{\partial f}{\partial r} + \frac{1}{3r^2}\left[\frac{\partial}{\partial r}(r^2 u)\right] p \frac{\partial f}{\partial p} + Q, \quad (3)$$

where $f = f(t,r,p)$ is the distribution function, r is the distance from the Galactic center, p is the momentum of particles, κ is the diffusion coefficient, u is the velocity of the background gas, and Q is the source term for the particles (Sgr A*). We assume that $u = 0$ because we are interested in the CRs inside the CMZ, which is too heavy to be moved by possible outflows from Sgr A*. We do not consider CRs carried by the outflows without entering into the CMZ. We assume that the CMZ is uniform and its dense gas occupies at $r < R_{\rm CMZ}$.

The actual CMZ has a disclike structure and does not entirely cover Sgr A* [29]. Thus, we expect that most of the CR protons do not plunge into the CMZ, and we assume that only a fraction λ of the protons accelerated in the RIAF are injected into the CMZ. Thus, the source term in Eq. (3) is written as $\int 4\pi c p^3 Q dp = \lambda L_{p,\rm tot} = \lambda \eta_{\rm cr}\dot{M}c^2$. Since the size of the CMZ ($R_{\rm CMZ} \sim 100$ pc) is much larger than that of the RIAF, we treat Q as a point source.

We assume that the diffusion coefficient of CRs outside the RIAF is given by

$$\kappa = 10^{28}\left(\frac{E_p}{10\ \rm GeV}\right)^{0.5}\left(\frac{B}{3\ \mu\rm G}\right)^{-0.5}\ \rm cm^2\ s^{-1}, \quad (4)$$

where E_p is the particle energy. This coefficient is for the ordinary interstellar space in the Galactic disc [39]. We only consider resonant scattering, which is valid at sufficiently low energies. Although the diffusion coefficient in the CMZ is not known, we apply Eq. (4) to stronger magnetic field cases. If there are strong magnetic fields ($B \sim$ mG) in the CMZ [29], the coefficient is much smaller than that in the intercloud space around the Galactic center ($B \sim 10\ \mu$G) [40]. In fact, it has been indicated that the diffusion coefficient in molecular gas around supernova remnants is much smaller than the ordinary value [41]. From now on, we fix magnetic fields at $B = 1$ mG for $r < R_{\rm CMZ}$ and 10 μG for $r > R_{\rm CMZ}$. We do not consider stochastic acceleration in the CMZ. This is because the diffusion coefficient we assumed in Eq. (4) is too large for effective particle acceleration. In fact, previous studies have shown that the diffusion coefficient must be as small as that for the Bohm diffusion for particles to be accelerated up to $\gtrsim$ TeV [34,42]. It is not certain whether such a small coefficient is realized by turbulence in and around the CMZ. We do not include cooling of the protons in Eq. (3), because the cooling time is larger than the diffusion time estimated based on Eq. (4) (see later).

CR protons interact with protons in the CMZ. For a given distribution function f, we calculate the production rate of gamma-ray photons using the code provided by [43] and the formula provided by [44] for $E_p < 1$ and $E_p > 1$ TeV, respectively. The results are not sensitive to the boundary energy (1 TeV). We also calculate the neutrino production rate at the same time. We consider the attenuation of very high energy gamma rays by pair production on the Galactic interstellar radiation field using the results shown in Fig. 3 of Ref. [45]. However, the following results are not much affected by the attenuation. The energy density of the interstellar radiation field ($\sim$10 eV cm^{-3}) is much smaller than that of the assumed magnetic field ($\sim$mG) [46]. Thus, the gamma-ray emission via inverse Compton scattering by secondary electrons can be ignored.

IV. GAMMA RAYS FROM THE CMZ AROUND SGR A*

Observations showed that the radius of the CMZ at the Galactic center is $R_{\rm CMZ,obs} = 200$ pc, the thickness is $H_{\rm CMZ,obs} = 75$ pc, and the mass is $M_{\rm CMZ} = 2 \times 10^7\ M_\odot$ [47,48]. Thus, the average density is $\rho_{\rm CMZ} = M_{\rm CMZ}/(\pi R_{\rm CMZ,obs}^2 H_{\rm CMZ,obs}) = 1.4 \times 10^{-22}$ g cm^{-3}. Since Eq. (3) assumes spherical symmetry, we define an effective radius

$$R_{\rm CMZ} \equiv \left(\frac{3M_{\rm CMZ}}{4\pi\rho_{\rm CMZ}}\right)^{1/3} = 130\ \text{pc}, \tag{5}$$

and we use this as the radius of the CMZ in the following calculations. The covering factor of the CMZ for $r < R_{\rm CMZ,obs}$ is $f_{\rm CMZ} = \pi R_{\rm CMZ,obs}^2 H_{\rm CMZ,obs}/(4\pi R_{\rm CMZ,obs}^3/3) = 0.5$, The fraction of CR protons that enter into the CMZ, λ, may be comparable to $f_{\rm CMZ}$. However, if the protons are not spherically emitted and they are, for example, carried by strong outflows perpendicular to the disclike CMZ, the fraction may be much smaller. Moreover, the inner edge of the CMZ may not have contact with Sgr A*. Thus, we assume that $\lambda \le 0.5$, and $\lambda \ll 0.5$ is very likely. Observations have shown that the mass of the SMBH is $M_{\rm BH} = 4.3 \times 10^6\ M_\odot$ [49], and the current mass accretion rate is $\dot{M} = 4 \times 10^{-8}\ M_\odot\,{\rm yr}^{-1}$ [23]. Since the Eddington luminosity is given by $L_{\rm Edd} = 1.26 \times 10^{38}\ (M_{\rm BH}/M_\odot)\ {\rm erg\,s^{-1}}$, the Eddington accretion rate is $\dot{M}_{\rm Edd} = 9.6 \times 10^{-3}\ M_\odot\,{\rm yr}^{-1}$. Thus, the normalized accretion rate is written as $\dot{m} = 4.2 \times 10^{-6}$. For these and the fiducial parameters, we obtain $E_{p,\rm eq} = 0.2$ TeV from Eq. (1). We solve Eq. (3) from $t = 0$ to 10^7 yr. There are no CRs at $t = 0$. The distribution of CRs has achieved a steady state at the end of the simulation because the diffusion time of CRs is only $t_{\rm diff,C} = R_{\rm CMZ}^2/(6\kappa) \sim 1.6 \times 10^5$ yr at $E_p \sim 1$ TeV. The following results are those at $t_0 = 10^7$ yr. Since this time scale is much larger than $t_{\rm diff,C}$, the energy spectrum of the CR protons is almost uniform in the CMZ [41,50]. As long as the spectrum of the injected CRs does not vary significantly, our model does not expect substantial variation in the gamma-ray spectrum across the CMZ (see later), which is consistent with observations. The distance to Sgr A* and the CMZ is assumed to be 8.5 kpc.

The inverse of the cooling time of CR protons due to pp interactions is

$$t_{pp}^{-1} \sim n_{\rm CMZ}\sigma_{pp} c K_{pp}, \tag{6}$$

where $n_{\rm CMZ} = \rho_{\rm CMZ}/m_p$ and $K_{pp}(\sim 0.5)$ is the proton inelasticity of the process. The total cross section of the process is given by

$$\sigma_{pp} = (34.3 + 1.88L + 0.25L^2)\left[1 - \left(\frac{E_{\rm th}}{E_p}\right)^4\right]^2\ \text{mb}, \tag{7}$$

where $E_{\rm th} = 1.22$ GeV is the threshold energy of production of π^0 mesons and $L = \ln(E_p/1\ \text{TeV})$ [44]. Thus, the cooling time is $t_{pp} \sim 7 \times 10^5$ yr at $E_p \sim 1$ TeV, which is larger than $t_{\rm diff,C}$. Since $t_{pp} > t_{\rm diff,C}$ is satisfied in the energy band of interest ($E_p \gtrsim 1$ TeV), we do not need to include the cooling effect in Eq. (3).

Figure 1 shows the gamma-ray flux and neutrino flux (per flavor) from the CMZ when $\dot{m} = 4.2 \times 10^{-6}$ and $\lambda = 0.01$ regardless of t. Other parameters are the fiducial ones. For comparison, we show the GeV and TeV gamma-ray fluxes obtained with Fermi and HESS observations [51,52]. The predicted gamma-ray flux is much smaller than the observations. The fraction of $\lambda \sim 0.5$ is needed in order that the flux is comparable to the observations at $E \sim 1$ TeV. However, as is noted above, the value of $\lambda = 0.5$ is probably too large for the actual CMZ. The gamma-ray

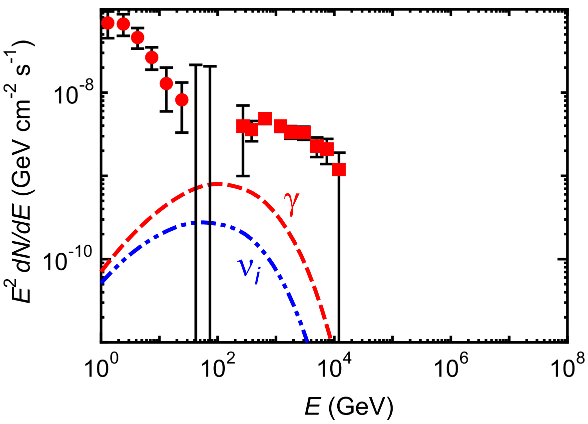

FIG. 1 (color online). Predicted gamma-ray flux (dashed line) and neutrino flux (two-dot dashed line) from the CMZ when $\dot{m} = 4.2 \times 10^{-6}$ and $\lambda = 0.01$. Filled circles and squares are the Fermi and HESS observations, respectively [51,52].

and neutrino spectra are similar and they are not represented by a power-law, because they reflect the proton spectrum [Eq. (2)].

Recent studies have indicated that the current activity of Sgr A* is exceptionally small, and that the average accretion rate more than ∼100 yrs ago might be much larger and it could be as much as $10^3 - 10^4$ times the current one [25–28]. Thus, we calculate the gamma-ray and neutrino fluxes when $\dot{m} = 0.001$ and $\lambda = 5 \times 10^{-4}$ regardless of t. The drop of activity in the past ∼100 yrs does not affect the results because the diffusion time of CRs is much larger than 100 yrs. Other parameters are the same as the fiducial ones. These give the typical energy of $E_{p,\mathrm{eq}} = 3.4$ TeV from Eq. (1). Note that for given $\dot{m}$ and M_{BH}, any combinations of parameters (α, ζ, β, and $R_{\mathrm{acc}}/R_{\mathrm{S}}$) that give the same $E_{p,\mathrm{eq}}$ give the same spectrum. Moreover, any combinations of λ and η_{cr} that give the same $\lambda\eta_{\mathrm{cr}}$ give the same spectrum. Figure 2 shows the results of this model; the gamma-ray spectrum at $E \sim 0.2 - 10$ TeV well reproduces that obtained with HESS. If observations for $E \gtrsim 10$ TeV become available in the future (e.g., Cherenkov Telescope Array; CTA [53], High Altitude Water Cherenkov detector; HAWC [54]), our model predicts a soft gamma-ray spectrum in that energy band. Since the designed sensitivities of CTA and HAWC at $E \sim 10 - 100$ TeV are better than that of HESS, the flux predicted in Fig. 2 could be easily detected. The gamma-ray image taken with HESS appears to coincide with the CMZ [52], which supports this model. Since the apparent size of the CMZ is $\sim 3° \times 0.5°$, it can be well resolved by CTA with a resolution of $\sim 1'$ [53]. Detailed maps of gamma rays will reflect not only the distribution of molecular gas but that of CRs. The latter may reflect the history of Sgr A* activities, if the activities significantly change on the diffusion time scale of the CRs.

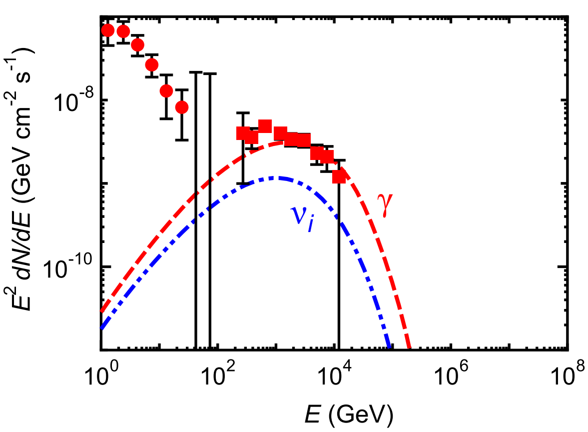

FIG. 2 (color online). Same as Fig. 1 but for $\dot{m} = 0.001$, and $\lambda = 5 \times 10^{-4}$.

From the current neutrino observations with IceCube, the flux of $\sim 3 \times 10^{-8}$ GeV cm^{-2} s^{-1} can be attributed to that from the Galactic center [10]. Since the predicted fluxes in Figs. 1 and 2 are smaller than that, they are consistent with the observations. However, as the statistics of neutrinos improve, we may detect an excess in the direction of the Galactic center in the future. In particular, observations with KM3NeT would be useful to detect the CMZ as a neutrino source if the flux is $\gtrsim 10^{-9}$ GeV cm^{-2} s^{-1} [55]. Our model predicts that the neutrino image should coincide with the gamma-ray image because both are the results of pp interactions.

Since parameters for the RIAF have some uncertainties, we adopt another model that can reproduce the neutrino flux at ∼1 PeV obtained with IceCube [19]. We change the parameter for the turbulence to $\zeta = 0.18$, and the acceleration efficiency of CRs in the RIAF to $\eta_{\mathrm{cr}} = 6 \times 10^{-3}$. We take $\dot{m} = 0.001$, which is the same as that in Fig. 2, and $\lambda = 3 \times 10^{-3}$ so that the flux at $E \sim 1$ TeV is consistent with the HESS observations. Other parameters are the fiducial ones. For these parameters, the typical energy is $E_{p,\mathrm{eq}} = 160$ TeV (Eq. (1)), which is much larger than that of the model in Fig. 2. The results are shown in Fig. 3. If this is the case, a relatively hard gamma-ray spectrum would be observed by CTA at $\sim 10 - 100$ TeV, and could be discriminated from the spectrum in Fig. 2. The gamma rays at $E \lesssim 1$ TeV should have another origin.

So far we have assumed that the accretion rate, $\dot{m}$, is constant. Here, we discuss the effects of variable $\dot{m}$. The x-ray light curve of Sgr A* in the past 500 yrs was derived in Ref. [28]. They showed that the x-ray luminosity is $L_X \sim 10^{39}$ erg s^{-1} in the past 50–500 yrs, and then it dropped to the current value of $L_X \sim 10^{33} - 10^{35}$ erg s^{-1}. The x-ray luminosity before 500 yrs ago is less constrained. Upper limits are placed to down to about 8×10^{40} erg s^{-1} for several periods within the past 4×10^4 yrs [56,57]. Before that, upper limits are $\sim 10^{41} - 10^{42}$ erg s^{-1} [56,57]. The x-ray luminosity of a RIAF is proportional to $\dot{m}^2$ [22]. Assuming that the x-ray luminosity follows the above

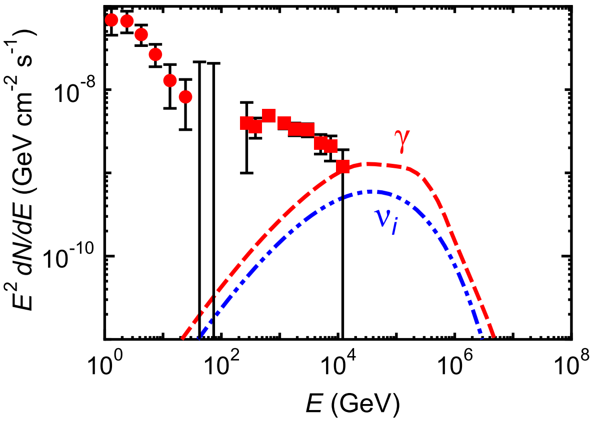

FIG. 3 (color online). Same as Fig. 1 but for $\dot{m} = 0.001$, $\lambda = 3 \times 10^{-3}$, $\zeta = 0.18$, and $\eta_{\rm cr} = 6 \times 10^{-3}$.

observations and upper limits, and that $t_0 = 10^7$ yr is the current time, we set $\dot{m} = 0.03$ for $0 < t < t_0 - 4 \times 10^4$ yr, $\dot{m} = 0.01$ for $t_0 - 4 \times 10^4$ yr $< t < t_0 - 1 \times 10^4$ yr, $\dot{m} = 0.001$ for $t_0 - 1 \times 10^4$ yr $< t < t_0 - 50$ yr, and $\dot{m} = 4.2 \times 10^{-6}$ for $t_0 - 50$ yr $< t < t_0$. Other parameters, including the fiducial values, are time independent, except for $\lambda = 4 \times 10^{-5}$ and $\zeta = 0.025$, which are chosen to be consistent with observations at $E \sim 0.2 - 10$ TeV.

Figure 4 shows the results. The gamma-ray flux from the outer region originates in CRs injected in earlier times. Since $\dot{m}$ decreases as time advances, the typical energy of the CRs, $E_{p,\rm eq}$, in the CMZ should decrease from the outer region to the inner region [Eq. (1)]. We obtain $E_{p,\rm eq} = 2.3$ TeV, when $\dot{m} = 0.03$. However, the shape of the gamma-ray spectrum from $0 < r < 0.1\ R_{\rm CMZ}$ is not much different than that from $0.9\ R_{\rm CMZ} < r < R_{\rm CMZ}$. The peak gamma-ray energy of the former is only a factor of 2 smaller than the latter. Most of the gamma-ray flux from the CMZ is associated with CRs injected when $\dot{m} = 0.03$, because they are injected during most of the past diffusion time ($t_0 - t_{\rm diff,C} < t < t_0 - 4 \times 10^4$ yr), where $t_{\rm diff,C} = R_{\rm CMZ}^2/(6\kappa) \sim 1.6 \times 10^5$ yr (at $E_p \sim 1$ TeV). Those CRs prevail in the CMZ even at present. CRs of $E \lesssim 1$ TeV injected when $\dot{m} \leq 0.001$ are located at $r \lesssim 0.25 R_{\rm CMZ}$. However, their short injection time scale compared with $t_{\rm diff,C}$ and the smaller injection rate ($L_{p,\rm tot} \propto \dot{m}$) make their contribution to the gamma-ray flux smaller. In other words, the contribution of CRs is represented in the form of $\int \lambda L_{p,\rm tot} dt$ integrated for the past diffusion time. Moreover, since the higher-energy CRs ($\gg$1 TeV) have shorter diffusion times, they escape faster from the CMZ than lower-energy CRs. This also makes the gamma-ray spectrum from the older CRs softer. Of course, if the typical CR energy, $E_{p,\rm eq}$, significantly varies in the past, while $\dot{m}$ does not much decrease [see Eq. (1)], the gamma-ray spectrum can change across the CMZ. Note that the gamma-ray luminosity of the RIAF is proportional to $\dot{m}^2$ and it is $\sim 0.001\, L_{p,\rm tot} \sim 10^{37}$ erg s^{-1} when $\dot{m} = 0.001$ [19]. Although this is larger than the current total gamma-ray luminosity of the CMZ at $\sim$1 TeV ($\sim 4 \times 10^{34}$ erg s^{-1}), the gamma-rays from the RIAF cannot be observed at present. This is because the gamma-ray luminosity of the RIAF almost immediately changes with $\dot{m}$, owing to the short (<1 yr) diffusion or escape time of the CRs in the RIAF [19].

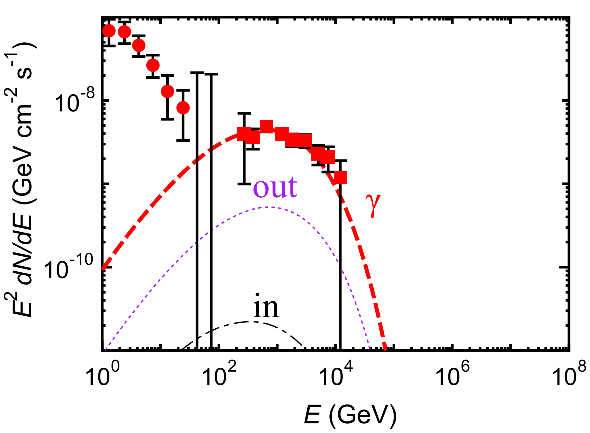

FIG. 4 (color online). Same as Fig. 1 but when $\dot{m}$ is variable (see text). Thick dashed line is the total gamma-ray flux. Thin dotted line (out) is the gamma-ray flux from $0.9 R_{\rm CMZ} < r < R_{\rm CMZ}$. Thin dot-dashed line (in) is that from $0 < r < 0.1 R_{\rm CMZ}$.

V. GAMMA RAYS FROM THE CMZ AROUND CENTAURUS A

Since some LLAGNs other than Sgr A* also have their own CMZs, gamma rays and neutrinos may be created there. As for neutrinos from their RIAFs, LLAGNs with $\dot{m} \sim 0.01 - 0.1$ most contribute to the neutrino flux on the Earth, because the neutrino production rate in a RIAF is sensitive to $\dot{m}$ and RIAFs are realized when $\dot{m} \lesssim 0.01 - 0.1$ [19]. If a fraction $\lambda \lesssim 10^{-3}$ of the CR protons accelerated in those RIAFs enter their CMZs as is the case of Sgr A*, the production rate of neutrinos in the CMZs is smaller than that in the RIAFs. Thus, the contribution of the former to the overall neutrino flux on the Earth is expected to be smaller than the latter. However, if the RIAF in a nearby galaxy is well covered with massive molecular gas or a CMZ and $\dot{m}$ is relatively large, the gamma rays from the CMZ may still be detectable as an individual source.

In Fig. 5, we show as an example the gamma-ray flux from Centaurus A (Cen A), which is a nearby radio galaxy and for which the origin of the gamma rays is under debate [58,59]. The distance to Cen A is assumed to be 3.84 Mpc. We do not include the absorption of the gamma rays. The radius, thickness, and mass of the CMZ are $R_{\rm CMZ,obs} = 195$ pc, $H_{\rm CMZ,obs} = 195$ pc, and $M_{\rm CMZ} = 8.4 \times 10^7\ M_\odot$, respectively [60]. The mass of the SMBH is $M_{\rm BH} = 5 \times 10^7\ M_\odot$ [61]. We choose $\dot{m} = 0.01$, $\lambda = 0.02$, and $\zeta = 0.03$ in order to reproduce the HESS results. Other parameters are the same as the fiducial ones. These give the typical energy of $E_{p,\rm eq} = 7.9$ TeV from

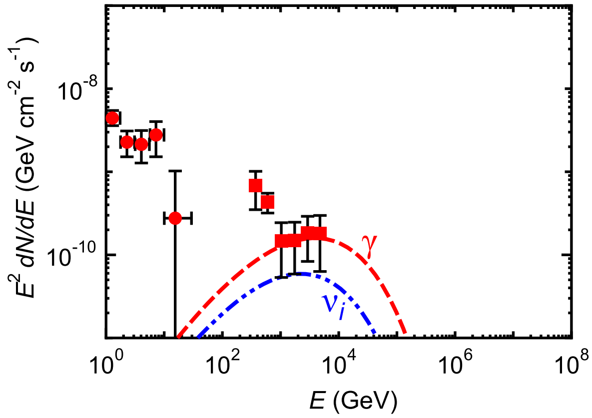

FIG. 5 (color online). Predicated gamma-ray flux (dashed line) and neutrino flux (two-dot dashed line) from Cen A. Parameters are shown in the text. Filled circles and squares are the Fermi and HESS observations, respectively [65,66].

Eq. (1). Cen A has a prominent cold gas disc [62] and, thus, the effective covering factor λ may be larger than that of Sgr A*. Figure 5 shows that our model can reproduce the HESS observations at $E \gtrsim 1$ TeV, although another component is required at $E \lesssim 1$ TeV. We note that the actual gamma-ray flux from the CMZ could be smaller if that from the CRs accelerated by other mechanisms (e.g., acceleration in the electronic field at the base of jets [63]) cannot be ignored. In fact, jets have been observed in Cen A [64].

VI. SUMMARY

We have shown that TeV gamma rays from the Galactic center can be used to test a model in which LLAGNs are the source of neutrinos observed with IceCube. In this model, protons are accelerated in the radiatively inefficient accretion flows (RIAFs) in the LLAGNs, and neutrinos are created through pp and $p\gamma$ interactions in the flows. Since Sgr A* at the center of the Galaxy is an LLAGN, we expect that the protons are being accelerated in Sgr A* and injected into the interstellar space.

In this study, we found that the central molecular zone (CMZ) surrounding Sgr A* works as an effective target of the high-energy protons escaped from the RIAF, and gamma rays and neutrinos are created there through pp interactions. We showed that our model can explain the gamma rays observed by HESS at $E \sim 0.2-10$ TeV if the accretion rate on Sgr A* was $\sim 10^3$ times larger in the past than it is today, as indicated by previous studies, and if the typical energy of the CR protons is $\sim$ TeV. In the near future, CTA could observe gamma rays at $\sim 10-100$ TeV, which could be used to estimate the typical energy of the CR protons more precisely. The gamma-ray emission from some nearby galaxies could be attributed to this mechanism if their LLAGNs are surrounded by molecular gas. Future comparison between observed gamma-ray and neutrino spectra and images would be useful to confirm this model.

ACKNOWLEDGMENTS

This work is partly supported by the challenge support program of Osaka University and by JSPS KAKENHI Grant No. 15K05080 (Y. F.). This work is also partly supported by a Grant-in-Aid for JSPS Fellowships No. 251784 (S. S. K.). K. M. acknowledges the Institute for Advanced Study for continuous support.

[1] M. G. Aartsen *et al.*, Phys. Rev. Lett. **111**, 021103 (2013).
[2] M. G. Aartsen *et al.*, Phys. Rev. Lett. **113**, 101101 (2014).
[3] M. G. Aartsen *et al.*, Phys. Rev. D **91**, 022001 (2015).
[4] A. Loeb and E. Waxman, J. Cosmol. Astropart. Phys. 05 (2006) 003.
[5] K. Murase, S. Inoue, and S. Nagataki, Astrophys. J. **689**, L105 (2008).
[6] K. Murase, M. Ahlers, and B. C. Lacki,, Phys. Rev. D **88**, 121301 (2013).
[7] K. Murase and K. Ioka, Phys. Rev. Lett. **111**, 121102 (2013).
[8] F. W. Stecker, Phys. Rev. D **88**, 047301 (2013).
[9] B. Katz, E. Waxman, T. Thompson, and A. Loeb, arXiv:1311.0287.
[10] M. Ahlers and K. Murase, Phys. Rev. D **90**, 023010 (2014).
[11] I. Tamborra, S. Ando, and K. Murase, J. Cosmol. Astropart. Phys. 9 (2014) 043.
[12] S. Yoshida and H. Takami, Phys. Rev. D **90**, 123012 (2014).
[13] X.-C. Chang and X.-Y. Wang, Astrophys. J. **793**, 131 (2014).
[14] D. B. Fox, K. Kashiyama, and P. Mészarós, Astrophys. J. **774**, 74 (2013).
[15] R.-Y. Liu, X.-Y. Wang, S. Inoue, R. Crocker, and F. Aharonian, Phys. Rev. D **89**, 083004 (2014).
[16] C. D. Dermer, K. Murase, and Y. Inoue, J. High Energy Astrophys. **3**, 29 (2014).
[17] K. Murase, Y. Inoue, and C. D. Dermer, Phys. Rev. D **90**, 023007 (2014).
[18] K. Kashiyama and P. Mészáros, Astrophys. J. **790**, L14 (2014).
[19] S. S. Kimura, K. Murase, and K. Toma, Astrophys. J. **806**, 159 (2015).
[20] P. Mészáros, Nucl. Phys. B Proc. Suppl. **256–257**, 241 (2014).
[21] K. Murase, arXiv:1410.3680.
[22] F. Yuan and R. Narayan, Annu. Rev. Astron. Astrophys. **52**, 529 (2014).

[23] F. Yuan, E. Quataert, and R. Narayan, Astrophys. J. **598**, 301 (2003).

[24] S. S. Kimura, K. Toma, and F. Takahara, Astrophys. J. **791**, 100 (2014).

[25] K. Koyama, Y. Maeda, T. Sonobe, T. Takeshima, Y. Tanaka, and S. Yamauchi, Publ. Astron. Soc. Jpn. **48**, 249 (1996).

[26] H. Murakami, K. Koyama, M. Sakano, M. Tsujimoto, and Y. Maeda, Astrophys. J. **534**, 283 (2000).

[27] T. Totani, Publ. Astron. Soc. Jpn. **58**, 965 (2006).

[28] S. G. Ryu, M. Nobukawa, S. Nakashima, T. G. Tsuru, K. Koyama, and H. Uchiyama, Publ. Astron. Soc. Jpn. **65**, 33 (2013).

[29] M. Morris and E. Serabyn, Annu. Rev. Astron. Astrophys. **34**, 645 (1996).

[30] M. Kusunose and F. Takahara, Astrophys. J. **748**, 34 (2012).

[31] M. Petropoulou, E. Lefa, S. Dimitrakoudis, and A. Mastichiadis, Astron. Astrophys. **562**, A12 (2014).

[32] T. M. Yoast-Hull, J. S. Gallagher III, and E. G. Zweibel, Astrophys. J. **790**, 86 (2014).

[33] F. Melia and M. Fatuzzo, Mon. Not. R. Astron. Soc. **410**, L23 (2011).

[34] T. Amano, K. Torii, T. Hayakawa, and Y. Fukui, Publ. Astron. Soc. Jpn. **63**, L63 (2011).D. R. Ballantyne, F. Melia, S. Liu, and R.M. Crockers, Astrophys. J. **657**, L13 (2007).S. Dimitrakoudis, A. Mastichiadis, and A. Geranios, Astropart. Phys., **31**, 13 (2009).

[35] K. Murase, K. Asano, T. Terasawa, and P. Mészáros, Astrophys. J. **746**, 164 (2012).

[36] J. Kakuwa, K. Toma, K. Asano, M. Kusunose, and F. Takahara, Mon. Not. R. Astron. Soc. **449**, 551 (2015).

[37] N. I. Shakura and R. A. Sunyaev, Astron. Astrophys. **24**, 337 (1973).

[38] P. A. Becker, T. Le, and C. D. Dermer, Astrophys. J. **647**, 539 (2006).

[39] S. Gabici, F. A. Aharonian, and S. Casanova, Mon. Not. R. Astron. Soc. **396**, 1629 (2009).

[40] K. Ferrière, Astron. Astrophys. **505**, 1183 (2009).

[41] Y. Fujita, Y. Ohira, S. J. Tanaka, and F. Takahara, Astrophys. J. **707**, L179 (2009).

[42] M. Fatuzzo and F. Melia, Astrophys. J. **750**, 21 (2012).

[43] N. Karlsson and T. Kamae, Astrophys. J. **674**, 278 (2008).

[44] S. R. Kelner, F. A. Aharonian, and V. V. Bugayov, Phys. Rev. D **74**, 034018 (2006).

[45] I. V. Moskalenko, T. A. Porter, and A. W. Strong, Astrophys. J. **640**, L155 (2006).

[46] T. A. Porter and A. W. Strong, International Cosmic Ray Conference (2005), Vol. **4**, p. 77, arXiv:astro-ph/0507119.

[47] D. Pierce-Price *et al.*, Astrophys. J. **545**, L121 (2000).

[48] G. Mou, F. Yuan, D. Bu, M. Sun, and M. Su, Astrophys. J. **790**, 109 (2014).

[49] S. Gillessen, F. Eisenhauer, S. Trippe, T. Alexander, R. Genzel, F. Martins, and T. Ott, Astrophys. J. **692**, 1075 (2009).

[50] A. M. Atoyan, F. A. Aharonian, and H. J. Völk, Phys. Rev. D **52**, 3265 (1995).

[51] F. Yusef-Zadeh *et al.*, Astrophys. J. **762**, 33 (2013).

[52] F. Aharonian *et al.*, Nature (London) **439**, 695 (2006).

[53] B. S. Acharya *et al.*, Astropart. Phys. **43**, 3 (2013).

[54] A. U. Abeysekara *et al.*, Astropart. Phys. **50–52**, 26 (2013).

[55] P. Sapienza, A. Trovato, R. Coniglione, and KM3NeT Consortium, Nucl. Instrum. Methods Phys. Res., Sect. A **725**, 45 (2013).

[56] C. K. Cramphorn and R. A. Sunyaev, Astron. Astrophys. **389**, 252 (2002).

[57] G. Ponti, M. R. Morris, M. Clavel, R. Terrier, A. Goldwurm, S. Soldi, R. Sturm, F. Haberl, and K. Nandra, in *IAU Symposium*, Vol. 303, edited by L. O. Sjouwerman, C. C. Lang, and J. Ott (Cambridge University Press, Cambridge, England, 2014), p. 333.

[58] S. Sahu, B. Zhang, and N. Fraija, Phys. Rev. D **85**, 043012 (2012).

[59] N. Sahakyan, R. Yang, F. A. Aharonian, and F. M. Rieger, Astrophys. J. **770**, L6 (2013).

[60] F. P. Israel *et al.*, Astron. Astrophys. **562**, A96 (2014).

[61] M. Cappellari, N. Neumayer, J. Reunanen, P. P. van der Werf, P. T. de Zeeuw, and H.-W. Rix, Mon. Not. R. Astron. Soc. **394**, 660 (2009).

[62] C. Henkel and T. Wiklind, Space Sci. Rev. **81**, 1 (1997).

[63] J. Aleksić *et al.*, Science **346**, 1080 (2014).

[64] M. J. Hardcastle *et al.*, Astrophys. J. **670**, L81 (2007).

[65] A. A. Abdo *et al.*, Astrophys. J. **719**, 1433 (2010).

[66] F. Aharonian *et al.*, Astrophys. J. **695**, L40 (2009).