Research in Astron. Astrophys. **2009** Vol. **9** No. **7**, 761 – 769
http://www.raa-journal.org *http://www.iop.org/journals/raa*

Research in Astronomy and Astrophysics

Injected spectrum for TeV γ-ray emission from the galactic center *

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Received 2008 October 28; accepted 2009 April 17

Abstract The detection of very high energy γ-ray emission from the Galactic center has been reported by four independent groups. One of these γ-ray sources, the 10 TeV γ-ray radiation reported by HESS, has been suggested as having a hadronic origin when relativistic protons are injected into and interact with the dense ambient gas. Assuming that such relativistic protons required by the hadronic model come from the tidal disruption of a star by the massive black hole of Sgr A*, we explore the spectrum of the relativistic protons. In the calculations, we investigate cases where different types of stars are tidally disrupted by the black hole of Sgr A*, and we consider that different diffusion mechanisms are used for the propagation of protons. The initial energy distribution of the injected spectrum of protons is assumed to follow a power-law with an exponential cut-off, and we derive the different indices of the injected spectra for the tidal disruption of different types of stars. For the best fit to the spectrum of photons detected by HESS, the spectral index of the injected relativistic protons is about 2.05 when a red giant is tidally disrupted by the black hole of Sgr A* and the diffusion mechanism is the Effective Confinement of Protons.

Key words: black hole physics — galaxies: jets — Galaxy: center

1 INTRODUCTION

The Galactic center (GC), where a lot of remarkable objects are harbored (Melia & Falcke 2001), is an important potential site for the production of high energy γ-ray emission. In recent years, TeV γ-ray emission from the GC had been reported by four independent groups, CANGAROO (Tsuchiya et al. 2004), Whipple (Kosack et al. 2004), HESS (Aharonian et al. 2004), and MAGIC (Albert et al. 2006). Among possible sites of production of the TeV signal is the entire diffuse 10 pc region (Aharonian & Neronov 2005b), the relatively young supernova remnant (SNR) Sgr A East (Crocker et al. 2005), the dark matter halo (Horns 2005; Profumo 2005; Gnedin & Primack 2004; Ellis et al. 2002) due to annihilation of suppersymmetric particles, and finally the black hole Sgr A* itself (Aharonian & Neronov 2005a). Observationally, both the energy spectrum and the flux measured by HESS (Aharonian et al. 2004) differ significantly from the results reported by the CANGAROO (Tsuchiya et al. 2004) and Whipple (Kosack et al. 2004) groups: the observed γ-ray emission from HESS shows a relatively hard energy spectrum which extends to the energy range of 10 TeV, and the best fitted spectral index is about –2.2. The angular scale of the TeV source by HESS within $1'$ around Sgr A* indicates that this γ-ray

* Supported by the National Natural Science Foundation of China.

source is located in the central ≤ 10 pc region (Aharonian et al. 2004). It suggests that the black hole of Sgr A* seems to be the most likely candidate with which the TeV radiation could be associated.

How is the production of TeV γ-ray emission possible with the features detected by HESS? For most TeV sources, particularly those unidentified at other wavelengths, it remains a mystery as to whether the observed γ-ray flux is produced by hadronic or leptonic processes. If the γ-rays arise from the decay of neutral pions ($\pi^0 \rightarrow \gamma\gamma$) produced in proton–proton scattering, it is well-established that a corresponding flux of neutrinos (produced in $\pi^\pm$ decays) must also be present (Stecker 1979). A hadronic origin of TeV γ-rays that is linked to the massive black hole has been addressed in detail by Aharonian & Neronov (2005b). They argued that the TeV γ-rays are produced indirectly through the processes of π^0-decay when relativistic protons are injected into and interact with the target. One of the key elements required by the hadronic model is the injection of numerous relativistic protons. In this regard, one should find that the TeV γ-ray emission produced via a hadronic model carries information about the injected relativistic protons. Therefore, studies of TeV emission from the GC present a unique opportunity to explore high-energy processes of particle acceleration and the energy spectrum of the particles.

The production of γ-ray emission via a hadronic origin also depends on the diffusion coefficient of protons in the ambient gas. As a result, a dense gas target and an available diffusion mechanism for the propagation of protons are necessary. Generally, the diffusion coefficient is a function of the injected proton's energy, which can be expressed as $D(E) = 10^{28}(E/1\mathrm{GeV})^\delta \kappa\,\mathrm{cm}^2\ \mathrm{s}^{-1}$, where $\delta \sim 0.3-0.6$ (Berezinskii et al. 1990) and $\kappa \sim 10^{-4}$ to 10^{-2} (Aharonian & Atoyan 1996) are dimensionless parameters. The three typical propagation scenarios characterized by different δ and κ values have been addressed by Aharonian & Neronove (2005b): the case of the effective confinement of protons (ECP) corresponds to $\delta = 0.5$ and $\kappa = 10^{-4}$, the Kolmogorov type turbulence (KTT) corresponds to $\delta = 0.3$ and $\kappa = 0.15$, and the Bohm diffusion (BD) corresponds to $\delta \sim 1.0$ and $\kappa \sim 10^{-2}$. For photons with a typical energy of 10 TeV, the diffusion coefficient is $1.0 \times 10^{26}\ \mathrm{cm}^2\ \mathrm{s}^{-1}$ for ECP, $2.4 \times 10^{28}\ \mathrm{cm}^2\ \mathrm{s}^{-1}$ for KTT, and $1.0 \times 10^{30}\ \mathrm{cm}^2\ \mathrm{s}^{-1}$ for BD.

In this paper, the TeV γ-ray emission is thought to be produced via a hadronic model, and the required relativistic protons come from the tidal disruption of stars by a massive black hole. We investigate the spectral nature of the injected relativistic protons, which is derived by comparing the γ-ray radiation predicted by the hadronic model with the observed γ-ray emission from HESS. As a mechanism for the production of the injected relativistic protons, Lu et al. (2006) argued that there are remarkable differences between the tidal disruption of a main sequence (MS) star and giant star. Thus, our calculation is carried out to try to model the tidal disruption of the different types of stars. The different propagation mechanisms of protons is considered as well. We describe the hadronic model in Section 2. The numerical calculation of the spectral energy distribution (SED) of the γ-ray emission and the properties of the injected protons are presented in Section 3. A brief discussion and conclusions are given in Section 4.

2 THE HADRONIC ORIGIN OF TEV γ-RAY RADIATION

2.1 Injected Relativistic Protons Supplied by a Massive Black Hole

There is strong evidence for the existence of massive black holes with masses from a few times 10^5 to a few times $10^9\,M_\odot$ in the centers of many galaxies (Haehnelt & Rees 1993; Kormendy & Gebhardt 2001). In our own Galaxy, the remarkable radio source Sgr A* in the Galactic central region (Melia & Falcke 2001), is most likely a massive black hole with a mass of $M_{\mathrm{bh}} \approx 3 \times 10^6\,M_\odot$ (Genzel et al. 2000; Ghez et al. 2000; Schödel et al. 2002). Accreting black holes (BHs) are believed to be sites of possible particle acceleration that form a powerful jet, with conditions that are also favorable for effective gamma-ray production (Aharonian & Neronove 2005b). However, such a model cannot be applied directly to the BH of Sgr A*. The current multi-wavelength observations show that Sgr A* has an extraordinarily low bolometric luminosity of $\sim 10^{36}\,\mathrm{erg\,s}^{-1}$. This indicates that the BH of Sgr A* is in its quiescent dim state, and no powerful jet exists at present. Nevertheless, Lu et al. (2006) proposed that the BH Sgr A* could have been naturally lit up and produced the injection of the relativistic protons required by the hadronic origin of the TeV γ-ray radiation when it captured and tidally disrupted a star. They assume that the black hole was active 300 years ago based on their observation. In their model, the tidal disruption of a red giant and a main sequence (MS) star have been discussed, respectively. They argued that for the two cases, the total energy carried by the relativistic protons of the jet is exactly the same. However, the injection times of the high energy protons are definitely different (see the table 1 of Lu et al. 2006). Considering that possibly only $\sim 10\%$ of the total jet energy could be converted into high-energy particles, we derive the injection energy of the relativistic protons

$$E_{\rm inj} \simeq 2.76 \times 10^{51}\,{\rm erg}, \tag{1}$$

and the total injection time

$$t_{\rm inj} \simeq \begin{cases} 2.08 \times 10^4\,{\rm yr}, & \text{for the red giant}, \\ 5.0 \times 10^2\,{\rm yr}, & \text{for the MS star}, \end{cases} \tag{2}$$

respectively.

2.2 The Spectrum of the Injected Protons

Considering that most of the injection energy of $E_{\rm inj}$ will be released in a characteristic time of $t_{\rm min}$

$$t_{\rm min} = R_{\rm d}/c, \tag{3}$$

where $R_{\rm d}$ is the distance between the central engine and the target, we take the source function of protons as

$$Q(E_{\rm p}, R, t) = f_{\rm p0}(E_{\rm p})\delta(t)\delta(R), \tag{4}$$

where t is the source age, R is the distance to the source of protons, $f_{\rm p0}$ is the initial energy distribution of the injected protons, and $f_{\rm p0}$ is assumed to follow

$$f_{\rm p0}(E_{\rm p}) = KE_{\rm p}^{-\gamma_0}(-E_{\rm p}/E_{\rm pmax}), \tag{5}$$

where K is the normalization constant, γ_0 is the spectral index, $E_{\rm p}$ is the proton energy and $E_{\rm pmax}$ is the energy where the exponential cut-off starts to dominate over the power-law.

The spectral energy distribution of the injected protons ($f_{\rm p}$) can be derived from the well known equation of cosmic ray propagation (Ginzburg & Syrovatskii 1964)

$$\frac{\partial f_{\rm p}}{\partial t} = \frac{D}{R^2}\frac{\partial}{\partial R}\left[R^2\frac{\partial f_{\rm p}}{\partial R}\right] + \frac{\partial}{\partial E_{\rm p}}(Pf_{\rm p}) + Q\,, \tag{6}$$

where $f_{\rm p} \equiv f_{\rm p}(E_{\rm p}, R, t)$ is the distribution function of particles at instant t and distance R from the source; P is the continuous energy loss rate determined by $P(E_{\rm p}) = E_{\rm p}/\tau_{\rm pp}$, where $\tau_{\rm pp} \approx 6 \times 10^7 n^{-1}$ yr (Gaisser 1990) is the characteristic lifetime of proton–proton collisions, depending on the number density of the ambient gas n; D is the diffusion coefficient which is assumed to be independent of R and t, but dependent on $E_{\rm p}$. In this paper, we consider the following three diffusion mechanisms (Lu et al. 2006)

$$D(E) = 10^{28}(E/1{\rm GeV})^{\delta}\kappa \quad {\rm cm^2\,s^{-1}}$$

$$\begin{cases} \delta = 0.5 & \kappa = 10^{-4} & \text{for ECP}, \\ \delta = 0.3 & \kappa = 0.15 & \text{for KTT}, \\ \delta = 1.0 & \kappa = 10^{-2} & \text{for BD}. \end{cases} \tag{7}$$

Considering the assumptions that a power-law and a high-energy cut-off injection spectrum exist (*cf.* Eq. (5)), in addition to a diffusion coefficient that depends on energy which follows a power-law (*cf.* Eq. (7)), the general solution of $f_{\rm p}(E_{\rm p}, R, t)$ is reduced to (Bosch-Ramon et al. 2005)

$$f_{\rm p}(E_{\rm p}, R, t) \approx \frac{KE_{\rm p}^{-\gamma_0}\exp(-E_{\rm p}/E_{\rm pmax})}{\pi^{3/2}R_{\rm dif}^3} \times \exp\left(-\frac{(\gamma_0 - 1)t}{\tau_{\rm pp}} - \frac{R^2}{R_{\rm dif}^2}\right)\,. \tag{8}$$

Here

$$R_{\rm dif}(E_{\rm p}, t) = 2\left(D(E_{\rm p})t\frac{\exp(t\delta/\tau_{\rm pp}) - 1}{t\delta/\tau_{\rm pp}}\right)^{1/2}, \tag{9}$$

is the diffusion radius (Aharonian & Atoyan 1996), corresponding to the radius of the sphere up to which the particles of energy $E_{\rm p}$ effectively propagate during the time t after their injection into the target.

2.3 γ-rays from the Hadronic Model

According to the hadronic origin, neutral pions are produced in proton–proton (pp) collisions and they will immediately decay to high energy γ-ray photons. The emissivity of the photons produced by π^0-decay (q_γ) is (Stephens & Badhwar 1981):

$$q_\gamma(E_\gamma, R, t) = 2\int_{E_{\pi\,\rm min}}^{E_{\pi\,\rm max}} \frac{q_\pi(E_\pi, R, t)}{\sqrt{E_\pi^2 - m_\pi^2 c^4}} dE_\pi\,, \tag{10}$$

where E_π and E_γ are the energies of the decaying pion and the emitted photon respectively, $E_{\pi\,\rm min} = E_\gamma + m_\pi^2 c^4$, m_π is the pion mass and c is the speed of light. $E_\gamma > 10^6$ eV, for $E_\gamma E_{\rm ph} \geqslant (2m_e c^2)^2$, where $E_{\rm ph}$ is the photon energy of the star light; q_π is the neutral pion emissivity from pp interaction, which satisfies (Aharonian & Atoyan 1996)

$$\begin{aligned} q_\pi(E_\pi, R, t) &= cn_H \int_{E_{\rm pmin}}^{E_{\rm pmax}} \delta(E_\pi - k_\pi E_{\rm kin}) \times \sigma_{\rm pp}(E_{\rm p}) f_{\rm p}(E_{\rm p}, R, t) dE_{\rm p} \\ &= \tfrac{cn_H}{k_\pi}\sigma_{\rm pp}(m_{\rm p}c^2 + E_\pi/k_\pi) f_{\rm p}(m_{\rm p}c^2 + E_\pi/k_\pi, R, t)\,, \end{aligned} \tag{11}$$

where k_π is the mean fraction of the kinetic energy of the proton ($E_{\rm kin} = E_{\rm p} - m_{\rm p}c^2$) transferred to the secondary pion per collision (Gaisser 1990), n_H is the density of particles of the target region, and $\sigma_{\rm pp} \approx 30[0.95 + 0.06\ln(E_{\rm kin}/1{\rm GeV})]\, mb$ is the cross section of the pp interaction.

Given that the target is homogenous, and its linear size must be small enough compared to R to assume the same energy distribution for the injected protons everywhere in the interaction region, the Spectral Energy Distribution (SED) of the emitted γ-rays due to pp interaction within a target at a given $t_{\rm inj}$ (age of the proton source) and $R_{\rm size}$ (distance from the proton source to the target) can be estimated:

$$E_\gamma f(E_\gamma) = \frac{V}{S} E_\gamma^2 \int_0^{R_{\rm size}} \int_{t_{\rm min}}^{t_{\rm diff}} q_\gamma(E_\gamma, R, t)\, dRdt, \tag{12}$$

where E_γ is the energy of the emitted γ-ray photons, $V = \frac{4\pi R_{\rm size}^3}{3}$ is the total volume of the interaction region, $t_{\rm diff}$ is the escape time of protons which is defined by $t_{\rm diff} = t_{\rm inj} + 300$ yr, and $S = 4\pi R_0^2$ is the detected area of the emitted γ-rays, where R_0 is the distance from the observer to the central engine.

3 APPLICATION TO γ-RAYS

The TeV γ-ray source detected by HESS indicates that it is located in the central 10 pc region (Aharonian et al. 2004), and the observed spectrum can be described by $F(E_\gamma) = (2.5 \pm 0.21) \times 10^{-12} E_\gamma^{-2.21}$ ph(cm^2 s TeV)$^{-1}$. We derived the spectrum of the γ-ray radiation produced by π^0 decay resulting from the interaction of relativistic protons with the ambient gas (*cf*. Eq. (12)). The initial spectrum of the injected protons is given by Equation (5), and the relativistic photons are assumed to come from the tidal disruption of stars by the BH of Sgr A*. The injected source function of the relativistic protons is satisfied with Equation (4), operating during the life of the jet, $t_{\rm inj}$, and supplying the energy, $E_{\rm inj}$. The adopted values of the parameters mentioned above are given in Table 1. Following this, we address the issues of different types of stars disrupted by the BH of Sgr A* and different diffusion mechanisms for the protons that might be relevant.

Table 1 Adopted Values of the Parameters

Parameter	Symbol	Value
Distance between the central engine and target	$R_{\rm d}$	10 pc
Density of the dense ISM region	n_H	10^3 cm^{-3}
Distance between the observer and central engine	R_0	8 kpc
Time of proton–proton interaction	$\tau_{\rm pp}$	10^5 yr
Injection time in a disrupted red giant	$t_{\rm inj}$	2.08×10^4 yr
Injection time in a disrupted MS star	$t_{\rm inj}$	5×10^2 yr
The mean fraction of the E_k of the protons transferred to the secondary pi per collision	k_π	0.17
Cutoff energy of the protons	$E_{\rm pmax}$	10^{18} eV
Kinetic energy for relativistic protons	$E_{\rm kin}$	2.76×10^{51} erg

3.1 Spectral Energy Distribution of γ-rays

In this subsection, we discuss the overall spectrum of γ-ray emission assuming that: (1) The diffusion mechanisms are the three cases of ECP, KTT, and BD; (2) The injected relativistic protons are supplied by the red giants and main sequence (MS) stars which were tidally disrupted by the BH of Sgr A*, respectively. The results are plotted in Figures 1 to 5. In these figures, the solid dot and square with error bars are data from HESS and EGRET, respectively.

Given the spectrum of the injected relativistic protons, Figures 1 and 2 demonstrate the SED of γ-rays as a function of three different diffusion mechanisms when a red giant and a MS star are tidally disrupted by the BH of Sgr A*. Figure 3 plots χ^2 by fitting the SED of γ-rays calculated from the model with the observation. In Figure 3, the left panel corresponds to the case of a red giant, and the right panel is for the case of a MS star. With the diffusion mechanism of EPC and adopting the best fit for the injection spectrum index, Figure 4 plots the SED of γ-rays when the BH of Sgr A* tidally disrupted a red giant and a MS star, respectively. The dependence of the SED of γ-rays on the cutoff energy of $E_{\rm max}$ is plotted in Figure 5 in the case that a red giant is disrupted. In Figure 5, we adopt the diffusion mechanism of ECP, and the spectral index of the injected protons is 2.05.

3.2 The Index of the Injected Proton Spectrum

We derive the spectrum of the injected protons by comparing the SED of the γ-ray emission calculated by the model with observations.

From Figures 1 and 2, we find that the GeV γ-ray radiation detected by EGRET could not be produced regardless of whichever value of the index of the injected proton spectrum is adopted. In addition, giving the spectrum and origins of the injected protons, the diffusion mechanisms of KTT and BD are excluded in accounting for the observations reported by HESS. With the ECP diffusion of protons, comparing the tidal disruption of a red giant with a MS star for the production of the SED of TeV γ-rays, we find that a red giant case mainly produces the soft components, and the MS star case is attributed to the hard components. Given the diffusion mechanism of the ECP and the central engine of ejected protons, the trend of the SED of TeV γ-ray radiation moves to a lower energy band with the increase of the injected spectral index, γ_0. The shape of the SED of γ-rays is independent of the diffusion mechanisms.

In Figure 3, χ^2 shows the best fitting to the data detected by HESS when the diffusion mechanism is the ECP. Here we find that the best fitting appears when χ^2 as function of the spectral index of γ_0 reaches its minimum value. The results show that the spectral index of the injected protons that are required is different when the BH of Sgr A* tidally disrupted a different type of star. We derive $\gamma_0 = 2.05$ for the tidal disruption of a red giant (*cf*. the left panel of Fig. 3) and $\gamma_0 = 1.81$ for the case of a MS star (*cf*. the right panel of Fig. 3). The scenario of Sgr A* disrupting a MS star is more reasonable than the case of disrupting a red giant when the observed energy of the emitted γ-photons becomes higher than 10 TeV

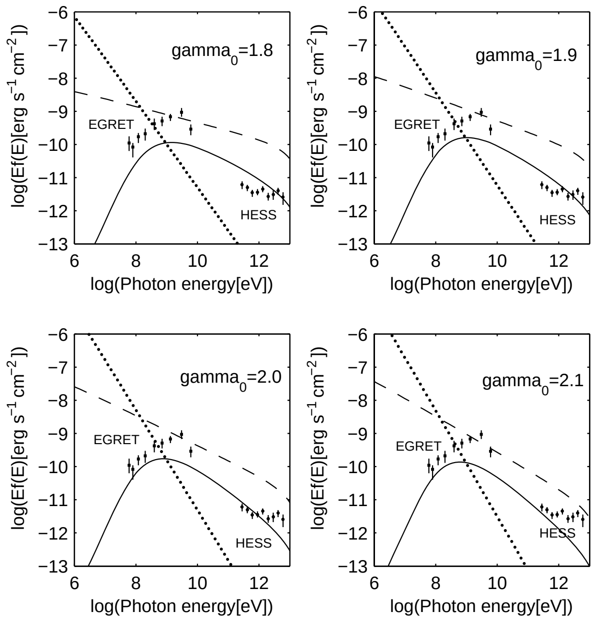

Fig. 1 With a given spectrum of the relativistic protons, Fig. 1 shows the SED of γ-rays as a function of three different diffusion mechanisms when the BH of Sgr A* disrupted a red giant: the solid line is ECP, the dashed line is KTT, and the dotted line is BD.

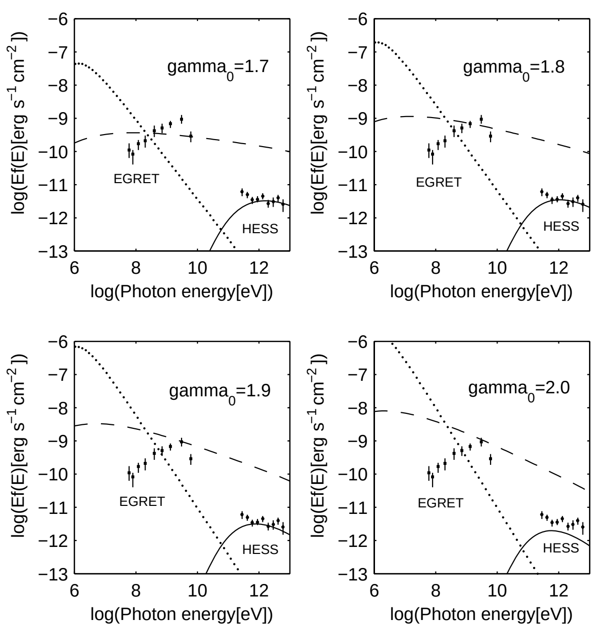

Fig. 2 With a given spectrum of the relativistic protons, Fig. 2 shows the SED of γ-rays as a function of three different diffusion mechanisms when the BH of Sgr A* disrupted a MS star: the solid line is ECP, the dashed line is KTT, and the dotted line is BD.

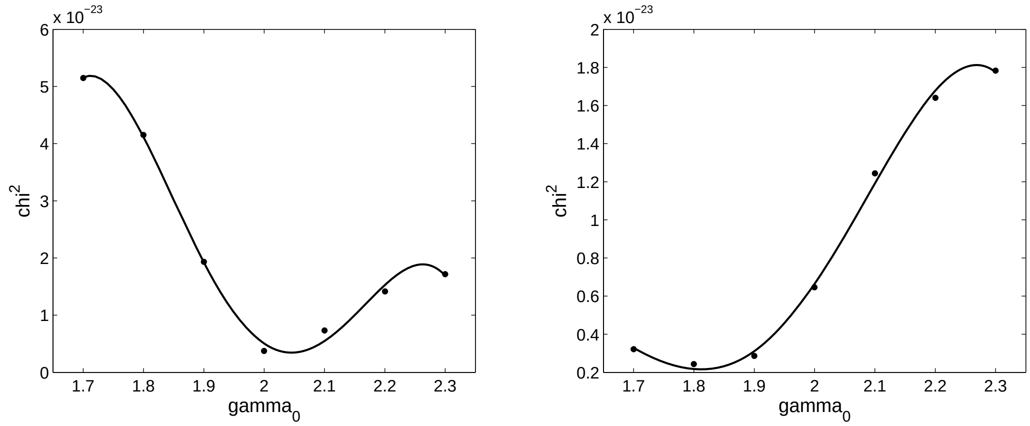

Fig. 3 χ^2 by fitting the SED of γ-rays detected by HESS with the different spectral indices of γ_0. The left and right panels correspond to the tidal disruption of a red giant and a MS star, respectively.

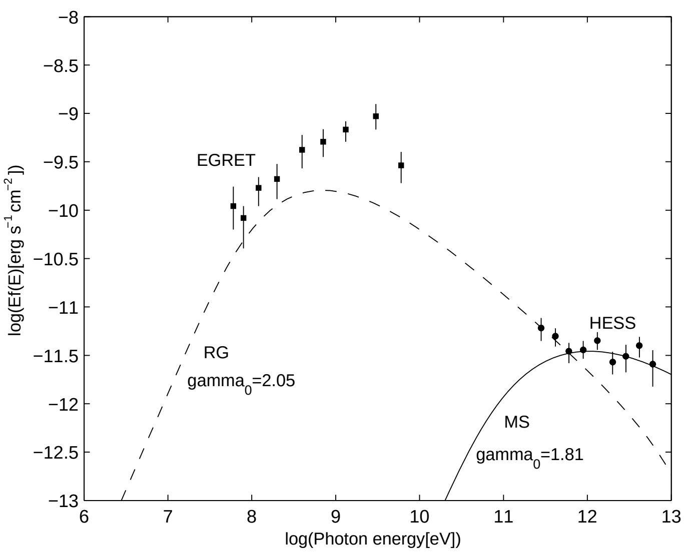

Fig. 4 SED of γ-rays plotted by the tidal disruption of a red giant star and a MS star, respectively. In this figure, the spectral index of γ_0 is adopted to be the best fitting.

of energy. In addition, the SED is not sensitive to the cut-off energy $E_{\rm pmax}$ for the best fitting either when a red giant or a MS star is tidally disrupted (Fig. 5).

In brief, by comparing the theoretical spectrum with the observational data from HESS within the central 10 pc of our Galaxy, we find that the theoretical energy distribution can fit best with the observational data when a red giant is tidally disrupted by the BH of Sgr A* and the diffusion mechanism of protons is the ECP. If this is the case, we derived that the power-law index of the injected relativistic protons is –2.05.

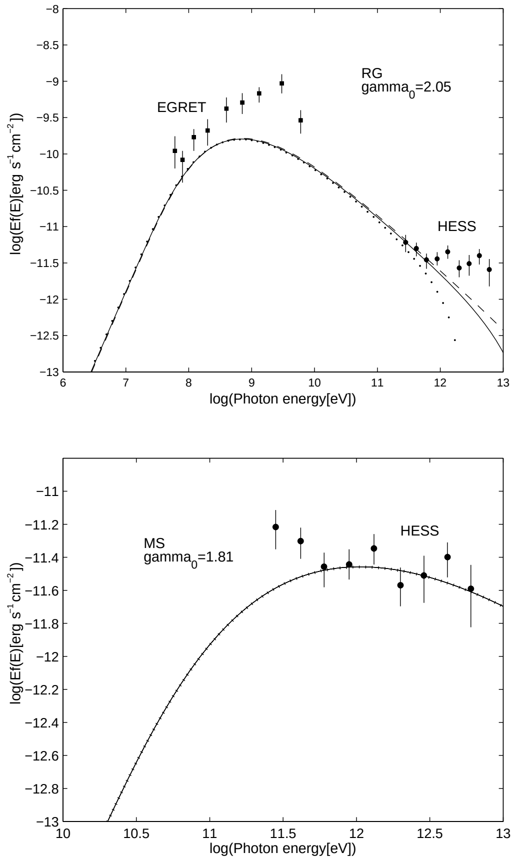

Fig. 5 SED of γ-rays with different cut-off energies: $E_{\rm pmax} = 1 \times 10^{17}$ eV (*dashed line*), 1×10^{18} eV (*solid line*), 1×10^{19} eV (*dotted line*). The upper and bottom panels correspond to the tidal disruption of a red giant and a MS star, respectively.

4 CONCLUSIONS AND DISCUSSION

With the assumption that TeV γ-ray emission is produced via the hadronic model, we studied the properties of the injected relativistic proton spectra by comparing the theoretical model with observational data. Capture and tidal disruption of a star by the BH of Sgr A* is the energy mechanism to produce high energy protons. To fit the TeV γ-ray radiation detected by HESS, we consider the spectrum of the injected relativistic protons. For the best fitting, we obtain the power-law index of the initial spectrum of the protons, $\gamma_0 = 2.05$. Comparing with the work of Aharonian & Neronov (2005b), we connected the injection power to the physical process of the tidal disruption of a MS star or a giant star rather than a parameter. If this is the case, the injected proton timescale, $t_{\rm inj}$, is shorter than 10^5 yr, and the injected proton power, $W_{\rm p}$, is higher than 10^{37} erg s^{-1}. Nevertheless, the total injected proton energy, $E_{\rm inj}$, estimated by the integral of injected proton power via the injected timescale is the same as that of Aharonian & Neronov (2005b). Consequently, the results for the power-law index of the initial spectrum of protons, with $\gamma_0 = 2.05$, estimated in this paper are very similar to that of Aharonian & Neronov (2005b).

We also constrain the type of stars tidally disrupted by the BH of Sgr A* and the diffusion mechanism of protons. The main difference between the ECP, KTT and BDD diffusion mechanisms is that the escape time of protons for these three cases are different. For the case of ECP, the escape time for protons is comparable with the characteristic time of p-p interactions, $t_{\rm pp}$. Comparing with the case of ECP, the proton escape timescales for the case of KTT and BDD are faster, respectively. The results show that the tidal disruption of a red giant as a central engine is more appropriate to explain the observed TeV γ-ray emission detected by HESS than that of a MS star, and the ECP is regarded as the diffusion mechanism for the propagation of protons through the target.

The EGRET data cannot be fitted well in the present model. One possible reason is that the secondary electrons produced in the pp interaction processes may contribute a lot at energies lower than TeV (Zhang & Fang 2007; Cheng et al. 2008). Alternatively, we argue that the BH of Sgr A* may tidally disrupt a red giant together with a MS star as central sources to fit the observed SED from EGRET to HESS, assuming that the γ-rays from MeV to TeV energies come from a hadronic origin. This will be discussed in further work.

Acknowledgements It is a pleasure to thank Y. H. Zhao for helpful discussions. This work was funded by the National Natural Science Foundation of China (Grant Nos. 10873015, 10778716, 10573021, 10778064, 10673001 and 10433010) and the National Basic Research Program of China (Grant 2009CB824800).

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