CAPTURE OF A RED GIANT BY THE BLACK HOLE SAGITTARIUS A* AS A POSSIBLE ORIGIN FOR THE TeV GAMMA RAYS FROM THE GALACTIC CENTER

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ABSTRACT

Nonthermal TeV γ-ray emission within a multiparsec scale has been observed from the center region of our Galaxy. We argue that these γ-rays are the result of transient activity of the massive black hole Sgr A* that resides at the Galactic center. Several thousand years ago, the black hole may have experienced an active phase by capturing a red giant star and forming an accretion disk, temporarily behaving like an active galactic nucleus. A powerful jet, which contains plenty of high-speed protons, was launched during the process. These runaway protons interact with the dense ambient medium, producing TeV γ-ray emission through the π0-decay process. We show that the total energy deposited in this way is large enough to account for observations. The diffusion length of protons is also consistent with the observed size of the TeV source.

Subject headings: accretion, accretion disks — black hole physics — galaxies: active — galaxies: jets — Galaxy: center

1. INTRODUCTION

It is known that there are many remarkable high-energy sources harbored in the Galactic center (GC) region (Melia & Falcke 2001). Recently, TeV γ-ray emission from the direction of the GC has been reported by three independent groups, Whipple (Kosack et al. 2004), CANGAROO (Collaboration of Australia and Nippon for a Gamma Ray Observatory in the Outback; Tsuchiya et al. 2004), and HESS (High Energy Stereoscopic System; Aharonian et al. 2004). At least four potential candidates are suggested for this TeV γ-ray emission, which are the black hole Sgr A* (Aharonian & Neronov 2005a; Atoyan & Dermer 2004; Levinson 2000), the compact and powerful 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), and the whole diffuse 10 pc region (Aharonian & Neronov 2005b). Interestingly, the angular scale of the TeV source was determined by HESS to be less than a few arcminutes, indicating that this γ-ray source is located in the central <10 pc region (Aharonian et al. 2004). It suggests that the black hole Sgr A*, with a mass of 2.6 × 106 M⊙ (Schödel et al. 2002), should be involved (Aharonian & Neronov 2005a).

Recently, 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 π0-decay when relativistic protons are injected into the dense ambient gas environment. The flux of this radiation component depends on the density of the target, the diffusion speed of protons in the interstellar medium, and the injection rate of protons. As a result, a dense gas target and an extremely large proton flux is required. However, since the black hole Sgr A* currently only emits faint electromagnetic radiation, it is largely uncertain how the protons could be accelerated to relativistic speeds.

It is well known that jets associated with accretion disks surrounding black holes are efficient in accelerating particles. For example, TeV γ-rays observed from several BL Lac objects (a subclass of active galactic nuclei) are argued to originate from relativistic jets (Pian et al. 1998). The jet model is also used to explain the production of TeV γ-rays from microquasars (Bosch-Ramon et al. 2005). However, such a jet model cannot be applied directly to the black hole Sgr A*. An extraordinarily low bolometric luminosity of ~1036 ergs s−1 has been estimated for the black hole through multiwavelength observations, which indicates that Sgr A* is in its quiescent dim state, and no powerful jet exists at present.

We propose that the black hole Sgr A* could be reactivated and produce a powerful jet by capturing a red giant (RG) star, temporarily behaving like an active galactic nucleus (AGN). This may have happened thousands of years ago, naturally providing a mechanism to generate the proton flux required by the hadronic model of Aharonian & Neronov. The structure of our paper is as follows. The capture process is described in § 2. We estimate the model parameters and the energy of the proton flux available for the production of TeV γ-rays in § 3. A brief discussion and the conclusion are presented in § 4.

2. RED GIANT CAPTURE AND THE LIGHTING UP OF SGR A*

2.1. The Capture of a Red Giant

Many if not all galaxies are expected to possess a massive black hole (Haehnelt & Rees 1993). It has been thought that the capture and tidal disruption of stars by such a massive black hole could result in flarelike activities in the central regions of AGNs and even in normal galaxies and globular clusters. The flare results from the rapid release of gravitational energy as the matter from the disrupted star plummets toward the black hole (Rees 1990; Shlosman et al. 1990). This process may even be the mechanism of γ-ray bursts (Cheng & Lu 2001). It is interesting to note that the presence of an extended high-temperature plasma at the GC region has been confirmed by Advanced Satellite for Cosmology and Astrophysics (ASCA) observations (Koyama et al. 1996), suggesting that the GC exhibited intermittent activities at least 300 yr ago. We propose that the black hole Sgr A* could have been naturally lit up and produced the currently observed TeV γ-rays when it captured a RG star.
The detailed capture and disruption process of a main-sequence (MS) star has been studied by several authors (Rees 1988; Cannizzo et al. 1990). Syer & Ulmer (1999) also discussed the capture rate of red giant stars by a massive galactic black hole in virialized star clusters. Compared with the capture of a MS star, the disruption of a RG star is different in that (1) RG disruption events generally last much longer, but are relatively fainter; (2) the tidal disruption radius of a RG star is typically equal to its pericenter radius; and (3) the size of the accretion disk formed in the capture process of a RG is larger. We believe that the capture of a RG star (rather than a MS star) is more appropriate to explain the observed \( \gamma \)-ray emission from the GC (this problem is further addressed in § 4).

We follow the treatments of Syer & Ulmer (1999) to study the capture of a RG star and scale our parameters to the physical conditions in the Galactic center. When a star of mass \( M \) passes by a black hole with a mass of \( M_{\text{bh}} \), the star could be captured at an average tidal radius of

\[
R_T = R_s \left( \frac{M_{\text{bh}}}{M} \right)^{1/3} \approx 8.35 \times 10^{13} M_6^{-1/3} m_s^{1/3} r_s \text{ cm},
\]

where \( m_s = M_s / M_\odot \), \( M_6 = M_{\text{bh}} / 10^6 M_\odot \), and \( r_s = R_s / 12 R_\odot \). For MS stars, \( R_s = 12 R_\odot \), but for RG stars, the radius ranges from 3 to 200 \( R_\odot \) (Syer & Ulmer 1999). The maximum radius of a RG star (200 \( R_\odot \)) is attained only during a short period (10%) of its evolutionary lifetime, so the typical radius of RG stars is actually \( \sim 12 R_\odot \), and we take \( r_s = 1 \) in our model. The capture rate of MS stars by a massive black hole has been discussed by Phinney (1989), Rees (1990), and Cannizzo et al. (1990). However, the capture rate of RG stars is more complicated, involving the mass function of stars, stellar evolution, the black hole mass, and the maximum radius of a RG (Syer & Ulmer 1999). By assuming a Salpeter mass function for the stars, Syer & Ulmer (1999) estimated the capture rate in our Galaxy as \( \dot{N}_{\text{MS}} \sim 4.78 \times 10^{-5} \text{ yr}^{-1} \) and \( \dot{N}_{\text{RG}} \sim 8.51 \times 10^{-6} \text{ yr}^{-1} \) (Table 1 in Syer & Ulmer 1999) for MSs and RGS, respectively.

Once a RG star is tidally disrupted, a fraction of its debris plummets to the black hole. The time for the debris to return to the pericenter \( t_{\text{min}} \) and the time for it to enter a circular orbit around the black hole \( t_{\text{cir}} \) (Syer & Ulmer 1999)

\[
t_{\text{min}} = \frac{2\pi R_T^3}{(GM_{\text{bh}})^{1/2}(2R_s)^{3/2}} \approx 4.57 m_s^{-1/2} \alpha_{-3}^{-1/2} M_6^{1/2} \text{ yr},
\]

\[
t_{\text{cir}} = n_{\text{orb}} t_{\text{min}} \approx 9.15 \left( \frac{n_{\text{orb}}}{2} \right) \left( \frac{t_{\text{min}}}{4.57 \text{ yr}} \right) \text{ yr},
\]

respectively, where \( n_{\text{orb}} \) is the number of orbits necessary for circularization, probably ranging between 2 and 10. We assume that the pericenter radius of the captured star equals its capture radius (Syer & Ulmer 1999) in the calculations.

After the debris circularization, either a thick torus or a thin disk would be formed around the black hole, depending on two timescales. One is the time to radiate a significant portion of the energy of the bound debris at the Eddington limit \( t_{\text{rad}} \). The other is the time to accrete a large fraction of the disk \( t_{\text{acc}} \). If \( t_{\text{acc}} \gtrsim t_{\text{rad}} \), a thin disk will form; otherwise, a thick torus will appear (Ulmer 1999). The former case is necessary to our model, since the jet associated with the accretion disk is efficient to accelerate particles. Below we show that a thin disk would truly be formed in the process that we consider.

The radiation timescale is (Syer & Ulmer 1999; Ulmer 1999)

\[
t_{\text{rad}} = \frac{\xi m_s M_c c^2 \eta}{L_{\text{Edd}}} \approx 21 \xi_0 m_6 M_{-1} \eta_1 \text{ yr},
\]

where \( \xi = 0.5 \xi_0 \) is the fraction of the stellar mass that goes into the bounded debris (Rees 1988), \( L_{\text{Edd}} \) is the Eddington luminosity, and \( \eta = 0.1 \eta_1 \) is the efficiency of transferring the rest mass to radiation energy in the accretion process, which is defined as \( \eta = L_{\text{disk}} / M_c c^2 \), where \( L_{\text{disk}} \) is the total radiated disk luminosity and \( M_c \) is the mass accretion rate of the disk. For a rapidly rotating black hole, \( \eta \sim 0.42 \).

For a standard accretion disk (Shakura & Sunyaev 1973), the accretion time can be estimated as

\[
t_{\text{acc}} = \left( \frac{h}{r} \right)^{-2} \alpha^{-1} \Omega_{K}^{-1} \approx 2.08 \times 10^4 \left( \frac{h}{r} \right)^{-2} \alpha^{-3} m_s^{-1/2} r_s^{3/2} \text{ yr},
\]

where \( r \) and \( h \) are the radius and height of the disk, respectively, \( \alpha \) is the viscous constant, and \( \Omega_{K} = (GM_{\text{bh}}/R_s^2)^{1/2} \) is the Keplerian velocity. The typical values for \( h/r \) are in the range 10^{-2} to 10^{-1} (Shakura & Sunyaev 1973). We define \( (h/r)_{-2} = (h/r)/10^{-2} \) and \( \alpha_{-3} = \alpha/10^{-3} \). From equations (4) and (5), we find \( t_{\text{acc}} \gg t_{\text{rad}} \); thus, a thin disk forms in our model.

The lifetime of our Galaxy is \( t_G \sim 10^{10} \text{ yr} \). We find that when the black hole captures a MS or a RG star, the relation of max \( t_{\text{acc}}, t_{\text{orb}}, t_{\text{Edd}} \) less than \( t_G \) is satisfied, where \( t_{\text{Edd}} = \text{r/10} \). This implies that the activity of the black hole triggered by the capture events is intermittent. For the RG star capture, one long flare can be observed that lasts for \( t_{\text{acc}} \sim 2.08 \times 10^9 \text{ yr} \).

2.2. Accretion

The time that the black hole becomes bright and active after the RG star capture depends on the evolution of its surrounding accretion disk. The overall evolution of the accretion rate is illustrated in Figure 1. Initially, the accretion rate of the disk exhibits an abrupt increase, since a local mass clumping in the innermost orbit of the disk is similar to a delta function (Rees 1988; see Fig. 1). This stage will last until the mass accumulation rate of the disk reaches its peak, \( \dot{M}_{\text{peak}} \). We refer to this stage as phase 1.
According to the simulations of Evans & Kochanek (1989), the value of $M_{\text{peak}}$ is

$$M_{\text{peak}} \sim 1.36 \dot{M}_{0.1} m_s^2 r_s^{-3/2} M_6^{-3/2} \dot{M}_{\text{Edd}},$$

(6)

where $\dot{M}_{\text{Edd}} = 2.46 \times 10^{-2} M_s \dot{M}_{\odot} \text{ yr}^{-1}$ is the Eddington accretion rate.

When $t > t_{\text{peak}}$, the accretion rate evolves as (Rees 1988; Phinney 1989)

$$\dot{M} \sim \frac{1}{3} \frac{M_s}{t_{\text{min}}} \left( \frac{t}{t_{\text{min}}} \right)^{-5/3}$$

$$\sim 2.97 \dot{M}_{0.1} m_s^2 r_s^{-3/2} M_6^{-3/2} \dot{M}_{\text{Edd}} \left( \frac{t}{t_{\text{min}}} \right)^{-5/3}. \quad (7)$$

From this point on, the black hole is activated and enters a luminous phase, acting like an AGN. This very active phase will continue until a critical time ($t_{\text{crit}}$) when the actual accretion rate falls below a critical value $\dot{M}_{\text{crit}}$ (Beckert & Duschl 2004, 2002). We refer to this stage as phase 2. During this phase, the radiation efficiency of the accretion disk is very high. After phase 2, the accretion flow becomes advection dominated. When advection takes over, the radiation efficiency drops drastically by several orders of magnitude (at least $\sim 10^5$; Beckert & Duschl 2002), resulting in a switch off of the AGN-like phase. We describe this stage as phase 3, during which the black hole becomes dim and no longer looks like a quasar. Beckert & Duschl (2002) pointed out that $M_{\text{crit}}$ should be less than $3 \times 10^{-3} M_{\text{Edd}}$ because no consistent advection-dominated accretion flow (ADAF) models with $M > 3 \times 10^{-3} M_{\text{Edd}}$ are feasible. However, the exact value for $M_{\text{crit}}$ is still uncertain, since it is related to the radiation mechanism that is taking effect during the phase transition (Blandford & Begelman 1999; Quataert et al. 1999). In our study, we use the observed data to determine the value of $M_{\text{crit}}$. Assuming that the transition from phase 2 to phase 3 is triggered by thermal instability of the disk (Shakura & Sunyaev 1973; Lightman 1974; Lu et al. 2000), the corresponding transition timescale is

$$\Delta t_u \sim (\alpha \Omega_K)^{-1} \approx 2.08 \alpha^{-3/5} m_s^{1/2} r_s^{3/2} \text{ yr}. \quad (8)$$

We see that the transition process is finished almost instantly. Note that a faint X-ray source (Baganoff et al. 2003) has been identified at the position of the GC, whose infrared radiation is also weak (Genzel et al. 2003). It indicates that the present accretion disk surrounding the black hole Sgr A* is probably ADAF (Narayan et al. 1995; Esin et al. 1998; Falcke & Markoff 2000). These observations also support our idea that the black hole is currently in phase 3.

The time corresponding to $M_{\text{peak}}$ can be estimated from equation (7) as

$$t_{\text{peak}} \sim 1.59 t_{\text{min}} \approx 7.25 m_s^{-1} r_s^{3/2} M_6^{1/2} \text{ yr}. \quad (9)$$

Although the jet formation itself is very difficult to model, observations are providing increasing evidence for the existence of powerful collimated outflows in black hole systems (Blandford & Konigl 1979; Fender et al. 2005; Gallo et al. 2005; Heinz & Grimm 2005). We assume that when the black hole Sgr A* evolves from phase 1 to phase 2, a powerful jet would form, originating at the inner edge of the disk (Markoff et al. 2001; Cheng & Lu 2001; Lu et al. 2000, 2003). For convenience, we define a dimensionless parameter

$$q_j = \frac{\dot{Q}_j}{M c^2},$$

(10)

where $\dot{Q}_j$ is the total jet power, including the rest energy of the expelled matter. The value of $q_j$ can range from $6 \times 10^{-3}$ to 0.4 (Fender et al. 2005; Gallo et al. 2005; Heinz & Grimm 2005).

It has been suggested that most of the black holes in the universe are rapidly spinning (Elvis et al. 2002; Volonteri et al. 2005). Recently, by analyzing the light curves of the X-ray and infrared flares from the GC region, the angular momentum of the black hole Sgr A* has been accurately determined as $a = 0.9939 \pm 0.0026$ (Aschenbach et al. 2004). The possible mechanism for spinning up this black hole has been discussed by Liu et al. (2006). Therefore, for Sgr A*, the radiation efficiency may be as high as $\eta \approx 0.42$. Combining equations (7) and (10), we have

$$\dot{Q}_j = 1.75 \times 10^{44} \eta_{0.42} q_j m_s^2 r_s^{-3/2} M_6^{-1/2} \left( \frac{t}{t_{\text{min}}} \right)^{-5/3} \text{ ergs s}^{-1},$$

(11)

where $\dot{Q}_{0.42} = \dot{Q}/0.42$ and $q_{-2} = q_j/10^{-2}$. The total energy of the jet is then

$$E_{\text{j tot}} = \int_{t_{\text{peak}}}^{t_{\text{crit}}} \dot{Q}_j \text{ dt}.$$

(12)

The value of $t_{\text{crit}}$ is determined in the next section.

3. JET ENERGY AND TeV GAMMA-RAY EMISSION

In spite of extensive observations, direct evidence for high-energy activities of the GC region, such as those observed in AGNs, is still lacking. Fortunately, strong fluorescent X-ray emission has been found from the cold iron atoms in the molecular cloud at the Sgr B2 region (Sunyaev et al. 1993; Koyama et al. 1996). The most favorable explanation for this emission is that the molecular cloud was once illuminated by intense X-rays from Sgr A* (Sunyaev & Churazov 1998; Cramphorn & Sunyaev 2002). According to this theory, the X-ray luminosity of Sgr A* should have been $L_X \sim 2 \times 10^{39}$ ergs s$^{-1}$ about 300 yr ago, which was most likely due to the capture of a star by the black hole. However, observations also show that the current X-ray luminosity of Sgr A* is only $2 \times 10^{36}$ ergs s$^{-1}$ (Koyama et al. 1996). Therefore, if this explanation is correct, then the luminosity of Sgr A* has decreased rapidly by a factor of $\sim 10^3$ in less than 300 yr. We note that in our framework, such a rapid dimming is possible only at the time of $t_{\text{crit}}$, when the accretion disk formed by capturing a star transitions from phase 2 to phase 3. As stated in §2.2, the transition could be finished in a few years (see eq. [8]), and the luminosity could decrease by a factor of $\sim 10^7$ after the transition. Thus, we suggest that the required luminosity of $L_X \sim 2 \times 10^{39}$ ergs s$^{-1}$ was just the power of the black hole system when it was approaching the endpoint of phase 2. Then the lifetime of the jet can be determined by setting $\eta M(t_{\text{crit}}) c^2 = L_X$. The result is

$$t_{\text{crit}} \sim 1.68 \times 10^6 \eta_{0.42} m_s^{-1/3} r_s^{1/3} M_6^{1/3} \text{ yr}. \quad (13)$$
Combining equations (9) and (11)–(13) and taking \( \eta = 0.42 \), \( q_i = 10^{-2} \), we obtain

\[
E_{j, \text{tot}} \simeq 2.76 \times 10^{51} \text{ ergs.} \tag{14}
\]

If a larger value of \( q_i \) is assumed, then \( E_{j, \text{tot}} \) would be even higher. Note that \( E_{j, \text{tot}} \) is the total kinetic energy of the jet. Possibly only \( \sim 10\% \) of it could be converted into high-energy particles.

The energy of the injected protons required by the hadronic origin of TeV \( \gamma \)-rays has been modeled by Aharonian & Neronov (2005b). It depends on the diffusion coefficient of protons in the ambient medium. Generally, the dependence of the diffusion coefficient on proton energy can be expressed as

\[
D(E) = 10^{26}(E/1 \text{ GeV})^{\delta} \text{ cm}^2 \text{ s}^{-1},
\]

where \( \delta = 0.3–0.6 \) (Berezinskii et al. 1990) and \( \kappa \sim 10^{-4} \) to \( 10^{-2} \) (Aharonian & Atoyan 1996) are dimensionless parameters. There are mainly three typical propagation scenarios, characterized by different \( \delta \) and \( \kappa \)-values (Aharonian & Neronov 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 \( \delta = 1.0 \) and \( \kappa = 10^{-2} \). For protons with a typical energy of 10 TeV, the diffusion coefficient is \( 1.0 \times 10^{26} \text{ cm}^2 \text{ s}^{-1} \) for ECP, \( 2.4 \times 10^{28} \text{ cm}^2 \text{ s}^{-1} \) for KTT, and \( 1.0 \times 10^{30} \text{ cm}^2 \text{ s}^{-1} \) for BD.

Assuming that the injection of protons lasts for \( \sim 10^5 \) yr, the required injection energy by the hadronic origin of the TeV \( \gamma \)-rays in these three cases can be estimated as

\[
E_{j, \text{tot}} = \tilde{W}_p 10^5 \text{ yr} \approx \begin{cases} 
2.21 \times 10^{49} \text{ ergs} & \text{for ECP}, \\
3.38 \times 10^{50} \text{ ergs} & \text{for KTT}, \\
3.15 \times 10^{51} \text{ ergs} & \text{for BD}, 
\end{cases} \tag{15}
\]

where \( \tilde{W}_p \) is the required injection rate of protons corresponding to the three diffusion mechanisms, which is (Aharonian & Neronov 2005b)

\[
\tilde{W}_p \approx \begin{cases} 
7.0 \times 10^{16} \text{ ergs}^{-1} & \text{for ECP}, \\
7.5 \times 10^{17} \text{ ergs}^{-1} & \text{for KTT}, \\
1.0 \times 10^{19} \text{ ergs}^{-1} & \text{for BD}, 
\end{cases} \tag{16}
\]

Comparing equation (15) with equation (14), and taking into account the efficiency (\( \sim 10\% \)) of converting \( E_{j, \text{tot}} \) into cosmic rays, we find that the required energy could be satisfactorily provided by our RG star capture model in at least two diffusion cases, i.e., the ECP and KTT diffusion. In fact, if we assume \( q_i > 0.1 \), then the jet energy would also be enough for the BD mechanism.

Note that the linear size of the TeV source is likely to be only \( \sim 10 \) pc (Aharonian et al. 2004). We now further check which propagation scenario can meet this requirement. Theoretically, the protons would diffuse to a radius of \( R = [4D(10 \text{ TeV})t_{\text{diff}}]^{1/2} \) (Aharonian & Atiyon 1996), where \( t_{\text{diff}} \) is the diffusion time of the injected protons when they propagate in the target. In our case, \( t_{\text{diff}} = t_{\text{acc}} + 300 \) yr. For the three diffusion mechanisms, the radius of the source is

\[
R = \sqrt{4D(10 \text{ TeV})t_{\text{diff}}} \approx \begin{cases} 
4.89 \text{ pc} & \text{for ECP}, \\
75.9 \text{ pc} & \text{for KTT}, \\
489 \text{ pc} & \text{for BD}, 
\end{cases} \tag{17}
\]

Equation (17) shows that for both BD and KTT propagation scenarios, the corresponding radius is obviously too large compared with observation. On the contrary, in the case of the ECP propagation scenario, we obtain \( R \sim 4.89 \) pc, then the linear size is \( 2R = 9.78 \) pc. It is in good agreement with the observed size of the TeV source. We thus believe that the ECP diffusion is taking effect in our framework.

In short, our analysis shows that the capture of a RG star by the black hole Sgr A* could be the energy source of the observed TeV \( \gamma \)-ray emission from our GC. The energy deposited in this way is large enough to produce a relativistic outflow of protons. The outflow could diffuse into a volume with the diameter of \( \sim 10 \) pc. The detailed process that transfers the energy of the injected protons into that of observed \( \gamma \)-rays has been discussed by other authors (Aharonian et al. 2004; Aharonian & Neronov 2005b) and is not addressed repetitiously here.

4. DISCUSSION AND CONCLUSIONS

A strong TeV \( \gamma \)-ray source has been detected at the Galactic center, whose size is probably less than 10 pc. It should be closely related to the black hole Sgr A* of our Galaxy. Aharonian & Neronov (2005b) suggested a hadronic origin for these \( \gamma \)-rays; i.e., they are produced through the \( \pi^0 \)-decay process when a strong flow of relativistic protons interacts with the dense ambient gas. However, the nature of this proton flow is largely unknown. In this paper, we show that the required proton outflow could have been reasonably produced when the black hole Sgr A* captured a RG star and formed an accretion disk around it in the past. The whole process can be divided into three phases. In phase 2, which lasts for \( \sim 10^5 \) yr, the black hole becomes active and luminous thanks to a relatively high accretion rate, temporarily behaving like an AGN. A relativistic outflow of protons can be ejected in this phase, whose total energy is as high as \( E_j, \text{tot} \sim 2.76 \times 10^{51} \) ergs, large enough to meet the requirement of the Aharonian & Neronov model.

According to our calculations, the propagation of protons in the target gas is through the ECP scenario. We show that the injected protons have diffused into a volume of \( \sim 9.78 \) pc, consistent with the observationally inferred size of the TeV source. Furthermore, when the 10 TeV protons diffuse in the target gas, their escape time is comparable with the characteristic time of proton-proton interactions, implying that the spectrum of the observed TeV \( \gamma \)-rays should be similar to that of the injected protons (Aharonian & Neronov 2005b). Since the \( \gamma \)-ray spectrum observed by HESS is \( J(E) = (2.5 \pm 0.21) \times 10^{-12} E^{-2.21} \) photons \( \text{cm}^{-2} \text{ s}^{-1} \text{ TeV}^{-1} \) (Aharonian et al. 2004), we can conjecture that the initial spectrum of the injection protons should be \( Q(E) \propto E^{-2.2} \exp (-E/E_0) \). Aharonian & Neronov (2005b) pointed out that the cutoff energy is \( E_0 = 10^{15} \) eV.

In our study, we mainly consider the case in which the captured star is a RG star. If the captured star is a MS one, things will be much different. In Table 1, we have listed the key quantities calculated for a MS star capture, comparing them directly with those of a RG star capture. Interestingly enough, we find that the energy injection by a MS star capture also meets the requirement of energetics. However, we note that \( t_{\text{crit}} > t_{\text{acc}} \) for a MS star; this means that the jet formed by the capture of a MS star terminates much earlier. In this situation, the diffusion timescale of the injected protons is \( t_{\text{diff}} \sim t_{\text{acc}} + 300 \) yr, which is much smaller than the diffusion time of a RG capture event. Consequently, within the jet lifetime, the protons originating from a MS star capture will diffuse to

\[
R = \sqrt{4D(10 \text{ TeV})t_{\text{diff}}} \approx \begin{cases} 
1.05 \text{ pc} & \text{for ECP}, \\
16.4 \text{ pc} & \text{for KTT}, \\
105 \text{ pc} & \text{for BD}, 
\end{cases}
\]
which is inconsistent with the size (~10 pc) of the TeV source inferred from current observations. This is the main reason that we prefer a RG star capture rather than a MS star capture in our framework.

However, to determine the size of the TeV source observationally is not an easy task because of its extended nature. We note that the HESS collaboration has not yet published the final analysis of its observations of the Galactic center on larger scales, so there is still a lack of information on TeV emission beyond the 10 pc scale at the area. It is thus possible that the actual size of the TeV source may be larger. In addition, the reduction of TeV emission may also be due to the decrease of the density of the gas at larger distances, but not the lack of an ultrarelativistic proton flow. Taking into account these factors, the MS star capture scenario still cannot be completely excluded. In fact, a comprehensive analysis of the TeV radiation and a thorough investigation of the environment within ~100 pc around Sgr A* are necessary for us to understand the history of the activities in the GC region.

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TABLE 1

| Star   | $r_0$ (yr) | $t_{\text{min}}$ (yr) | $t_{\text{peak}}$ (yr) | $t_{\text{acc}}$ (yr) | $t_{\text{crit}}$ (yr) | $E_{\text{tot}}$ (ergs) |
|--------|------------|------------------------|-------------------------|------------------------|------------------------|--------------------------|
| MS.....| 1/12       | 0.11                   | 0.174                   | 5.0 × 10^4            | 3.78 × 10^7            | 2.76 × 10^51              |
| RG.....| 1          | 4.57                   | 7.25                    | 2.08 × 10^4           | 1.68 × 10^4           | 2.76 × 10^51             |

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