HIGH-ENERGY GAMMA RAYS FROM THE MASSIVE BLACK HOLE IN THE GALACTIC CENTER

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ABSTRACT

Accreting black holes (BHs) are believed to be sites of possible particle acceleration with conditions that are also favorable for effective gamma-ray production. However, because of photon-photon pair production, only low-energy (MeV) gamma rays can escape these compact objects with typically very large compactness parameters, $\kappa = (L/L_{\text{Edd}})(R_g/R) > 0.01$, given that in most cases the accretion disks within 10 Schwarzschild radii, $R_g$, radiate with a power exceeding 10% of the Eddington luminosity, $L_{\text{Edd}}$. Therefore, the high-energy gamma-ray emission of these objects (both of stellar mass and supermassive BHs) is generally suppressed, and consequently, the unique information on possible particle acceleration processes near the event horizon of the BH is essentially lost. Fortunately, this is not the case for the supermassive BH located at the dynamical center of our Galaxy (Sgr A*), which, thanks to its extraordinary low bolometric luminosity ($<10^{-8}L_{\text{Edd}}$), is transparent for gamma rays up to very high energies, $E \sim 10$ TeV. We discuss different scenarios of gamma-ray production in Sgr A* and show that for a reasonable set of parameters one can expect detectable gamma-ray fluxes of both hadronic and electronic origin. Some of these scenarios are applicable not only for the TeV gamma-ray emission recently reported from the direction of Galactic center, but they may have broader implications relevant to highly variable nonthermal emission of Sgr A* in radio, IR, and X-ray bands.

Subject headings: acceleration of particles — black hole physics — Galaxy: nucleus — gamma rays: theory

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1. INTRODUCTION

The central 10 pc region of our Galaxy is an extraordinary site that harbors many interesting sources packed with an unusually high density around the most remarkable object of this region, the compact radio source Sgr A*. The latter most likely associates with a hypothetical supermassive black hole (BH), $M \approx 3 \times 10^6 M_\odot$, located very close to the dynamical center of the Galaxy (Genzel et al. 2000; Ghez et al. 2000; Schödel et al. 2002). The upper limits on the size of the source at millimeter wavelengths on the level of ~0.1 mas (e.g., Krichbaum et al. 1998) tell us that the emission is produced within 10 Schwarzschild radii, $R_g$, around the BH. The time variability recently detected at X-rays (Baganoff et al. 2001; Porquet et al. 2003; Goldwurm et al. 2003) and near-IR wavelengths (e.g., Genzel et al. 2003) on $\lesssim 1$ hr timescales is independent evidence that the radiation comes from regions located very close to the event horizon of the BH.

The temporal and spectral features of radiation of Sgr A* are quite unusual and, as a whole, essentially different from other compact galactic and extragalactic sources containing BHs. This concerns, first of all, the extraordinary low luminosity of Sgr A*. Many scenarios have been proposed to explain this effect, invoking, in particular, advection- (Narayan et al. 1995) and convection-dominated (Quataert & Gruzinov 2000; Narayan et al. 2002; Iguemenchchev 2002) accretion flow models, an advection-dominated inflow-outflow solution (Blandford & Begelman 1999), an inefficient accretion flow model (Yuan et al. 2003), Bondi-Hoyle-type models (Melia & Falcke 2001), jet models (Falcke & Markoff 2000), and models assuming interactions of stars with cold accretion disks (Nayakshin & Sunyaev 2003). Concerning the radiation mechanisms, there is little doubt that the emission components at radio wavelengths, and most likely also at the IR and X-ray wavelengths, have nonthermal origin. Currently, the most favored models are different versions of the so-called synchrotron self-Compton (SSC) scenario, which assumes that the radio and millimeter emission is due to electron synchrotron radiation, while the X-rays are explained by inverse Compton (IC) scattering of the same (relatively low energy) electron population (for a review, see Melia & Falcke 2001). On the other hand, if the recently detected TeV emission from the Galactic center also comes from the inner parts of Sgr A*, this would imply that relativistic particles (protons and/or electrons) are accelerated to very high energies in the vicinity of the BH. Below we show that these particles play a nonnegligible role in the formation of the energy spectrum of radiation at low frequencies as well. This allows decisive tests of models of very high energy gamma-radiation through simultaneous multiwavelength studies of Sgr A*.

1.1. Broadband Observations of Sgr A*: A Short Overview

The radio to millimeter radiation of Sgr A* is characterized by a very hard spectrum (see Fig. 1) with spectral index $\alpha \approx 0.3$ ($F_\nu \propto \nu^\alpha$), low-frequency turnover at $\nu \approx 1$ GHz, and high-frequency cutoff at $\nu \approx 10^3$ GHz (Zylka et al. 1995). The hard spectral index can be explained by optically thin synchrotron emission from Maxwellian-type energy distribution of relativistic electrons (Duschl & Lesch 1994; Beckert et al. 1996) or by...
synchrotron self-absorption of radiation in an optically thick source (Melia et al. 2000). It should be noted, however, that the measurements of photon scattering by interstellar plasma indicate that the radiation at different wavelengths is produced at different distances from BH (Lo et al. 1998; Bower et al. 2004). Namely, while the millimeter emission originates from a compact region of a size $R_{\text{m}} \sim 200 R_g$ \((R_g = 2GM/c^2 \sim 10^{12}$ cm is the gravitational radius of the BH in the Galactic center(GC)), the radio emission is produced at larger distances. On the other hand, the near-IR and X-ray flares, with variability time scales $t_{\text{fl}} \sim 10^{-5}$ s (Genzel et al. 2003) and $t_{\text{fl}} \sim 10^{-2}$–$10^{-1}$ s (Baganoff et al. 2001; Porquet et al. 2003), indicate that the radiation at higher frequencies is produced quite close to the BH horizon. It has been shown recently by Liu et al. (2004) that acceleration of moderately relativistic electrons ($\gamma_e \sim 100$) by plasma wave turbulence near the BH event horizon and subsequent spatial diffusion of highest energy electrons can explain the wavelength-dependent size of the source. The same electron population can explain the X-ray flares through the IC scattering due to dramatic changes of physical conditions during the flare (Markoff et al. 2001; Liu et al. 2004).

Very hard X-ray emission up to 100 keV, with a possible detection of a 40 minute flare from the central 10$^\circ$ region of the Galaxy has been reported recently by the INTEGRAL team (Bélanger et al. 2004).

In the gamma-ray band, 100 MeV–10 GeV gamma rays from the region of the GC have been reported by the EGRET team (Mayer-Hasselwander et al. 1998). The luminosity of MeV–GeV gamma rays ($L_{\text{MeV–GeV}} \sim 10^{37}$ ergs s$^{-1}$) exceed by an order of magnitude the luminosity of Sgr A* at any other wavelength band (see Fig. 1). However, the angular resolution of EGRET was too large to distinguish between the diffuse emission from the region of about 300 pc and the point source at location of Sgr A*.

GLAST, with significantly improved performance (compared to EGRET), can provide higher quality images of this region as well as more-sensitive searches for variability of GeV emission. This would allow more conclusive statements concerning the origin of MeV–GeV gamma rays.

TeV gamma-radiation from the GC region recently has been reported by the CANGAROO (Tsuchiya et al. 2004), Whipple (Kosack et al. 2004), and HESS (Aharonian et al. 2004) collaborations. Among possible sites of production of the TeV signal are the entire diffuse 10 pc region (as a result of interactions between cosmic rays and the dense ambient gas), the relatively young supernova remnant Sgr A East (Fazio & Melia 2003), the dark matter halo (Bergström et al. 1998; Gnedin & Primack 2004) due to annihilation of supersymmetric particles, and finally Sgr A* itself. It is quite possible that some of these potential gamma-ray production sites contribute comparatively to the observed TeV flux. Note that 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 (see Fig. 1). If this is not a result of mis-calibration of detectors but rather due to the variability of the source, Sgr A* seems to be the most likely candidate to which the TeV radiation could be associated, given the localization of a pointlike TeV source by HESS within 1 of Sgr A*.

However, for unambiguous conclusions, one needs long-term continuous monitoring of the GC region with well-calibrated TeV detectors and especially multiwavelength observations of Sgr A* together with radio, IR, and X-ray telescopes. With the potential to detect short (<1 hr) gamma-ray flares at the energy flux level below 10$^{-17}$ ergs s$^{-1}$, HESS should be able to provide meaningful searches for variability of TeV gamma rays on timescales <1 hr, which is crucial for identification of the TeV source with Sgr A*.

In this paper we assume that Sgr A* does indeed emit TeV gamma rays, and we explore possible mechanisms of particle acceleration and radiation that could lead to production of very high gamma rays in the immediate vicinity of the associated supermassive black hole. At the same time, since the origin of TeV radiation reported from the direction of the GC is not yet established, any attempt to interpret these data quantitatively would be rather premature and inconclusive. Moreover, any model calculation of TeV emission of a compact source with characteristic dynamical timescales of <1 hr would require data obtained at different wavelengths simultaneously. Such data are not yet available for Sgr A*. Therefore, in this paper we present calculations for a set of generic model parameters with a general aim to demonstrate the ability (or inability) of certain models to produce detectable fluxes of TeV gamma rays without violating the data obtained at radio, IR, and X-ray bands (see Fig. 1). More specifically, we discuss the following possible models in which TeV gamma rays can be produced because of (1) synchrotron/curvature radiation of protons, (2) photo-meson interactions of highest energy protons with photons of the compact source, (3) inelastic p-p interactions of multi-TeV protons in the accretion disk, and (4) Compton cooling of multi-TeV electrons accelerated by induced electric field in the vicinity of the massive BH.

2. INTERNAL ABSORPTION OF GAMMA RAYS

The very low bolometric luminosity of Sgr A* makes this object unique among the majority of Galactic and extragalactic compact objects containing black holes. One of the interesting consequences of the faint electromagnetic radiation of Sgr A* is that the latter appears transparent for gamma rays up to very
high energies. Thus, the TeV studies of Sgr A* introduce a unique opportunity to study high-energy processes of particle acceleration and radiation in the immediate vicinity of the event horizon. In this regard one should note that TeV gamma rays observed from several BL Lac objects (a subclass of active galactic nuclei [AGNs]) originate in relativistic jets quite far from the central compact engine; therefore, they do not carry direct information about the processes in the vicinity of the central BH.

Generally, the AGN cores and X-ray binaries harboring supermassive and stellar mass black holes are characterized by very dense ambient photon fields, which do not allow the high-energy gamma rays to escape freely from their production regions. In the isotropic field of background photons, the cross section of photon-photon pair production depends on the product of colliding photons, \( s = E_\gamma/\mu m_e c^2 \). Starting from the threshold at \( s = 1 \), the cross section \( \sigma_{\gamma\gamma} \) rapidly increases, achieving the maximum \( \sigma_0 \approx \sigma_T/5 \approx 1.3 \times 10^{-25} \text{ cm}^2 \) at \( s \approx 4 \), and then decreases as \( s^{-1} \ln s \). Because of the relativistic narrow distribution of \( \sigma_{\gamma\gamma}(s) \), gamma rays interact most effectively with the background photons of energy
\[
e_{\mu} \approx 1(E/1 \text{ TeV})^{-1} \text{ eV}.
\]

Thus, the optical depth for a gamma ray of energy \( E \) in a source of luminosity \( L \) at energy given by equation (1) and size \( R \) can be written in the form
\[
\tau(E) = \frac{L_t \sigma_T(E)}{4\pi R c \epsilon_b} \approx 10^8 \left( \frac{L_t}{L_{\text{Edd}}} \right) \left( \frac{R_g}{R} \right) \left( \frac{E}{1 \text{ TeV}} \right).
\]

Here the optical depth is normalized to the compactness parameter \( \kappa = (L_t/L_{\text{Edd}})(R/R_g)^{-1} \), which does not depend on the mass of the BH; therefore, it is applicable to both stellar mass and supermassive BHs. One can see from this estimate that for a typical AGN or an X-ray binary with NIR and optical lumino-

\[ L \geq 10^{-5} L_{\text{Edd}}, \]  

TeV gamma rays cannot escape the source unless they are produced far from the BH, at distances exceeding \( 10 R_g \).

The luminosity of Sgr A* is unusually low for an accreting massive BH. At NIR and optical wavelengths the luminosity does not exceed \( 10^{-3} L_{\text{Edd}} \); therefore, TeV gamma rays can escape the source even if they are produced at \( R \approx R_g \). Numerical calculations of the optical depth based on the spectral energy distribution (SED) of Sgr A* shown in Figure 2 confirm this conclusion. It is seen that, indeed, only at energies above \( 10 \text{ TeV} \) does the absorption of gamma rays become significant, even if one assumes that the production region of radiation is limited within \( 2R_g \).

It is interesting to note that the decrease of the pair production cross section well above the pair production threshold (\( s \gg 1 \)) makes the source transparent again but at TeV energies. These gamma rays are not absorbed on their way to the Earth either and can be detected by arrays like the Pierre Auger Observatory. However, at such large energies gamma rays can be absorbed because of pair production in the magnetic field inside the source.

The mean free path of a gamma-ray photon of energy \( E \) in a magnetic field of strength \( B \) can be approximated as (Erber 1966)

\[
\Lambda_{B\gamma} \approx \frac{2hE}{0.16\alpha_\mu_3 m_e c^3 K_{1/3}(2/3)\zeta},
\]

where \( \zeta = (E/m_e c^2)(B/B_{\text{crit}}) \), \( B_{\text{crit}} = 4.4 \times 10^{13} \text{ G} \), and \( K_{1/3}(x) \) is the modified Bessel function. The mean free path of gamma rays as a function of energy for different magnetic fields is shown in Figure 3. It is seen that the mean free path of \( \geq 10^{17} \text{ eV} \) gamma rays in the magnetic field of strength \( B = 10 \text{ G} \) becomes shorter than the gravitational radius of the BH of mass \( 3 \times 10^6 M_\odot \). For very strong magnetic fields, \( B \geq 10^6 \text{ G} \), the source is opaque for \( \geq 1 \text{ TeV} \) gamma rays as well.

Generally, the process of interactions of gamma rays with a magnetic field cannot be reduced to a simple absorption effect. Indeed, the secondary electrons interacting with radiation and

1 Note that \( B \), which enters in eq. (3) through the parameter \( \xi \), is the component of magnetic field normal to the photon momentum. This means that the absorption length of the gamma ray propagating along the lines of an ordered magnetic field can be larger than the mean free paths shown in Fig. 3.
magnetic fields produce new gamma rays, which in turn lead to a new generation of electron-positron pairs; thus, a nonthermal cascade develops features that strongly depend on the energy densities of photon and magnetic fields (see, e.g., Aharonian & Plyasheshnikov 2003). Note that, since the pair production of gamma rays in the \((B, E)\) parameter space of interest \((E \leq 10^{18} \text{ eV} \text{ and } B \leq 10^6 \text{ G})\) always takes place in the regime when \(\xi = (\varepsilon/m_e c^2)(B/B_\varepsilon) \ll 1\), interactions with the magnetic field quickly lead to degradation of the energy of leading particles (synchrotron photons are produced with energies far below the energy of the parent electrons and, therefore, cannot support effective development of the cascade).

Generally, Klein-Nishina cascades in photon fields last longer; however, in the presence of even a relatively weak magnetic field, they can be strongly suppressed because of the synchrotron cooling of electrons. In Sgr A*, where the energy density of low-frequency radiation is estimated \(w_{\text{rad}} \approx 1(R/10R_\odot)^{-2}\) ergs \(\text{cm}^{-3}\), for effective development of an electromagnetic cascade the strength of the magnetic field should not exceed \((8\pi w_{\text{rad}})^{1/2} \approx 5 \text{ G} \) for such a strong, chaotic magnetic field, we can avoid the upper limit given by equation (6). Nevertheless, it cannot be arbitrarily large, because even in a regular field charged particles suffer radiative losses due to curvature radiation. Note that as long as we are interested in high-energy nonthermal emission, the curvature radiation should not be treated as a source of energy losses but rather a radiative process with a nonnegligible contribution to the gamma-ray emission of the accelerator. In the case of the black hole in the GC, this contribution could be quite significant (Levinson 2000). Compared to synchrotron radiation, the spectrum of curvature radiation of protons can extend to higher energies. Assuming that proton acceleration proceeds at the maximum possible rate, \(\dot{E} \sim eB\), and is balanced by losses due to curvature radiation, one arrives at the following estimate of the maximum photon energy,

\[
\epsilon_{\text{max}} = \frac{3E_p^3}{2m_p R} \approx 0.2 \left(\frac{B}{10^4 \text{ G}}\right)^{3/4} \text{TeV}.
\]

Formally, equation (7) allows extension of the spectrum of curvature radiation to 10 TeV if the magnetic field exceeds \(B \approx 10^6 \text{ G}\). However, as discussed in \S 2, for such a strong magnetic field, the source is not transparent for TeV gamma rays (see Fig. 3).

3.1.2. Photo-Meson Interactions

Protons can produce TeV radiation through interactions with ambient photon fields. The photo-meson processes are especially effective at energies \(~10^{15} \text{ eV}\), because such energetic protons start to interact with the most copious (far-IR and millimeter) photons. Despite the low luminosity of Sgr A*, \(L_{\text{IR}} \approx 10^{10} \text{ ergs s}^{-1}\), because the small source size (e.g., Melia & Falcke 2001) makes the density of IR photons appear sufficiently high,

\[
N_{\text{ph}} \approx \frac{L_{\text{IR}}}{4\pi R_{\text{IR}}^2 e_{\text{ph}}} \approx 10^{13} \left(\frac{10^{13} \text{ cm}}{R_{\text{IR}}}\right)^2 \text{cm}^{-3},
\]

for effective collisions with protons. Protons also interact with ambient photons through the pair production (Bethe-Heitler) process. Although the cross section of pair production is larger than the photo-meson cross section by 2 orders of magnitude, only a small \((10^{-3})\) fraction of the proton energy per interaction is converted into electromagnetic secondaries. Therefore, at energies above the photo-meson production threshold, hadronic interactions dominate over the pair which does not depend on the strength of the magnetic field \((\alpha_{\varepsilon} = 1/137\) is the fine-structure constant). This leads to the self-regulated synchrotron cutoff (Aharonian 2000) at \(\epsilon_{\text{cut}} = a c e_{\max}\), where the parameter \(a\) varies between 0.3 in the case with monoenergetic electrons and ~1 for power-law distribution of electrons with an exponential cutoff.
A distinct feature of this scenario is that TeV gamma-ray emission is accompanied by detectable fluxes of ultra–high-energy neutrons and possibly gamma rays and neutrinos. In particular, the luminosity of Sgr A* in neutrons at $\geq 10^{18}$ eV can be as high as $L_n \sim 10^{46}$ erg s$^{-1}$. The corresponding point-source flux of $10^{18}$ eV neutrons from the direction of the GC, $F_n \sim 30$ neutrons km$^{-2}$ yr$^{-1}$, exceeds by a factor of 100 the background of charged cosmic rays within $1^\circ$ (the angular resolution of Auger); therefore, it should be detectable by Auger as a background-free signal. The expected flux of $10^{17}$–$10^{18}$ eV neutrinos from Sgr A* is also (marginally) detectable with Auger (Bertou et al. 2002).

In this model the flux of X-rays strongly depends on the magnetic field in the region of the IR source. For the magnetic field $B \gtrsim 10$ G, the secondary electrons are cooled effectively, which leads to the X-ray/TeV energy flux ratio $\gtrsim 0.1$. Therefore, the interpretation of the TeV flux measured by HESS within this model predicts an X-ray flux higher than the quiescent X-ray flux measured by Chandra.

3.1.3. Proton-Proton Scenario

Acceleration of protons to extremely high energies, $E \sim 10^{18}$ eV, is a key element of the above scenario of proton–photon interactions. This implies the existence of a strong magnetic field, $B \gtrsim 10^4$ G, in the compact region limited by a few gravitational radii. If the field close to the BH is significantly weaker, the efficiency of photo-meson processes is dramatically reduced. In this case, interactions of protons with protons and nuclei of ambient plasma become the main source of production of gamma rays and electrons of “hadronic” origin.

Protons can also be accelerated to TeV energies in the accretion disk, e.g., through strong shocks developed in the accretion flow. The efficiency of gamma-ray production in this case is determined by the ratio of accretion time $R/v_{\text{radial}} \sim 10^{-3} - 10^{-4}$ s (depending on the site[s] of particle acceleration and the accretion regime) to the $p$–$p$ cooling time,

$$t_{pp} = \frac{1}{\sigma_{pp} N_c} \approx 1.5 \times 10^7 \left(\frac{10^8 \text{ cm}^{-3}}{N}\right) \text{s},$$

where $N$ is the number density of the accretion plasma, which depends on the regime and geometry of accretion. For any reasonable assumption concerning the density of the ambient thermal plasma and the accretion regime, the efficiency of converting the energy of accelerated protons into secondary gamma rays and electrons is quite low, as small as $10^{-4}$. Therefore, even with the most favorable conditions, the acceleration rate of high-energy protons should exceed $L_p \approx 10^{39} \text{ erg s}^{-1}$ in order to provide detectable fluxes of TeV gamma rays. Although the required acceleration power is significantly larger than the total electromagnetic luminosity of Sgr A*, it is still acceptable for a BH of mass $\gtrsim 10^6 M_\odot$.

The results of numerical calculation of the photon spectrum produced in $p$–$p$ interactions are shown in Figure 5. The shape of the overallSED, as well as local spectral features, depend both on the high-energy cutoff $E_0$ and the strength of the magnetic field. If protons are accelerated to energies above 1 TeV, then the synchrotron radiation of secondary $e^+e^-$ pairs from $\pi$ meson decays extends to hard X-ray domain. In particular, acceleration of protons beyond $E_0 \gtrsim 10$ TeV during a transient activity of the source may result in a X-ray flare with rather flat SED like the flares observed by the XMM-Newton (Goldwurm et al. 2003) and INTEGRAL (Bélanger et al. 2004).
satellites (see Fig. 5). Note that although the characteristic radiative cooling time of protons exceeds by many orders of magnitude the observed variability timescales of X-rays, $\Delta t \leq 1$ hr, the latter can be naturally explained by the time when the accelerated protons confined in the magnetic fields of the accretion flow cross the event horizon.

If in the quiescent state the acceleration of protons is limited by relatively low (GeV) energies, the maximum of the synchrotron radiation moves toward IR and millimeter wavelengths. Interestingly, if one assumes narrow, e.g., Maxwellian-type energy distribution of protons, the resulting distribution of electrons also will be quite narrow, with a mean energy approximately 10 times less than the proton energy. Since the synchrotron cooling time of these electrons,

$$t_{\text{synch}} = 4 \times 10^{4} \left(\frac{10 G}{B}\right)^{3/2} \left(\frac{10^{-2} \text{ eV}}{\epsilon}\right)^{1/2} \text{s,} \hspace{1cm} (12)$$

exceeds the typical dynamical timescale of the source, the radiative losses do not significantly deform the production spectrum of secondary electrons, and therefore, resulting synchrotron radiation at radio waves should have very hard SEDs with spectral index of $\sim$0.3. Thus, with a certain combination of model parameters, one can describe quite well the observed radio to IR spectrum by synchrotron radiation of secondary electrons (see Fig. 5). This model is quite similar to the traditional interpretation of the low-frequency radiation of Sgr A* by directly accelerated electrons with Maxwellian-type distribution (Duschl & Lesch 1994). The only difference is that in this case, the narrow-energy distribution of electrons is resulting from hadronic interactions of protons with very flat ($\Gamma < 1$) acceleration spectrum and cutoff below 10 GeV. While in the case of primary electrons we do not expect significant gamma-ray emission (because both the IC and bremsstrahlung channels of gamma-ray production are suppressed), in the case of synchrotron radiation of secondary electrons one should expect very strong $\pi^0$-decay gamma-ray emission at MeV–GeV energies (see Fig. 5). Interestingly, the predicted MeV–GeV gamma-ray fluxes are quite close to the EGRET observations of the GC region. However, the poor angular performance of these observations as well as the lack of information about the variability do not allow any certain conclusions in this regard. On the other hand, the future observations by GLAST at GeV energies should help to elucidate the origin of electrons responsible for the radio to IR emission of Sgr A*. An independent, and to a certain extent more straightforward, inspection of the “hadronic” origin of the broadband SED can be provided by TeV observations and especially by future “km$^3$” class neutrino detectors (e.g., Halzen & Hooper 2002), which are expected to be sufficiently sensitive for detection of a hard spectrum TeV neutrino signal (from decays of secondary $\pi^+$ mesons) with the flux comparable to the TeV gamma-ray flux, i.e., $J_{\nu}(\nu \geq 1 \text{ TeV}) \sim 10^{-11} \nu \text{ cm}^{-2} \text{s}^{-1}$. A clear observational signature of this scenario could be a robust correlation between TeV and X-ray radiation components: X-ray flares should be accompanied by TeV flares (unless the synchrotron cooling time significantly exceeds the accretion time, which can be realized if the magnetic field is low and/or there is very fast accretion in the inner part of the disk). In this regard, it is difficult to overestimate the importance of continuous monitoring of Sgr A* at gamma-ray energies between 100 GeV and 10 TeV by the HESS telescope array and at hard X-rays by the Chandra, XMM-Newton, and INTEGRAL satellites with comparable sensitivities for detection of flares at the energy flux level of $10^{-11}$ ergs cm$^{-2}$ s$^{-1}$ on 1 hr timescales. In particular, any detection of TeV gamma rays with an energy flux exceeding the X-ray flux by an order of magnitude would be strong evidence against the $p$-$p$ origin of TeV radiation.

3.2. Curvature Radiation–Inverse Compton (CRIC) Model

The models of TeV gamma-ray emission associated with accelerated protons have a drawback: the efficiency of converting proton power into electromagnetic radiation is rather low. In the photo-hadron scenario the efficiency is only 0.1%, while in the proton-proton scenario it is even lower. The radiative energy loss rate of electrons is much higher, and therefore, the models associated with accelerated electrons provide more economic ways of producing high-energy gamma rays. Obviously, these electrons should be accelerated to multi-TeV energies. This immediately constrains the strength of the chaotic component of the magnetic field in the region of acceleration. Assuming that electrons are accelerated at a rate $dE/dt \sim \kappa eB$ ($\kappa \leq 1$), from the balance of the acceleration and synchrotron energy loss rates one finds

$$E_{\epsilon} \leq \frac{3/4}{2\pi^2 \epsilon} \frac{m_c^2}{B^{1/2}} \simeq 1.5 \times 10^{13} \left(\frac{B}{10 \text{ G}}\right)^{-1/2} \kappa^{1/2} \text{ eV.} \hspace{1cm} (13)$$

Thus, even in the case of the maximum acceleration rate ($\kappa = 1$), electrons cannot be accelerated to multi-TeV energies unless the random $B$ field is $\leq 10$ G.

The requirement of particle acceleration at the maximum rate imposes strong restrictions on the possible acceleration mechanisms. In this regard, acceleration in ordered electric and magnetic fields, e.g., by the rotation-induced electric field near the BH, provides maximum energy gain. Moreover, in the ordered field the energy dissipation of electrons is reduced to curvature radiation losses, which increases the maximum achievable energy of electrons to

$$E_{\epsilon} = \left(\frac{3m_e^4 R^2 B}{2e}\right)^{1/4} \approx 10^{14} \left(\frac{B}{10 \text{ G}}\right)^{1/4} \text{ eV.} \hspace{1cm} (14)$$
Note that this estimate weakly depends on the strength of the magnetic field. On the other hand, electrons may also suffer significant Compton losses, which would result in the reduction of $E_c$ given by equation (14). Remarkably, the radiative losses of both curvature and Compton channels are released in the form of high-energy and very high energy gamma rays. Indeed, the IC scattering of 100 TeV electrons on IR photons produces in the Klein-Nishina regime, and thus the IC spectrum peaks at energy $E_{\gamma} \approx 10^{14} \text{ eV}$. At the same time the curvature radiation results in the second peak in the spectrum, which appears at significantly lower energies,

$$
\epsilon_{\text{curv}} = \frac{3E_e^3}{2m_e^2 R} \approx 2 \times 10^6 \left( \frac{E_e}{10^{14} \text{ eV}} \right)^3 \text{ eV}. \tag{15}
$$

We call the scenario of producing curvature and IC photons by electrons accelerated in regular magnetic and electric fields the curvature radiation–inverse Compton (CRIC) model. Quantitative calculations of high-energy radiation within the framework of this model require a “self-consistent” approach in which the spectrum of radiation is calculated simultaneously with the spectrum of parent electrons, because the spectrum of high-energy electrons itself is determined by the balance of acceleration and radiative energy loss rates.

An example of such self-consistent computation is shown in Figure 6. The calculations are performed within the model in which electrons are accelerated by the electric field induced by the BH rotation (for details of the model, see Neronov et al. 2004). The propagation of electrons in external electromagnetic field is calculated numerically, taking into account the radiation reaction force. The spectra of synchrotron/curvature and IC radiation components are evaluated at each point of the electron trajectory. The spectra shown in Figure 6 are the result of summing up the spectra from about $10^4$ electron trajectories close (within $2R_g$) to the BH horizon and subsequent propagation of the secondary gamma rays through the IR emission source, which is assumed to be confined within $\sim 10R_g$. We assume a 10 G regular $B$ field in the acceleration zone, and a 30 G chaotic field in the IR source.

In Figure 6 one can see two distinct components in the gamma-ray production spectrum (thin solid curve), which sharply peak at $\sim 1 \text{ GeV}$ and 100 TeV. The GeV peak is due to the curvature radiation, and the 100 TeV peak is formed because of IC scattering that proceeds in the Klein-Nishina limit. However, the highest energy gamma rays, $E_{\gamma} \sim 10^{14}-10^{15}$ eV, cannot freely escape the source. They effectively interact with IR photons, producing electron-positron pairs. The synchrotron radiation of these electrons in an irregular field leads to the redistribution of the initial gamma-ray spectrum (Fig. 6, thick solid curve).

It should be noted that the fluxes shown in Figure 6 are obtained under the assumption that there is isotropic emission of electrons in the acceleration zone. However, both curvature and IC radiation components produced during the acceleration of electrons are emitted anisotropically. This means that the presence or absence of a sharp feature in the spectrum at GeV energies (see Fig. 6) depends on the configuration of the magnetic field in the acceleration zone and the viewing angle. The dependence of the IC component on the geometry of the source is less dramatic, because most of the energy of this component is absorbed and redistributed in the IR source. The quantitative analysis of this effect is beyond the framework of this paper and will be discussed elsewhere.

4. SUMMARY AND CONCLUSIONS

The origin of the TeV gamma-ray emission from the direction of the Galactic center reported recently by three independent groups is not yet established. Despite localization of the region of gamma-ray emission by HESS (within 3’ for an extended source or for a multiple-source cluster and 1’ for a point-like source), several objects remain as likely candidates for TeV emission. These are, in particular, the central 10 pc region filled by dense gas clouds and cosmic rays, the young supernova remnant Sgr A East, the dark matter halo, and the central compact radio source Sgr A*. Although any of these sources may contribute nonnegligibly to the observed gamma-ray flux, in this paper we discuss a few possible TeV gamma-ray production scenarios related to Sgr A*, namely in the immediate vicinity of the associated supermassive black hole (BH).

Production of high-energy gamma rays within $10R_g$ of a BH (of any mass) could be copious because of effective acceleration of particles by the rotation-induced electric fields close to the event horizon or by strong shocks in the inner parts of the accretion disk. However, these energetic gamma rays generally cannot escape the source because of severe absorption due to interactions with the dense, low-frequency radiation through photon-photon pair production. This is true for both stellar-mass and supermassive BHs. But, fortunately, the supermassive BH in our Galaxy is an exception because of its unusually low bolometric luminosity. As shown in § 2, gamma rays up to several TeV can escape the source even if they are produced within a few gravitational radii (see Fig. 2); the propagation effects related to the possible cascading in the photon field may extend the high-energy limit to 10 TeV or even beyond. On the other hand, TeV gamma rays are not absorbed in the magnetic field unless the strength of the $B$ field in this region does not exceed $10^5 \text{ G}$ (see Fig. 3).

Thus, the identification of the TeV signal (or a fraction of this signal) detected from the direction of the Galactic center with Sgr A* would provide a unique opportunity to study the high-energy processes of particle acceleration and radiation in the immediate vicinity of the BH. The transparency of Sgr A* for gamma rays, as well as the recent reports of detection of TeV
radiation from the direction of the Galactic center, initiated the present work with the main objective to explore possible processes of high-energy gamma-ray production within several gravitational radii of BH and to study the impact of these processes on the formation of broadband SED of Sgr A*. We found that at least three scenarios can provide detectable TeV gamma-ray emission.

1. The first scenario is related to protons accelerated to \( \sim 10^{18} \text{ eV} \). These protons can produce very high energy gamma rays through synchrotron and curvature radiation. But in both cases, the energy of gamma rays does not extend to TeV energies. In the case of synchrotron radiation, it is limited by the so-called self-regulated cutoff around 300 GeV. On the other hand, curvature radiation of TeV gamma rays in a BH of mass \( \sim 3 \times 10^6 M_\odot \) requires a magnetic field exceeding \( 10^5 \text{ G} \). However, such a strong field would prevent the escape of gamma rays because of electron-positron pair production. A more effective channel for producing TeV gamma rays is the photomeson processes. The millimeter-IR source in Sgr A* is rather faint, but it is very compact and therefore provides sufficient density of seed photons for interactions with \( 10^8 \text{ eV} \) protons. The efficiency of this process is not very high (it does not exceed 0.1%), but the required power in accelerated protons of about \( 10^{38} \text{ ergs s}^{-1} \) is well below the Eddington luminosity of the BH. This scenario predicts detectable fluxes of \( 10^{18} \text{ eV} \) neutrons and perhaps gamma rays and neutrinos.

2. TeV gamma rays can also be produced by significantly lower energy protons, accelerated by the electric field close to the gravitational radius or by strong shocks in the accretion disk. In this case, the gamma-ray production is dominated by interactions of \( \geq 10^{17} \text{ eV} \) protons with the accretion plasma. Because of the low efficiency of this process (\( p-p \) cooling time is much longer than the characteristic dynamical time of the accretion flow), the interpretation of the observed TeV fluxes by \( \pi^0 \)-decay gamma rays requires proton acceleration power as large as \( 10^{39} \text{ ergs s}^{-1} \), which however is still below, by at least by 4 orders of magnitude, the Eddington luminosity of the central black hole. This scenario predicts unavoidable TeV neutrino flux, which can be detected by the future neutrino detector NEMO located in the Northern Hemisphere. This scenario predicts strong TeV–X-ray–IR correlations. Therefore, simultaneous observations of Sgr A* with IR, X-ray, and TeV telescopes with a goal of detection of subhour flares at these three energy bands may provide evidence in favor or against this scenario.

3. Although interactions of electrons with ambient photon and magnetic fields proceed with much higher efficiency than the gamma-ray production by protons in the previous two channels, a detectable TeV gamma-ray emission requires effective acceleration of electrons to energies well above 1 TeV. A viable site of acceleration of such energetic electrons could be compact regions within a few gravitational radii, provided that electrons move along the lines of regular magnetic field. In this case the electrons produce not only curvature radiation, which peaks around 1 GeV, but also inverse Compton gamma rays (produced in the Klein-Nishina regime) with the peak emission around 100 TeV. However, these energetic gamma rays cannot escape the source. They effectively interact with the IR photons and perhaps also with the magnetic field, produce relativistic electron and positron pairs, and thus initiate electromagnetic cascades inside the IR source. The observed TeV gamma rays can be readily accommodated by this model from the point of view of both the required acceleration power of electrons \( \left( W_p \sim L_{\text{TeV}} \sim 10^{35}-10^{36} \text{ ergs s}^{-1} \right) \) and the reproduction of the observed spectral shape of TeV gamma rays. Obviously, no neutrinos are expected within the framework of this model.

Finally, we want to emphasize that as long as the source(s) of the TeV emission arriving from the direction of the Galactic center is (are) not identified, the results of this paper should not be treated as an attempt to interpret the TeV data but rather should be regarded as a demonstration that the central supermassive BH in our Galaxy is able indeed to produce detectable fluxes of TeV gamma rays.

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