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 favorable conditions also 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 parameter, $\kappa = \frac{L}{L_{\rm Edd}}\frac{R_{\rm g}}{R} \geq 0.01$, given that in most cases the accretion disks within 10 Schwarzschild radii $R_{\rm g}$ radiate with a power exceeding 10 percent of the Eddington luminosity, $L_{\rm Edd}$. Therefore the high energy gamma-ray emission of these objects (both of stellar mass and super-massive 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 super-massive BH located at the dynamical center of our Galaxy (Sgr A*), which thanks to its extraordinary low bolometric luminosity ($\leq 10^{-8} L_{\rm Edd}$) 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 may have broader implications relevant to highly variable nonthermal emission of Sgr A* in radio, IR and X-ray bands.

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

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 mm-wavelengths on the level of ~ 0.1 milli-arcseconds (e.g. (Krichbaum et al. 1998)) tell us that the emission is produced within 10 Schwarzschild radii around BH. The time variability recently detected at X-rays (Baganoff et al. 2001; Porquet et al. 2003; Goldwurm et al. 2003) and near-infrared wavelengths (e.g. (Genzel et al. 2003)) on ≤ 1 h timescales is an independent evidence that the radiation comes from regions located very close to the event horizon of 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 (Quataert & Gruzinov 2000; Narayan et al. 2002; Igumenshchev 2002) dominated accretion flow models, advection dominated inflow-outflow solution (Blandford & Begelman 1999), inefficient accretion flow model (Yuan et al. 2003)), Bondi-Hoyle type models (Melia & Falcke 2001), Jet models (Falcke & Markoff 2000), models assuming interactions of stars with cold accretion disk (Nayakshin & Sunyaev 2003), *etc.* Concerning the radiation mechanisms, there is little doubt that the emission components at radio, and most likely also at the IR and X-ray wavelengths have nonthermal origin. The currently most favored models are different versions of the so-called Synchrotron-Self-Compton (SSC) scenario which assumes that the radio and mm emission is due to electron synchrotron radiation, while the X-rays are explained by inverse Compton scattering of the same (relatively low energy) electron population (see for a review (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 non-negligible role in the formation of 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. Broad-band observations of Sgr A*: a short overview

The radio to mm radiation of Sgr A* is characterized by a very hard spectrum (see Fig. 1) with spectral index $\alpha \simeq 0.3$ ($F_\nu \sim \nu^\alpha$), low-frequency turn-over at $\nu \simeq 1$ GHz and high-frequency cut-off at $\nu \simeq 10^3$ 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 scattering of photons by interstellar plasma indicate (Lo et al. 1998; Bower et al. 2004) that the radiation at different wavelengths is produced at different distances from BH. Namely while the mm emission originates from a compact region of a size $R_{\rm ir} \simeq 20 R_g$ ($R_{\rm g} = 2GM/c^2 \simeq 10^{12}$ cm is the gravitational radius of the BH in GC), the radio emission is produced at larger distances. On the other hand, the near-infrared and X-ray flares, with variability time scales $t_{\rm IR} \sim 10^4$ s (Genzel et al. 2003) and $t_{\rm x} \sim 10^2 - 10^3$ 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 ($\gamma_{\rm e} \sim 100$) 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 inverse Compton 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 40min flare from the central 10 arcmin region of the Galaxy recently has been reported by the *INTEGRAL* team (Bélanger et al. 2004).

In the γ-ray band 100 MeV-10 GeV gamma-rays from the region of GC have been reported by the EGRET team (Mayer-Hasselwander et al. 1998). The luminosity on MeV/GeV gamma-rays $L_{\rm MeV/GeV} \simeq 10^{37}$ erg/s 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 (compared to EGRET) performance 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 H.E.S.S. (Aharonian et al. 2004) collaborations. Amongst possible sites of production of TeV signals are the entire diffuse 10 pc region as result of interactions of cosmic rays with the dense ambient gas, the relatively young supernova remnant Sgr A East (Fatuzzo & Melia 2003), the Dark Matter Halo (Bergström et al. 1998; Gnedin & Primack 2004) due to annihilation of super-symmetric particles, and finally Sgr A* itself. It is quite possible that some of these potential gamma-ray production sites contribute comparably to the observed TeV flux. Note that both the energy spectrum and the flux measured by H.E.S.S. (Aharonian et al. 2004) differ significantly from the results reported by CANGAROO (Tsuchiya et al. 2004) and Whipple (Kosack et al. 2004) groups (see Fig. 1). If this is not a result of miscalibration of detectors, but rather is 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 point-like TeV source by H.E.S.S. within 1 arcmin around Sgr A*. But 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 h) gamma-ray flares at the energy flux level below 10^{-11} erg/s, H.E.S.S. should be able to provide meaningful searches for variability of TeV gamma-rays on timescales less than 1 hour 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 explore possible mechanisms of particle acceleration and radiation which 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 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 time scales less than 1 hour 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 for production of detectable fluxes of TeV gamma-rays without violation the data obtained at radio, infrared and X-ray bands (see Fig. 1). More specifically, we discuss the following possible models in which TeV gamma-rays can be produced due to (i) synchrotron/curvature radiation of protons, (ii) photo-meson interactions of highest energy protons with photons of the compact IR source, (iii) inelastic p-p interactions of multi-TeV protons in the accretion disk, (iv) Compton cooling of multi-TeV electrons accelerated by induced electric field in the vicinity of the massive BH.

2. Internal absorption of γ-rays

The very low bolometric luminosity of Sgr A* makes this object rather unique among the majority of galactic and extragalactic compact objects containing black holes. One of the interesting consequence 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* open 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 AGN) 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 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, $s = E\epsilon/m_{\rm e}^2c^4$. Starting from the threshold at $s = 1$, the cross-section $\sigma_{\gamma\gamma}$ rapidly increases achieving the maximum $\sigma_0 \approx \sigma_{\rm T}/5 \simeq 1.3 \times 10^{-25}$ cm^2 at $s \approx 4$, and then decreases as $s^{-1}\ln s$. Because of relatively narrow distribution of $\sigma_{\gamma\gamma}(s)$, gamma-rays interact most effectively with the background photons of energy

$$\epsilon_b \approx 1(E/1\ \mathrm{TeV})^{-1}\ \mathrm{eV}\ . \tag{1}$$

Thus the optical depth for a gamma-ray of energy E in a source of luminosity L_ϵ at energy given by Eq.(1) and size R can be written in the form

$$\tau(E) = \frac{L_\epsilon \sigma_{\rm T}(E)}{4\pi R c \epsilon_b} \simeq 10^8 \left[\frac{L_\epsilon}{L_{\rm Edd}}\right] \left[\frac{R_{\rm g}}{R}\right] \left[\frac{E}{1\ {\rm TeV}}\right]. \tag{2}$$

Here the optical depth is normalized to the compactness parameter $\kappa = (L_\epsilon/L_{\rm Edd})(R/R_{\rm g})^{-1}$ which does not depend on the mass of BH, therefore is applicable to both stellar mass and super-massive BHs. One can see from this estimate that for a typical AGN or an X-ray binary with NIR/optical luminosity $L \geq 10^{-5} L_{\rm Edd}$, TeV gamma-rays cannot escape the source unless they are produced far from BH, at distances exceeding 10^3 Schwarzschild radii.

The luminosity of Sgr A* is unusually low for an accreting massive BH. At NIR/optical wavelengths the luminosity does not exceed 10^{-8}, therefore TeV gamma-rays can escape the source even if they are produced at $R \sim R_{\rm g}$. Numerical calculations of the optical depth based on the spectral energy distribution of Sgr A* shown in Fig. 2 confirm this conclusion. It is seen that indeed only at energies above 10 TeV the absorption of gamma-rays becomes significant, even if one assumes that the production region of radiation is limited within $2R_{\rm g}$.

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 again transparent, but at EeV energies. These gamma-rays are not absorbed on they way to the Earth either and can be detected by arrays of highest energy cosmic rays like AUGER. However, at such large energies gamma-rays can be absorbed due to 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)

$$\Lambda_{B\gamma} \approx \frac{2\hbar E}{0.16 \alpha_f m_e c^3 K^2_{1/3}(2/3\xi)} \tag{3}$$

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

Generally, the process of interactions of gamma-rays with magnetic field cannot be reduced to a simple absorption effect. Indeed, the secondary electrons interacting with radiation and magnetic fields produce new gamma-rays, which in turn lead to a new generation of electrons-positron pairs; thus, a nonthermal cascade develops the features of which strongly depend on the energy densities

[1]Note, that B which enters in Eq. (3) through the parameter ξ, 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

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 ($E \leq 10^{18}$ eV and $B \leq 10^6$ G) always takes place in the regime when $\xi = (E/m_e c^2)(B/B_{\rm cr}) \ll 1$, 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, therefore cannot support effective development of the cascade).

Generally, Klein-Nishina cascades in photon fields last longer, however in the presence of even relatively week magnetic field they can be strongly suppressed due to synchrotron cooling of electrons. In Sgr A* where the energy density of low-frequency radiation is estimated $w_{\rm rad} \sim 1(R/10R_{\rm g})^{-2}$ erg/cm^3, for effective development of an electromagnetic cascade the strength of the magnetic field should not exceed $(8\pi w_{\rm rad})^{1/2} \simeq 5$ G.

3. Gamma Ray emission mechanisms

High energy gamma-rays from compact regions close to the event horizon of a massive black can be produced in various ways due to acceleration of protons and/or electrons and their interactions with ambient magnetic and radiation fields, as well as with the thermal plasma. Below we discuss the basic features of different possible gamma-ray production scenarios in Sgr A*.

3.1. Gamma-rays related to accelerated protons

3.1.1. Synchrotron and curvature radiation of protons

Gamma-rays produced by relativistic protons and nuclei are often called "hadronic gamma-rays". However, this is not the case of interactions of protons with magnetic field. Namely, the mechanisms associated with the synchrotron and curvature radiation components have electromagnetic origin. These processes become important in compact, strongly magnetized astronomical environments. Moreover, they are unavoidable in the so-called extreme accelerators in which particles are accelerated at the maximum possible rate, $\dot{E} = eB$, determined by classical electrodynamics (Aharonian et al. 2002). In the case of the Galactic Center, protons can be boosted to the maximum possible energy, assuming that acceleration takes place within 10 gravitational radii around the central black hole:

$$E_p \sim eBR \simeq 10^{18} \left[\frac{B}{10^4 \ \mathrm{G}}\right] \left[\frac{M}{3 \times 10^6 M_\odot}\right] \ \mathrm{eV} \ . \quad (4)$$

Thus, for the given magnetic field B, the synchrotron radiation formally could extend up to the characteristic energy

$$\epsilon \sim 0.1 \left[\frac{B}{10^4 \ \mathrm{G}}\right]^2 \left[\frac{M}{3 \times 10^6 M_\odot}\right]^2 \ \mathrm{TeV} \ . \quad (5)$$

However, even for an "ideal" combination of parameters allowing the most favorable acceleration/cooling regime when the proton acceleration proceeds at the maximum rate and the energy losses are dominated by synchrotron cooling, the characteristic energy of synchrotron radiation is limited by

$$\epsilon_{\max} = \frac{9}{4\alpha_f} m_p c^2 \simeq 0.3 \text{ TeV} , \tag{6}$$

which does not depend on the strength of magnetic field ($\alpha_f = 1/137$ is the fine-structure constant). This leads to the self-regulated synchrotron cut-off (Aharonian 2000) at $\epsilon_{\rm cut} = a\epsilon_{\rm c,max}$, where the parameter a varies between 0.3 in the case monoenergetic electrons and ~ 1 for power-law distribution of electrons with an exponential cutoff.

This implies that the proton synchrotron radiation cannot explain the gamma-ray flux observed from the direction of GC up to several TeV, unless the radiation takes place in a source relativistically moving towards the observer with bulk motion Lorentz factor exceeding 10. Another possibility for extension of the high energy end of the spectrum to multi-TeV domain can be realized if the proton acceleration and γ-ray production regions are separated from each other. For example, assuming that protons are accelerated in a regular field configuration while moving along field lines, and later are injected into a region with strong chaotic magnetic field, we may avoid the upper given by Eq.(6). Nevertheless it cannot be arbitrary large because even in a regular filed 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 non-negligible contribution to the gamma-ray emission of the accelerator. In the case of the black hole in 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

$$\epsilon_{\max} = \frac{3E_p^3}{2m^3 R} \simeq 0.2 \left[\frac{B}{10^4 \rm G}\right]^{3/4} \text{TeV} \tag{7}$$

Formally, Eq. (7) allows extension of the spectrum of curvature radiation to 10 TeV, if the magnetic field exceeds $B \simeq 10^6$ G. However, as discussed in the previous section, for such a strong magnetic field, the source is not transparent for TeV γ-rays (see in 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 $\sim 10^{18}$ eV because such energetic protons start to interact with the most copious, far infrared and mm, photons. Despite the low luminosity of Sgr A* , $L_{\rm mm} \simeq 10^{36}$ erg/s, because of the small source size (e.g. Melia and Falke 2001) the density of infrared photons appears sufficiently high,

$$n_{\rm ph} \sim \frac{L_{\rm IR}}{4\pi R_{\rm IR}^2 c\epsilon_{\rm ph}} \simeq 10^{13} \left[\frac{10^{13}\ {\rm cm}}{R_{\rm IR}}\right]^2 \ {\rm cm}^{-3} \ , \tag{8}$$

for effective collisions with protons.

Protons interact with ambient photons also through the pair production (Bethe-Heitler) process. Although the cross-section of pair production is larger than the photo-meson cross section by two 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 production. The mean free path of protons through the photon field of density given by Eq.(8) is estimated

$$\Lambda_{p\gamma} \sim \frac{1}{\sigma_{p\gamma} f n_{\rm ph}} \simeq 10^{15} \left[\frac{R_{\rm IR}}{10^{13}\ {\rm cm}}\right]^2 \ {\rm cm} \tag{9}$$

(on average $\sigma_{p\gamma} f \simeq 10^{-28}$ cm^2, where $\sigma_{p\gamma}$ is the cross-section and f is the inelasticity coefficient).

Since $\Lambda_{p\gamma}$ exceeds by two orders of magnitude the linear size of the IR source, $R_{\rm mm} \sim 10^{13}$ cm, only 1 percent of the energy of protons is converted into secondary particles (at such high energies protons cannot be effectively confined and therefore almost freely escape the IR source). Thus, in order to provide γ-ray luminosity at the level of $L_\gamma \simeq 10^{35}$ erg/s, one has to require an injection power of high energy protons

$$L_p \sim \frac{\Lambda_{p\gamma}}{R_{\rm mm}} L_\gamma \approx 10^{37} \left[\frac{R_{\rm IR}}{10^{13}\ {\rm cm}}\right] \ {\rm erg/s} \tag{10}$$

For the parameters characterizing the IR emission region, the secondary π-mesons decay before interacting with the ambient plasma, therefore their energy is immediately released in the form of neutrinos and γ-rays of energies $10^{17}-10^{18}$eV. The secondary neutrons are produced with somewhat larger energies. While neutrinos and neutrons, as well as gamma-rays of energies below 10^{12} eV and perhaps also above 10^{18} eV, escape freely the emission region, gamma-rays of intermediate energies between 10^{12} and 10^{18} eV, as well as secondary electrons from $\pi^{\pm}$-decays effectively interact with the ambient photon and magnetic fields, and initiate IC and/or (depending on the strength of the magnetic field) synchrotron cascades. The cascade development stops when the typical energy of γ rays is dragged down to $\leq 10^{12}$ eV. The energy spectra of gamma-rays calculated for two different values of ambient magnetic field, $B = 0.1$ and 10 G, are shown in Fig. 4.

A distinct feature of this scenario is that TeV gamma-ray emission is accompanied by detectable fluxes of ultrahigh energy neutrons, and possibly also gamma-rays and neutrinos. In particular, the luminosity of Sgr A* in neutrons at $\geq 10^{18}$ eV can be as high as $L_{\rm n} \sim 10^{36}$ erg/s. The corresponding point-source flux of 10^{18} eV neutrons from the direction of the Galactic Center,

$F_{\rm n} \simeq 30$ neutrons/(km^2 yr), exceeds by a factor of 100 the background of charged cosmic rays within 1 degree (the angular resolution of AUGER), therefore 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. 2001).

In this model the flux of X-rays strongly depends on the magnetic field in the region of the infrared source. For the magnetic field $B \geq 10$ G, the secondary electrons are cooled effectively which leads to the X/TeV energy flux ratio larger than 0.1. Therefore the interpretation of the TeV flux measured by H.E.S.S. within this model predicts 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 existence of a strong magnetic field, $B \geq 10^4$ G, in the compact region limited by a few gravitational radii. If the field close to the black hole 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 be accelerated to TeV energies also 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 $R/v_{\rm r} \sim 10^3 - 10^4$ s (depending on the site(s) of particle acceleration and the accretion regime) to the $p-p$ cooling time,

$$t_{\rm pp} = \frac{1}{\sigma_{pp} n c} \simeq 1.5 \times 10^7 \left[\frac{10^8 \ {\rm cm}^{-3}}{n}\right] \ {\rm s} \ , \tag{11}$$

where n is the number density of the accretion plasma; it 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 conversion of energy of accelerated protons into secondary gamma-rays and electrons is quite low, as small as 10^{-4}. Therefore, even at most favorable conditions, the acceleration rate of high energy protons should exceed $L_{\rm p} \approx 10^{39}$ erg/s 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*, yet it is still acceptable for a black hole of mass $\geq 10^6 M_\odot$.

The results of numerical calculation of the photon spectrum produced in $p-p$ interactions are shown in Fig. 5. The shape of the overall spectral energy distribution, 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 π-meson decays extends to hard X-ray domain. In particular, acceleration of protons beyond $E_0 \geq 10$ TeV during a transient activity of the source may result in a X-ray flare with rather flat spectral energy distribution (SED) like the flares observed by XMM (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, $\Delta t \leq 1$ h, the latter can be naturally explained by the time when the accelerated protons confined in 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 towards 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 mean energy approximately 10 times less than the proton energy. Since the synchrotron cooling time of these electrons,

$$t_{\rm synch} = 4 \times 10^4 \left[\frac{10 \text{ G}}{B}\right]^{3/2} \left[\frac{10^{-2} \text{ eV}}{\epsilon}\right]^{1/2} \text{ s} \;, \tag{12}$$

exceeds the typical dynamical timescale of the source, the radiative losses do not deform significantly the production spectrum of secondary electrons, and therefore resulting synchrotron radiation at radio waves should have very hard SED with spectral index ≈ 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 π^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 Galactic Center region. However, the poor angular performance of these observations as well as 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 broad-band SED can be provided by TeV observations, and especially by future "km3" 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 $\pi^{\pm}$-mesons) with the flux comparable to the TeV gamma-ray flux, i.e. $J_\nu(\geq 1 \text{ TeV}) \sim 10^{-11} \ \nu/\text{cm}^2\text{s}$. A clear observational signature of this scenario could be 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 magnetic field is low and/or very fast accretion in the inner part of the disk). In this regard, it is difficult to overestimate the importance of continuous monitoring of of Sgr A* at gamma-ray energies between 100 GeV to 10 TeV by the H.E.S.S. telescope array and at hard X-rays by Chandra, XMM and INTEGRAL satellites with comparable sensitivities for detection of flares at the energy flux level of 10^{-11} erg/cm^{2}s on hour 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 a 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 conversion of 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 production of 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 $dE/dt \sim \kappa e B$ ($\kappa \leq 1$), from the balance of the acceleration and synchrotron energy loss rates one finds

$$E_{\rm e} \leq \frac{3^{3/4} m_e^2}{2^{3/4} e^{3/2} B^{1/2}} \simeq 1.5 \times 10^{13} \left[\frac{B}{10 \text{ G}}\right]^{-1/2} \kappa^{1/2} \text{ eV} \ . \tag{13}$$

Thus, even in the case of maximum acceleration rate ($\kappa = 1$) electrons cannot be accelerated to multi-TeV energies unless the random B-field is less than 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 black hole provides maximum energy gain. Moreover, in the ordered field the energy dissipation of electrons is reduced to curvature radiation loses which increases the maximum achievable energy of electrons to

$$E_e = \left[\frac{3 m_e^4 R^2 B}{2e}\right]^{1/4} \simeq 10^{14} \left[\frac{B}{10 \text{ G}}\right]^{1/4} \text{ eV} \ . \tag{14}$$

Note that this estimate weakly depends on the strength of the magnetic field. On the other hand, electrons may suffer also significant Compton losses which would result in reduction of E_e given by Eq.(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 inverse Compton scattering of 100 TeV electrons on infrared photons proceeds in the Klein-Nishina regime, and thus the IC spectrum peaks at energy $E_\gamma \simeq E_e \simeq 100$ TeV. At the same time the curvature radiation results in the second peak in the spectrum which appears at significantly lower energies,

$$\epsilon_{\rm curv} = \frac{3 E_e^3}{2 m_e^3 R} \simeq 2 \times 10^8 \left[\frac{E_e}{10^{14} \text{ eV}}\right]^3 \text{ eV} \ . \tag{15}$$

Below we will call the scenario of production of Curvature and IC photons by electrons accelerated in regular magnetic/electric fields as *CRIC* model. Quantitative calculations of high energy radiation within the framework of this model requires "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 Fig. 6. The calculations are performed within the model in which electrons are accelerated by the electric field induced by the black hole 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 inverse Compton radiation components are calculated at each point of the electron trajectory. The spectra shown in Fig. 6 are result of summing up the spectra from about 10^4 electron trajectories close (within 2 gravitational radii) to the black hole horizon and subsequent propagation of the secondary gamma-rays through the infrared emission source which is assumed to be confined within ~ 10 gravitational radii. We assume 10 G regular B-field in the acceleration zone, and 30 G chaotic field in the infrared source.

In Fig. 6 one can see two distinct components in the gamma-ray *production* spectrum (thin solid line) which sharply peak at ~ 1 GeV and 100 TeV. The GeV peak is due to the Curvature radiation, and 100 TeV peak is formed due to inverse Compton scattering that proceeds in the Klein-Nishina limit. However the highest energy gamma-rays, $E_\gamma \sim 10^{14} - 10^{15}$ eV, can not freely escape the source. They effectively interact with infrared photons with production of electron-positron pairs. The synchrotron radiation of these electrons in an irregular field leads to the re-distribution of the initial gamma-ray spectrum (heavy solid line in Fig. 6).

It should be noted that the fluxes shown in Fig. 6 are obtained under assumption of isotropic emission of electrons in the acceleration zone. However, both Curvature and inverse Compton 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 inverse Compton component on the geometry of the source is less dramatic because the most of the energy of this component is absorbed and redistributed in the infrared 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 reported recently from the direction of the Galactic Center by three independent groups is not yet established. Despite localization of the region of gamma-ray emission by H.E.S.S. – within 3 arcmin for an extended source or for a multiple-source cluster, and 1 arcmin 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 non-negligibly into 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.

Production of high energy gamma-rays within 10 gravitational radii of a black hole (of any mass) could be copious due to 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, generally these energetic gamma-rays 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 black holes. But, fortunately, the supermassive black hole in our Galaxy is an exception because of its unusually low bolometric luminosity. As shown in Sec. 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 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 BH. The transparentness 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 broad-band spectral energy distribution of Sgr A*. We found that at least 3 scenarios can provide detectable TeV gamma-ray emission.

(i) The first scenario is related to protons accelerated to $\sim 10^{18}$ 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 the black hole of mass $\sim 3 \times 10^6 M_\odot$ requires magnetic field exceeding 10^5 G. But such a strong field would prevent escape of gamma-rays due to electron-positron pair production. A more effective channel for production of TeV gamma-rays is the photo-meson processes. The mm-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^{18} eV protons. The efficiency of this process is not very high – it does not exceed 0.1 per cent – but the required power in accelerated protons of about 10^{38} erg/s is well below the Eddington luminosity of the black hole. This scenario predicts detectable fluxes of 10^{18} eV neutrons, and perhaps also gamma-rays and neutrinos.

(ii) TeV gamma-rays can be produced also 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 $\geq 10^{13}$ eV protons with the accretion plasma. Because of the low efficiency of this process (*pp* cooling time is much longer than the characteristic dynamical time of the accretion glow), the interpretation of the observed TeV fluxes by π^0-decay gamma-rays requires proton acceleration power as large as 10^{39} erg/s, which however is still below, 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 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 sub-hour flares at these three energy bands, may provide evidence in favor or against this scenario.

(iii) Although interactions of electrons with ambient photon and magnetic fields proceed with much higher efficiency than the gamma-ray production by protons in the above 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 by 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 infrared photons and perhaps also with the magnetic field, produce relativistic electron and positron pair, and thus initiate electromagnetic cascades inside the infrared source. The observed TeV gamma-rays can be readily accommodated by this model from the point of view of both required acceleration power of electrons ($\dot{W}_e \sim L_{\rm TeV} \sim 10^{35} - 10^{36}$erg/s 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 black hole in our Galaxy is able indeed to produce detectable fluxes of TeV gamma-rays.

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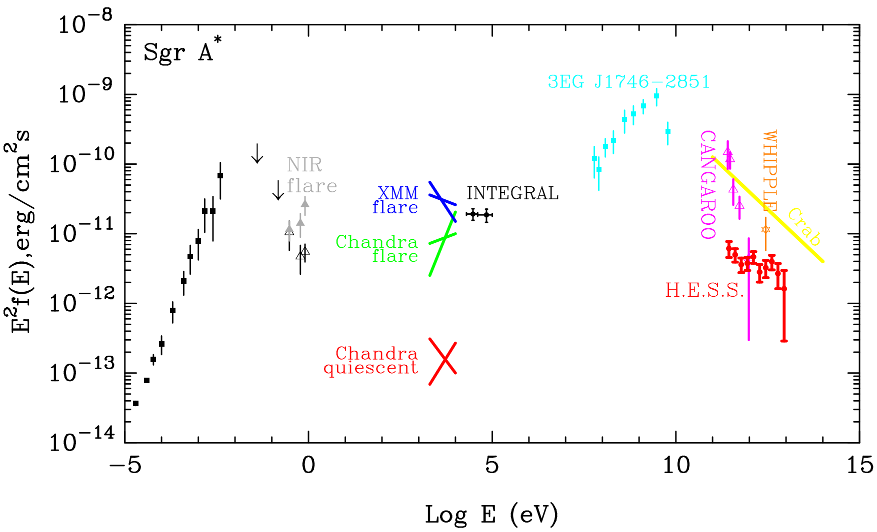

Fig. 1.— Broad-band spectral energy distribution of Sgr A*. Radio data are from (Zylka et al. 1995), and the infrared data for quiescent state and for flare are from (Genzel et al. 2003). X-ray fluxes measured by Chandra in the quiescent state and during a flare are from (Baganoff et al. 2001; Baganoff et al. 2003). XMM measurements of the X-ray flux in a flaring state is from (Porquet et al. 2003). In the same plot we show also the recent INTEGRAL detection of a hard X-ray flux, however because of relatively poor angular resolution the relevance of this flux to Sgr A* hard (Bélanger et al. 2004) is not yet established. The same is true also for the EGRET data (Mayer-Hasselwander et al. 1998) which do not allow localization of the GeV source with accuracy better than 1 degree. The very high energy gamma-ray fluxes are obtained by the CANGAROO (Tsuchiya et al. 2004), WHIPPLE (Kosack et al. 2004) and H.E.S.S. (Aharonian et al. 2004) groups. Note that the GeV and TeV gamma-ray fluxes reported from the direction of the Galactic Center may originate in sources different from Sgr A*, therefore, strictly speaking, they should be considered as upper limits of radiation from Sgr A*.

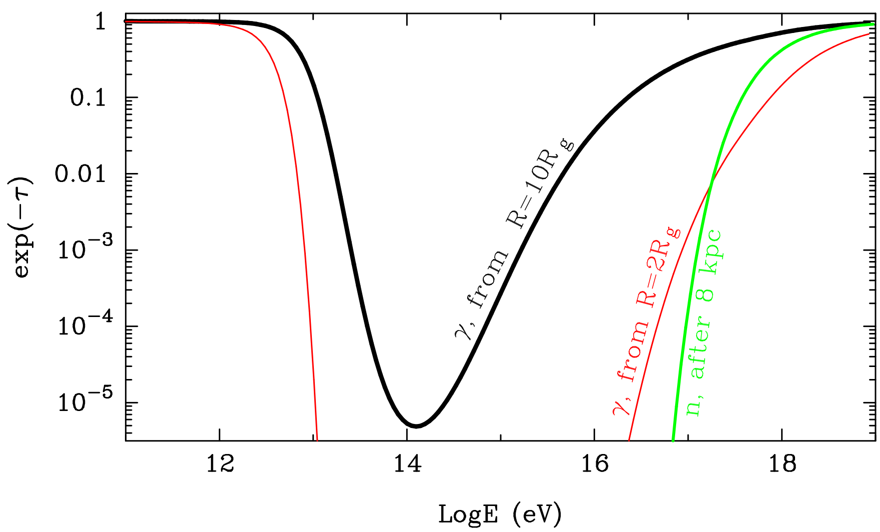

Fig. 2.— Attenuation of γ-rays in Sgr A* due to internal photon-photon pair production dominated by interactions of high energy gamma-rays with radiation of the compact infrared source. The main uncertainty of the optical depth τ is caused by the uncertainty of location of the infrared source. Two solid curves marked "γ" are calculated assuming that the infrared emission of Sgr A* is produced within $10R_g$ and $2R_g$ around the central black hole of mass $3 \times 10^6 M_\odot$. External absorption of γ-rays due to interactions with the 2.7 K CMBR (not shown in the figure) is noticeable ($\sim e^{-1} \approx 1/3$) only at energies around 10^{15} eV (Gould & Schrèder 1967). However at these energies gamma-radiation is already strongly suppressed due to the internal absorption. The curve marked "n" shows attenuation of the neutron flux $\exp(-d/\Lambda)$, where $\Lambda \approx 10(E/10^{18}$ eV) kpc is the decay mean free path of a neutron of energy E, and $d = 8$kpc is the distance to the Galactic Center.

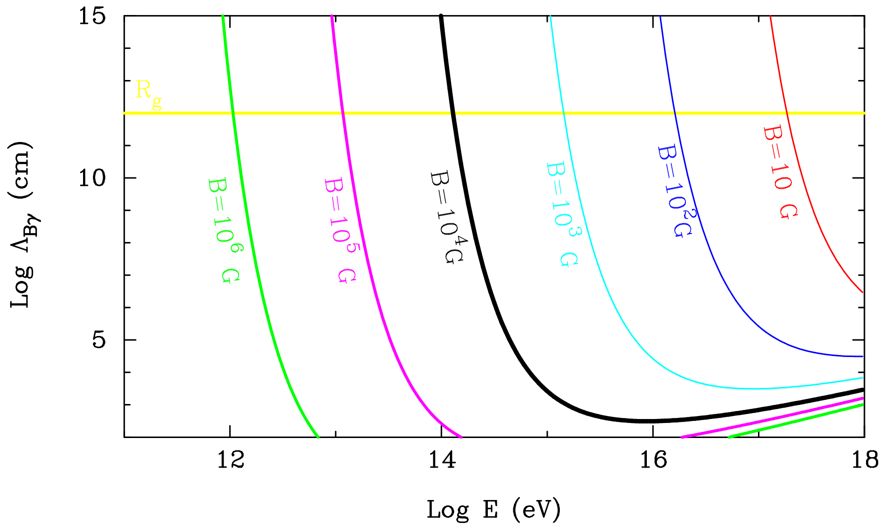

Fig. 3.— Absorption lengths of γ-rays due to pair production in magnetic field calculated for several values of the strength of magnetic field (indicated at the curves). Horizontal line shows the gravitational radius of a $3 \times 10^6 M_\odot$ black hole.

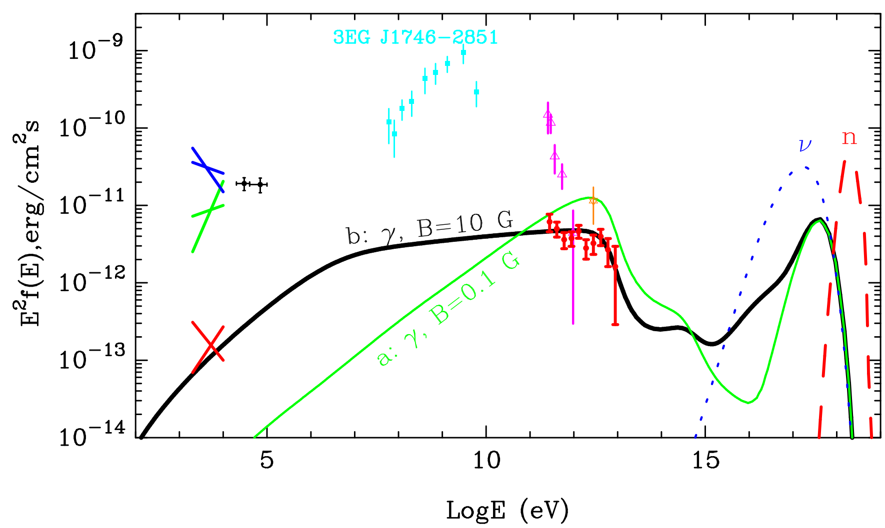

Fig. 4.— Broadband spectrum of γ-rays (solid lines), neutrons (dash line) and neutrinos (dots) from Sgr A* due to interactions of extremely high energy protons with ambient photon and magnetic fields. Protons accelerated to energies 10^{18} eV in the regular magnetic field close to the gravitational radius $R \sim R_{\rm g}$, propagate through the infrared emission region of size $R = 10R_{\rm g}$. The calculations correspond to two assumptions for the strength of the magnetic field in the region of the infrared emission: $B = 0.1$ G (a) and $B = 10$ G (b). The curves represent the spectra of cascade γ-rays emerging the source. Note that because of development of electromagnetic cascades, suppression of γ-rays around 10^{14} eV is significantly less than one would expect from simple photon-photon absorption effect. The γ-ray and neutron fluxes are corrected for the absorption of γ-rays due to interactions with 2.7 K CMBR (which results in the formation of a "valley" in the spectrum at 10^{15} eV), and for the decay of neutrons, assuming 8 kpc distance to the source.

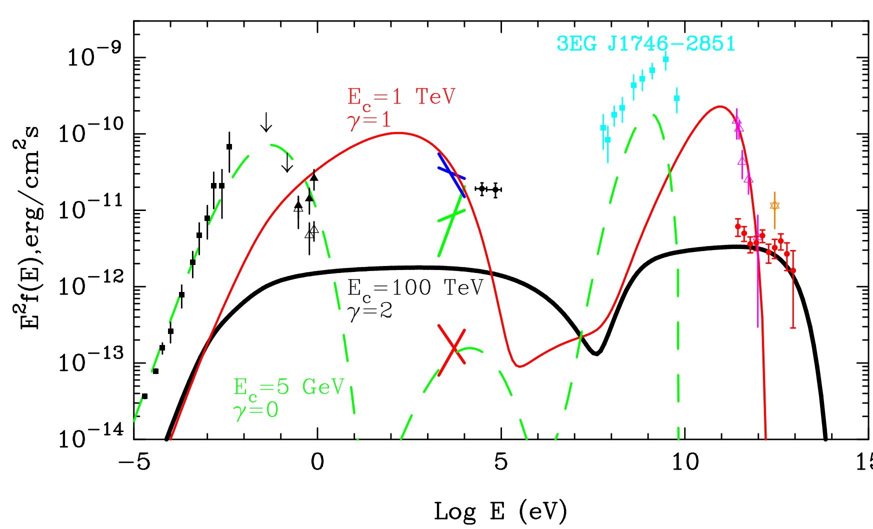

Fig. 5.— Spectral energy distribution of the broad-band electromagnetic radiation initiated by $p-p$ interactions in the accretion disk. It is assumed that the accelerated protons with spectrum $E^{-\Gamma}\exp\left(-E/E_c\right)$ are injected into the thermal plasma of density 10^8 cm^{-3}, and together with the accretion flow cross the region of the size $R \approx 10R_g$ cm and fall under the black hole horizon after 10^4 s. The following parameters have been assumed: (1) heavy solid curve: $\Gamma = 2$, high energy exponential cut-off at $E_c = 100$ TeV, total acceleration rate $L_{\rm p} = 5\times10^{38}$ erg/s; (2) thin solid curve: $\Gamma = 1$, $E_c = 1$ TeV, $L_{\rm p} = 10^{40}$ erg/s; (3) dashed curve: narrow ($\Gamma = 0, E_c = 5$ GeV) distribution of protons, $L_{\rm p} = 10^{40}$ erg/s. For all three cases the magnetic field is assumed to be $B = 10$ G.

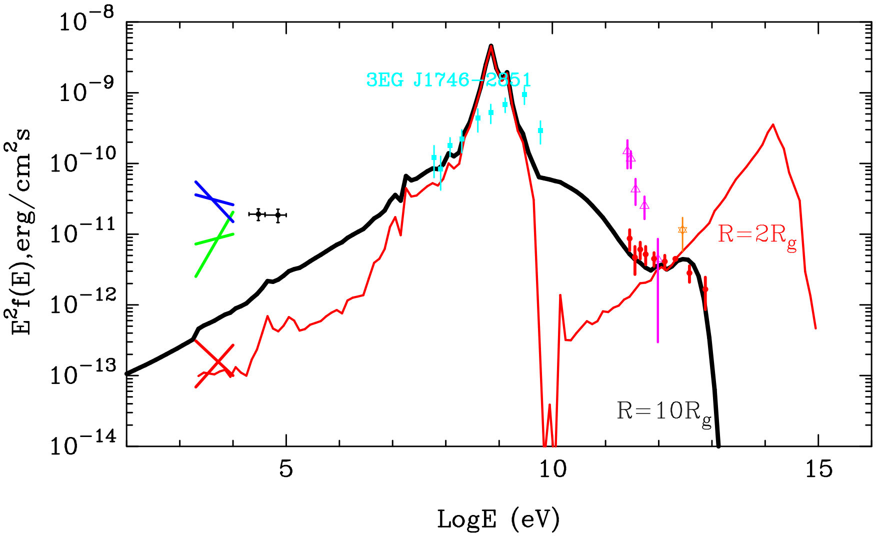

Fig. 6.— Broad-band spectral energy distribution of radiation produced by electrons within the *CRIC* model (see the text). Thins solid curve - gamma-ray production spectrum formed as superposition of the Curvature and inverse Compton emission components which accompany electron acceleration by the rotation-induced electric field within ($R = 2R_{\rm g}$); heavy curve - the spectrum of gamma-rays modified after the passage of the infrared source of size $R = 10R_{\rm g}$. The strength of the regular magnetic field in the electron acceleration region is assumed $B = 10$ G. The strength of the random magnetic field in the region of infrared emission is assumed $B = 30$ G.