INTERNAL $\gamma\gamma$ OPACITY IN ACTIVE GALACTIC NUCLEI AND THE CONSEQUENCES FOR THE TeV OBSERVATIONS OF M87 AND Cen A

KATHARINA A. BRODATZKI1, DAVID J. S. PARDY2, JULIA K. BECKER1, AND REINHARD SCHLICKEISER1

1 Institut für Theoretische Physik, Lehrstuhl IV: Weltraum-und Astrophysik, Ruhr-Universität Bochum,
D-44780 Bochum, Germany; kb@tp4.rub.de
2 Department of Physics, Queen’s University, Kingston, Ontario, K7L 3N6, Canada

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ABSTRACT

Low-luminosity active galactic nuclei (LLAGNs) possess the characteristic features of more luminous active galactic nuclei (AGNs) but exhibit a much lower nuclear Hα luminosity ($L_{\text{H}α} < 10^{40}$ erg s$^{-1}$) than their more luminous counterparts. M87 (NGC 4486) and Centaurus A (NGC 5128, Cen A) are well studied nearby LLAGNs. As an additional feature they show $\gamma$ radiation up to TeV ($10^{12}$ eV) energies, but the origin of this radiation has not been resolved. The coincident observation of a radio and TeV flare in M87 suggests that the TeV radiation is produced within around 50–100 gravitational radii of the central supermassive black hole, depending on the assumed value of the mass of the black hole. Strong radiation fields can be produced in the central region of an (LL)AGN, e.g., by the accretion flow around the black hole, the jet plasma, or stars closely orbiting the black hole. These radiation fields can lead to the absorption of emitted TeV photons, and, in fact, high optical depths of such fields can make TeV detection from inner regions impossible. In this paper, we consider the accretion flow around the black hole as the most prominent source for such a radiation field and we calculate accordingly the probability for absorption of TeV photons produced near the black holes in M87 and Cen A assuming a low-luminosity Shakura–Sunyaev disk (SSD). We find that the results are very different between the two LLAGNs. While the inner region of M87 is transparent for TeV radiation up to $\sim 20$ TeV within the allowed parameter range, the optical depth in Cen A is $\gg 1$, leading to an absorption of TeV photons that might be produced near the central black hole. These results imply either that the TeV $\gamma$ production sites and processes are different for both sources or that LLAGN black holes do not accrete (at least only) in the form of a low-luminosity SSD.

Key words: accretion, accretion disks – galaxies: active – galaxies: individual (M87, CenA) – opacity – radiation mechanisms: thermal

Online-only material: color figures

1. INTRODUCTION

The current most favored model for active galactic nuclei (AGNs), which are highly active, very compact regions in galactic centers, is the “unified AGN model” developed by Urry & Padovani (1995). In this model, many differences in the spectra of AGNs arise as a consequence of their orientation in Earth’s view rather than from different physical properties. The most characteristic component of an AGN is the central black hole of the host galaxy. Strong gravitational tides attract surrounding material to form the accretion flow around the black hole, and a dust torus is formed surrounding the accretion flow. Additionally, radio-loud galaxies typically have relativistic jets that transport plasma particles from black hole vicinities to outer regions of the galaxy. Depending on the orientation of an AGN toward the Earth, some regions of the galaxy are observable, whereas others are obscured. Consequently, the spectral energy distributions (SEDs) of some AGNs show features such as broad or narrow emission lines or highly luminous accretion disks, whereas others do not.

For a long time blazars were the only known extragalactic sources that seemed to emit $\gamma$ radiation up to TeV ($10^{12}$ eV) energies. The angle between the line of sight and the relativistic jet of blazars is very small, meaning the jet points toward Earth. As a result, radiation emitted by relativistic particles along the jet is strongly influenced by relativistic effects; on Earth we observe the emitted photons at higher energies and intensities than they actually have inside the jet. This makes blazars detectable at increasingly higher energies.

The detection of TeV $\gamma$ radiation from radio galaxies M87 (NGC 4486; Aharonian et al. 2003, 2006) and Centaurus A (NGC 5128 and henceforth Cen A; Aharonian et al. 2009) revealed another class of extragalactic TeV $\gamma$-ray sources. These two objects are also AGNs, but their jets make larger angles with our line of sight. For such non-blazar AGNs the observed TeV energies of the photons cannot arise from relativistic effects but must be produced inside the source. However, both their production mechanism and site are still unknown. Nevertheless, recent observations of M87 hint that the TeV photons are produced near the black hole (Acciari et al. 2009).

M87 and Cen A are both Fanaroff–Riley I (FR I; Fanaroff & Riley 1974) radio galaxies, meaning radio-loud but optically underluminous ($M_V > -23$; Melia 2009) AGNs in centers of (almost exclusively) elliptical galaxies. Due to their low nuclear luminosity they belong to the class of low-luminosity active galactic nuclei (LLAGNs). LLAGNs have similar characteristic features to luminous AGNs but exhibit nuclear luminosities that are orders of magnitude lower than their more luminous counterparts. Interestingly, LLAGNs are often radio-loud and in several cases host relativistic radio jets (Ho 2008; Nagar et al. 2002). The existence of jets in LLAGNs could indicate a connection between their low luminosity and the formation of outflows. Furthermore, the “big blue bump,” meaning the optical-to-UV radiation that is presumably the emission from a geometrically thin yet optically thick disk common to luminous AGNs, seems to be absent in some LLAGNs (Ho 2008). The lack of this thin disk characteristic favors a different accretion model than the thin disk in lumin-
nous AGNs. Due to the low-luminosity nature of such objects, the accretion could be explained by the radiatively inefficient accretion flow (RIAF) model in which the energy of accreted particles is either advected with the matter into the black hole (the so-called advection-dominated accretion flow; Narayan & Yi 1994, 1995a, 1995b) or redirected into an outflow instead of being radiated away. Accretion flows that form outflows assort well with the radio loudness and the occurrence of jets in LLAGNs. Such RIAFs have a rather spherical geometrical shape and hence a much lower optical depth than geometrically thin disks.

On the other hand, there is also evidence that at least part of the accretion flow in a typical LLAGN is in a thin disk (Maoz 2007). In this paper, we scrutinize the accretion form in LLAGNs with the aid of observed TeV γ radiation from M87 and Cen A. Due to the different physical properties in the sundry accretion flows (like proton or electron density, the temperature of the particles, the degree of interaction between them, the type of radiation production, etc.), the interaction of the accretion flow with TeV photons produced in its vicinity varies widely between different flows. The comparison of absorption probability with observations could point out which type of accretion flow can be ruled out for LLAGNs. In this paper, we assume that the accretion in M87 and Cen A is in the form of a thin disk and accordingly calculate the strength of TeV photon absorption, with production sites at varying distances above the black hole, by disk photons. M87 and Cen A are excellent objects for our investigation since the mass of their black holes and observed bolometric luminosities are quite different. These variables hold much weight in the formation of accretion flows and therefore greatly affect the absorption probability of TeV photons. Models that are very sensitive to black hole mass and bolometric luminosity could have problems forecasting the absorption probability for both M87 and Cen A since their relevant parameters vary considerably, as can be seen in Table 1.

Throughout the paper we use the following notation.
1. \( m = M/M_\odot \) is the black hole mass in units of the solar mass \( M_\odot \).
2. \( r = R/R_G \) is the radius of a ring segment of an accretion disk around a black hole in units of gravitational radius for the black hole.
3. \( \dot{m}_{\text{Edd}} = M/M_{\text{Edd}} \) is the mass accretion rate in units of the Eddington accretion rate.

4. \( \epsilon = E/m_e c^2 \) is the energy of a photon in units of the rest energy of an electron, where \( m_e \) denotes the electron rest mass and \( c \) is the speed of light in vacuum.

### 2. ACCRETION IN LLAGNs

Currently, the reason for the difference in luminosity between luminous AGNs and LLAGNs is not clear. One possibility is that their accretion modes are different. The mode of accretion depends on the amount of available accretion material and how efficiently the gravitational energy of accreted material is converted into electromagnetic radiation. In black hole accretion mechanics, the gravitational potential energy converted to radiation energy produces an associated luminosity of \( L_{\text{acc}} = \eta M c^2 \). Here, \( M \) is the mass accretion rate and the factor \( \eta \) measures the efficiency of gravitational-energy-to-radiation conversion. \( \eta = 1 \) implies total conversion of the released gravitational energy into radiation, but in-fallen particles can retain some of their kinetic energy, meaning that not all of the energy is converted into radiation energy and hence \( \eta \) is below unity. After crossing the event horizon of the black hole at the Schwarzschild radius, \( R_S = 2R_G \), where

\[
R_G = \frac{G M_\odot}{c^2} \approx 1.475 \times 10^5 \text{ m cm}
\]

is the gravitational radius, the kinetic energy carried with the material into the black hole contributes to its mass. For accretion onto a black hole, \( \eta \approx 0.1 \) is a reasonable and well-used estimate (Frank et al. 1992).

The Eddington luminosity is of great importance in accretion physics. It is the released electromagnetic radiation energy in spherical symmetric accretion assuming hydrostatic equilibrium:

\[
L_{\text{Edd}} = \frac{4 \pi c G M_\odot m_p}{\sigma_T} = \frac{4 \pi c G M_\odot m_p}{\sigma_T} \approx 1.5 \times 10^{38} \text{ m erg s}^{-1} \propto m,
\]

with the mean molecular weight \( \mu \), the proton rest mass \( m_p \), and the Thomson cross section \( \sigma_T \). The Eddington accretion rate \( M_{\text{Edd}} \) is defined as the accretion rate required to achieve \( L_{\text{Edd}} \):

\[
L_{\text{Edd}} = \eta M_{\text{Edd}} c^2.
\]

For the mass accretion rate in units of the

| Features                      | M87                                      | Cen A                                      |
|-------------------------------|------------------------------------------|--------------------------------------------|
| Black hole mass \( m = M/M_\odot \) | \((3.2 \pm 0.9) \times 10^{11}, (6.4 \pm 0.5) \times 10^{12}\) | \((4.5^{+1.7}_{-1.0}) \times 10^{7}, (5.5 \pm 3.0) \times 10^{7}\) |
| Gravitational radius \( R_G \) | \(4.72 \times 10^{14} \text{ cm} = 1.53 \times 10^{-4} \text{ pc}, 9.44 \times 10^{14} \text{ cm} = 3.06 \times 10^{-4} \text{ pc}\) | \(7.375 \times 10^{23} \text{ cm} = 2.390 \times 10^{-6} \text{ pc}\) |
| Distance from Earth \( d \) | \((16.7 \pm 0.2) \text{ Mpc}\) | \((3.8 \pm 0.1) \text{ Mpc}\) |
| Inclination \( i \) | \((15 - 25)^{(4)} (30 - 35)^{(7)}, (30 - 45)^{(8)}\) | \((15 - 80)^{(9)}, (50 - 80)^{(10)} \text{ (pc-scale)}\) |
| Nuclear X-ray luminosity \( L_X \) | \(7.0 \times 10^{40} \text{ erg s}^{-1} ((0.5-7) \text{ keV})^{(11)}\) | \(~5 \times 10^{43} \text{ erg s}^{-1} ((2-10) \text{ keV})^{(12)}\) |
| Luminosity \( L_{bol} \) | \(~10^{42} \text{ erg s}^{-1}^{(13)}\) | \(~10^{43} \text{ erg s}^{-1}^{(14)}\) |

**Notes.**
- \(^a\) For \( m = 3.2 \times 10^9 \).
- \(^b\) For \( m = 6.4 \times 10^9 \).

**References.**
1. Macchetto et al. 1997;
2. Gebhardt & Thomas 2009;
3. Neumayer et al. 2010;
4. Mei et al. 2007;
5. Harris et al. 2009;
6. Acciari et al. 2009;
7. Bicknell & Begelman 1996;
8. Ly et al. 2007;
9. Aharonian et al. 2009 and references therein;
10. Tingay et al. 1998;
11. Di Matteo et al. 2003;
12. Evans et al. 2004;
13. Reynolds et al. 1996;
14. Karovska et al. 2002.
Eddington accretion rate, it follows that

\[
m_{\text{Edd}} := \frac{M}{M_{\text{Edd}}} = \frac{\eta M c^2}{\eta M_{\text{Edd}} c^2} = \frac{L_{\text{acc}}}{L_{\text{Edd}}} \approx \frac{L_{\text{acc}}}{1.5 \times 10^{38} \text{ erg s}^{-1} m} \propto \frac{L_{\text{acc}}}{m},
\]

(3)

and with this the ratio of the accretion rate to the black hole mass

\[
\frac{m_{\text{Edd}}}{m} \propto \frac{L_{\text{acc}}}{m^2}. \quad (4)
\]

Several astrophysical sources have been observed to emit on the order of \(L_{\text{Edd}}\).

The accretion mode in luminous AGNs must be radiatively efficient, making the standard thin accretion disk or Shakura–Sunyaev disk (SSD; Shakura & Sunyaev 1973) the favored accretion model. The SSD has a mass accretion rate at or slightly below the Eddington limit (\(m_{\text{Edd}} \lesssim 1\)) and provides high optical depth.

The accretion mode of an LLAGN is still unclear. It might proceed in a radiatively inefficient way. Several models exist for such RIAFs (Yuan et al. 2003) that offer differing reasons for radiation inefficiency.

One way to describe AGN accretion is that during their life-time they switch between two phases. There is a short active phase with a high mass accretion rate near the Eddington accretion rate (\(m_{\text{Edd}} \lesssim 1\)) demonstrating high radiation efficiency (\(\eta \approx 0.1\)), as well as a long quiescent stage during which the mass accretion rate lies a few orders of magnitude below \(M_{\text{Edd}}\) (\(m_{\text{Edd}} \ll 1\)) and the radiation efficiency is relatively low (\(\eta \ll 1\)). Therefore, luminous and low-luminosity AGNs seem to represent different stages in the lives of supermassive black holes in galactic centers. While AGN black holes seem to spend most of their lifetimes in a quiescent stage, there is strong evidence that their most substantial growth primarily occurs during their brief active period (Maoz 2007 and references therein).

Even though observations show evidence for transitions from such low- to high-accretion-rate phases, the existence of an RIAF has not yet been proven. Furthermore, Maoz (2007) has analyzed the SEDs of 13 nearby galaxies with low-ionization nuclear emission-line region (LINER) nuclei, the most common form of LLAGNs. As a type-2 LINER, M87 was among the studied objects. The result of the study was that, contrary to common opinion, the objects exhibited significant non-stellar UV flux. Indeed, the UV/X-ray luminosity ratios are similar to those of Seyfert 1 nuclei, which have ~10^4 times higher luminosities. Nevertheless, the radio emission of these objects is remarkable. The luminosity ratio between radio and other wavelengths is heavily dependent on the luminosity of the object and increases with decreasing luminosity. Hence, it is possible that LLAGNs (at least partially) accrete in the form of a thin SSD. Therefore, as a first test, we assume an SSD as the accretion flow model in the LLAGNs M87 and Cen A to calculate the absorption of TeV photons produced near the black hole by SSD photons.

### 2.1. Shakura–Sunyaev Disk (SSD)

In order to fall into the supermassive black hole, material inside the accretion disk must lose some of its angular momentum. Because the total angular momentum of the disk is conserved, the angular momentum of the infalling material must be transferred to the remaining material inside the disk. In the SSD, the magnetorotational instability (MRI; Balbus & Hawley 1991) is believed to be the mechanism responsible for this process. As a consequence of the gain in angular momentum, the remaining material moves in the opposite direction (away from the black hole). This implies that not all of the accretion material can actually be accreted onto the black hole. Material with non-zero angular momentum can only fall into the black hole if there is other material that can move away from the innermost regions.

The SSD is the best model to describe accretion in luminous AGNs because it is the accretion mode with the highest efficiency of gravitational energy dissipation leading to very luminous disks. The gravitational energy of the accreted material is at first converted into kinetic energy while the material moves toward the black hole and then by viscous stresses into thermal energy, which then can be radiated away. Because the radiative cooling is very efficient, the material becomes relatively cool, and the accretion flow assumes a geometrically thin, disk-like shape. The luminosity of the whole disk lies in the range of (if not a little below) the Eddington luminosity.

Two further important properties of the SSD are the inner and outer radii, \(r_{\text{min}} = R_{\text{min}}/R_G\) and \(r_{\text{max}} = R_{\text{max}}/R_G\), respectively. The inner radius is well defined and lies at \(r_{\text{min}} = R_{\text{ISCO}}/R_G = 6\), which is the innermost stable circular orbit around a Schwarzschild black hole. At smaller distances the material falls directly into the black hole. The outer radius is not well defined. It can be estimated, however, that for a Schwarzschild black hole 50% of the energy is emitted between \(r = 6\) and \(r = 30\) (Netzer 2006). This implies that the highest amount of radiation is emitted in the inner part of the SSD, and therefore \(r_{\text{max}} \approx 2000\) is a good approximation for the outer radius of an SSD.

The material inside the SSD is assumed to be in local thermal equilibrium and to radiate like a perfect blackbody. The temperature at a radius \(r = R/R_G\) is then

\[
\Theta(r) = \frac{k_B T(r)}{m_c c^2} = 5.5328 \cdot 10^{-12} \left(\frac{L_{\text{acc}} \text{ erg/s}}{m^2 r^3} \right)^{\frac{1}{2}} \left(1 - \frac{6}{\sqrt{r}} \right)^{\frac{1}{2}} \propto \left(\frac{L_{\text{acc}} \text{ erg/s}}{m^2 r^3} \right)^{\frac{1}{2}} \left(m^{-1/2} \tilde{Y}(r) \propto L_{\text{acc}}^{1/4} m^{-1/2}, \quad (5)
\]

where \(k_B\) is the Boltzmann constant, and the function

\[
\tilde{Y}(r) := 5.5328 \cdot 10^{-12} r^{-3/4} \left(1 - \frac{6}{\sqrt{r}} \right)^{\frac{1}{2}} \quad (6)
\]

contains the radial dependence. The highest temperature is achieved near the inner edge of the SSD. Figure 1 shows the profile of the temperatures of the SSDs in M87 and Cen A. The absolute temperature only depends on the ratio of the disk luminosity, \(L_{\text{acc}}\), and the square of the black hole mass, \(m\). The spectrum of the whole SSD is the superposition of many blackbody spectra from SSD regions with different temperatures.

### 2.2. Low-luminosity SSD

Since the luminosities of LLAGNs lies orders of magnitude below the Eddington luminosity, we set the observed bolometric luminosity \(L_{\text{bol}}\) to be the luminosity of the SSD released due
to accretion, \( L_{\text{bol}} = L_{\text{acc}} \). The bolometric luminosity of the nucleus of M87 lies in the range of \( L_{\text{bol}} \sim 10^{42} \text{ erg s}^{-1} \) (Reynolds et al. 1996). This implies a mass accretion rate of \( m_{\text{acc}} \sim 10^{-6} \). Although the nucleus of Cen A was observed at an only slightly higher luminosity of \( L_{\text{bol}}^{\text{Cen A}} \sim 10^{43} \text{ erg s}^{-1} \) (Karovska et al. 2002), due to the black hole’s mass being two orders of magnitude reduced from the mass of the black hole in M87, the mass accretion rate in Cen A lies three orders of magnitude above the one in M87 (\( m_{\text{acc}}^{\text{Cen A}} \sim 10^{-3} \)). Furthermore, it follows for the ratio of disk luminosity and the square of the black hole mass that

\[
\frac{L_{\text{bol}}}{m^2} \approx \begin{cases} 
10^{23} \text{ erg s}^{-1} & \text{for M87 and } m = 3.2 \times 10^6 \\
2.5 \times 10^{22} \text{ erg s}^{-1} & \text{for M87 and } m = 6.4 \times 10^6 \\
4 \times 10^{22} \text{ erg s}^{-1} & \text{for Cen A and } m = 5.0 \times 10^7 
\end{cases}
\]  

(7)

In the following section we use these values to calculate the optical depth for TeV photons produced near the black hole.

3. ATTENUATION OF TeV PHOTONS BY THE SSD RADIATION FIELD

In astrophysics, electron–positron pair production in photon–photon collisions is of utmost importance for high-energetic photons crossing low-energy photon fields and can lead to a significant absorption of the former. As previously mentioned, we consider this process as the main source of the attenuation of TeV photons in M87 and Cen A.

3.1. Electron–Positron Pair Production in Photon–Photon Collisions

If the energy of the two photons (with energies \( \epsilon_1 = E_1/m_e c^2 \) and \( \epsilon_2 = E_2/m_e c^2 \)) in their center-of-mass (COM) system is at least as large as the rest energy of two electrons, then the photons can interact and create an electron–positron pair. The total cross section for this process is (Gould & Schréder 1967):

\[
\sigma_{\gamma\gamma}(\beta_{\text{cm}}) = \frac{3}{16} \sigma_T \left( 1 - \beta_{\text{cm}}^2 \right) \left[ 3 - \beta_{\text{cm}}^2 \right] \times \ln \left( \frac{1 + \beta_{\text{cm}}}{1 - \beta_{\text{cm}}} \right) - 2 \beta_{\text{cm}} \left( 2 - \beta_{\text{cm}}^2 \right).
\]  

(8)

where \( \sigma_T \) is the Thomson cross section for an electron, \( \beta_{\text{cm}} = \sqrt{1 - \gamma_{\text{cm}}^2} = \sqrt{1 - 2/(\epsilon_1 \epsilon_2 (1 - \mu))} \) is the electron–positron velocity in the COM system in units of the speed of light, and \( \gamma_{\text{cm}} \) is the electron–positron COM frame Lorentz factor. The strength of this collision is characterized by the invariant energy \( \epsilon_{\text{tot}} = E_{\text{tot}}/m_e c^2 \):

\[
\epsilon_{\text{tot}}^2 = 2 \epsilon_1 \epsilon_2 (1 - \mu),
\]  

(9)

where \( \mu = \cos \theta \) is the cosine of the angle \( \theta \) between the interacting photons in the laboratory system. To create an electron–positron pair (each of them with energy \( E_{e^\pm} = \gamma_{\text{cm}} m_e c^2 \)), the total energy has to be

\[
E_{\text{tot}} = 2 \gamma_{\text{cm}} m_e c^2 \text{ or } \epsilon_{\text{tot}} = 2 \gamma_{\text{cm}}.
\]  

(10)

From this and Equation (9) it follows that

\[
\epsilon_{\text{tot}}^2 = 2 \epsilon_1 \epsilon_2 (1 - \mu) = 4 \gamma_{\text{cm}}^2 \Rightarrow \epsilon_1 \epsilon_2 (1 - \mu) = 2 \gamma_{\text{cm}}^2.
\]  

(11)

The highest probability for this interaction lies near the threshold energy, where \( \gamma_{\text{cm}} = 1 \),

\[
\epsilon_1 \epsilon_2 (1 - \mu) = 2.
\]  

(12)

Therefore, the highest probability of interaction of TeV photons with disk photons occurs at energies around

\[
E_{\text{disk}} = \epsilon_{\text{disk}} m_e c^2 \approx \frac{2 (m_e c^2)^2}{E_\gamma (1 - \mu)} \approx \frac{0.5 \text{ eV}}{E_\gamma (1 - \mu)} \sim \text{eV}.
\]  

(13)

3.2. Optical Depth

Determining the absorption probability for a TeV photon (with energy \( \epsilon_\gamma \)) traversing the disk photon field (photon energy \( \epsilon_d \), photon density \( n_d(\epsilon_d) \)) is achieved by calculating the optical depth for this process (Jauch & Rohrlich 1976):

\[
\tau_{\gamma\gamma}(\epsilon_\gamma, l) = \int_0^l d l' \int d \Omega (1 - \mu) \int_{2(\epsilon_\gamma/\epsilon_d)}^\infty d \epsilon_d n_d(\epsilon_d) \sigma_{\gamma\gamma}(\epsilon_\gamma, \epsilon_d, \mu) .
\]  

(14)

TeV radiation with the initial intensity \( I_0 \) is attenuated to the value

\[
I(l, \epsilon_\gamma) = I_0(\epsilon_\gamma) e^{-\tau(\epsilon_\gamma, l)}
\]  

(15)

after the travel distance \( l \) through the absorbing medium. For \( \tau \ll 1 \) there is no strong absorption, and \( I(l) \approx I_0 \), while in the case of \( \tau \gg 1 \) the TeV radiation is attenuated.

3.3. Internal \( \gamma\gamma \) Opacity in LLAGNs

Figure 2 shows the inner regions of an LLAGN with a supermassive black hole located in the point of origin. The SSD lies in the \( x\gamma \) plane, and perpendicular to the disk is the propagating jet along the \( z \)-axis. At a height \( z_0 \) above the black hole, the TeV photon is produced and is able to interact with, one of the SSD photons. We assume the SSD extends from the radius \( r_{\text{min}} = 6 \) to the radius \( r_{\text{max}} = 2000 \), as noted previously.

Every SSD area \( dA = dr \, d\phi \) produces disk photons at the interaction point with spectral photon density

\[
\frac{d n(\epsilon_d)}{dA} = \frac{2H}{\epsilon_d^3} \frac{\epsilon_d^2}{\epsilon_\gamma/\theta - 1}.
\]  

(16)
angles of $\theta < \pi/2$ are more probable. Therefore, TeV photons emitted at low inclinations interact with higher energy disk photons than TeV photons emitted under a larger angle to the jet. Hence, whether an increased $i$ increases or decreases the optical depth depends on the SSD spectrum.

Furthermore, for very small inclinations of $i \lesssim 10^\circ$, relativistic effects must be considered. In such cases the particles inside the jet move with highly relativistic velocities along our line of sight; therefore, the emitted radiation is observed at higher energy and intensity than it had inside the source. Due to this relativistic beaming, blazars can be observed on Earth up to TeV energies even though the emitting particles did not produce such high energetic radiation in their COM system.

### 3.3.2. Black Hole Mass ($m$)

The mass of the black hole greatly affects the physics of the accretion disk, so one can predict intuitively that it will vary the optical depth calculation. The temperature of the flow (and therefore the emitted blackbody spectrum), the scaling of the AGN by the gravitational radius, and the mass accretion rate strongly depend on the black hole mass. On the whole, the term for the optical depth is dominated by the exponential function in its denominator (cf. Equation (20)), so a higher black hole mass implies a lower optical depth.

### 3.3.3. Bolometric Luminosity ($L_{\text{bol}}$) of the Accretion Disk

A decrease/increase of $L_{\text{bol}}$ and an increase/decrease of the square of the black hole mass have a similar effect on the optical depth. Therefore, a higher bolometric luminosity leads to an increase of the optical depth and vice versa.

### 3.4. Comparison with Other Models

The optical depth for GeV photons traveling through a disk photon field has been calculated by Becker & Kafatos (1995) for blazars in general and for 3C 279 in particular. Becker & Kafatos (1995) assumed a two-temperature disk with a hot inner (two-temperature) region extending from $r_{\text{min}} = 6$ to $r_{\text{max}}$, where $30 \lesssim r_{\text{max}} \lesssim 100$, and a cool (single-temperature) region for $r > r_{\text{max}}$. They assumed the X-ray disk emission relevant for TeV $\gamma$-ray absorption to be produced in the hot inner region, where electrons with a nearly constant temperature of $T_e \sim (10^9\text{–}10^{10})$ K upscatter UV radiation from the cool outer region, modeled the emission by a power-law, and scaled it to the observed X-ray luminosity. A similar calculation for M87 has been made by Cheung et al. (2007) and Neronov & Aharonian (2007), who assumed IR target photon sources with linear sizes of $r = 1$ and $r = 25$, respectively. While Cheung et al. (2007) concluded that the core region is transparent of sight; therefore, the emitted radiation is observed at higher energetic radiation in their COM system.

#### 3.3.1. Inclination ($i$)

The inclination of the AGN determines (1) the distance between the TeV photon and the SSD, and therefore the density of disk photons in the trajectory of the TeV photon, and (2) the angle between the scattering photons. An increase in the inclination implies a higher SSD photon density and hence a higher optical depth; however, the influence of the latter effect on optical depth is not as obvious. Since the probability of interaction is highest near the threshold of electron–positron pair production (cf. Equation (12)), the highest probability of interaction between any given TeV photon and a disk photon depends highly on the interaction angle. For low inclinations ($i < 45^\circ$) interaction angles of $\theta > \pi/2$ are rather unlikely, whereas for larger inclinations ($45^\circ < i < 90^\circ$) interaction

\[
\frac{dl_{\text{acc}}}{dA} = \frac{L_{\text{acc}}}{\pi R_G^2 (r_{\text{max}}^2 - r_{\text{min}}^2)}. \tag{17}
\]

Here, $d$ is the distance between the emission site of the SSD photon and the $\gamma$ interaction point (Böttcher & Dermer 2005),

\[
d^2 = r_G^2 + l^2 + z_0^2 + 2 l (z_0 \cdot \cos i - r G \cdot \sin i \cdot \cos \phi), \tag{18}
\]

and

\[
\mu = \frac{l + z_0 \cdot \cos i - r G \cdot \sin i \cdot \cos \phi}{d}, \quad H = z_0 + l \cos i. \tag{19}
\]

Therefore, the optical depth is

\[
\tau_{\gamma\gamma}(\epsilon_\gamma) = \frac{2R_G^2}{c^3} \int_0^\infty dl \int_{r_{\text{min}}}^{r_{\text{max}}} dr \int_0^{2\pi} d\phi \int_0^{\pi/2} d\epsilon_d \frac{\epsilon_d^2}{\sigma_{\gamma\gamma}(\epsilon_\gamma, \epsilon_d, \mu)} \frac{(1 - \mu)H}{d^3} \exp(\epsilon_d/\Theta(r)) - 1. \tag{20}
\]

As can be seen from this expression, the optical depth for the TeV photons depends on the black hole mass, the disk luminosity, and the inclination of the AGN. In the following we discuss the expected influence of these quantities on the optical depth.

#### 3.4.1. Comparison with Other Models

The optical depth for GeV photons traveling through a disk photon field has been calculated by Becker & Kafatos (1995) for blazars in general and for 3C 279 in particular. Becker & Kafatos (1995) assumed a two-temperature disk with a hot inner (two-temperature) region extending from $r_{\text{min}} = 6$ to $r_{\text{max}}$, where $30 \lesssim r_{\text{max}} \lesssim 100$, and a cool (single-temperature) region for $r > r_{\text{max}}$. They assumed the X-ray disk emission relevant for TeV $\gamma$-ray absorption to be produced in the hot inner region, where electrons with a nearly constant temperature of $T_e \sim (10^9\text{–}10^{10})$ K upscatter UV radiation from the cool outer region, modeled the emission by a power-law, and scaled it to the observed X-ray luminosity. A similar calculation for M87 has been made by Cheung et al. (2007) and Neronov & Aharonian (2007), who assumed IR target photon sources with linear sizes of $r = 1$ and $r = 25$, respectively. While Cheung et al. (2007) concluded that the core region is transparent of sight; therefore, the emitted radiation is observed at higher energetic radiation in their COM system.

#### 3.5.3. Comparison with Other Models

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and Figure 3. The Astrophysical Journal (A color version of this figure is available in the online journal.)

The most dominant galaxy in the Virgo Cluster. Although not much larger in its linear extension than the Milky Way, due to its elliptical shape M87 contains many more stars and much more mass than the Galaxy. The central region of this huge radio galaxy, M87, whose counterpart at radio wavelengths is the strong radio source Virgo A, harbors a supermassive black hole with a mass of $m = (3.2-6.4) \times 10^9$. This black hole seems to be what triggers the observed activity of the core region, such as the impressive 2 kpc-long jet. Discovered in 1918 by Curtis, today the jet has been resolved over an array of wavelengths (radio, optical, and X-ray). The polarization of the observed electromagnetic radiation from the jet is typical of synchrotron radiation and supports the conclusion that the jet consists of relativistically moving particles transported from the nucleus to outer regions of the galaxy. The angle between the jet and our line of sight is not well known. While Bicknell & Begelman (1996) quote a jet angle of $i = (30 - 35)\degree$, Ly et al. (2007) assume a larger value of $i = (30 - 45)\degree$ and Acciari et al. (2009) a smaller value of $i = (15 - 25)\degree$. In our calculations, we test the cases $i = 20\degree$, $30\degree$, and $40\degree$. The gravitational radius of the black hole in M87 is

$$R_G = \frac{GM}{c^2} \approx 4.72 \times 10^{14} \left(\frac{m}{3.2 \times 10^9}\right) \text{cm}$$

$$= \begin{cases} 
4.72 \times 10^{14} \text{cm} = 1.53 \times 10^{-4} \text{pc} & \text{for } m = 3.2 \times 10^9 \\
9.44 \times 10^{14} \text{cm} = 3.06 \times 10^{-4} \text{pc} & \text{for } m = 6.4 \times 10^9.
\end{cases}$$

(21)

Although M87 harbors an AGN, the optical emission from the nucleus is rather low. With an observed bolometric luminosity of the nucleus of $L_{\text{bol}} \sim 10^{42} \text{ erg s}^{-1}$ (Reynolds et al. 1996), M87 lies five to six orders of magnitude below the Eddington luminosity and is therefore an LLAGN, as (LL)AGN M87 is classified as a radio galaxy of the FR I type. Furthermore, M87 is a type-2 LINER galaxy, where the nucleus shows narrow emission lines but no broad line emission. M87 has been observed at TeV energies several times (Aharonian et al. 2006; Albert et al. 2008; Acciari et al. 2008, 2009). The highest measured energy of the $\gamma$ rays is $E_{\gamma}^{\text{max}} \approx 20 \text{ TeV}$ (Acciari et al. 2008). The TeV spectrum of 2005 shows variability on timescales of days, which strongly constrains the size of the TeV $\gamma$-emission region to $\sim 55 R_G$ or equivalently $108 R_G$ (Aharonian et al. 2006). Since the jet of M87 is misaligned, the Doppler factor is $\delta \sim 1$ (Giannios et al. 2010), resulting in an extension of the emission region of $\sim 10 R_G$. Moreover, radio observations of M87 from 2007 suggest that the TeV radiation is produced not more than $\sim 0.015$ pc away from the central black hole (Walker et al. 2008), which corresponds to $\sim 100 R_G$, assuming a black hole mass of $m = 3.2 \times 10^9$, and to $\sim 50 R_G$, assuming a black hole mass of $m = 6.4 \times 10^9$.

4. CALCULATION OF THE OPTICAL DEPTH FOR $\gamma\gamma$ INTERACTIONS IN M87 AND Cen A

4.1. M87

4.1.1. Features

M87 (NGC 4486) is a giant elliptical and perhaps the most dominant galaxy in the Virgo Cluster. Although not much larger in its linear extension than the Milky Way, due to its elliptical shape M87 contains many more stars and much more mass than the Galaxy. The central region of this huge radio galaxy, M87, whose counterpart at radio wavelengths is the strong radio source Virgo A, harbors a supermassive black hole with a mass of $m = (3.2-6.4) \times 10^9$. This black hole seems to be what triggers the observed activity of the core region, such as the impressive 2 kpc-long jet. Discovered in 1918 by Curtis, today the jet has been resolved over an array of wavelengths (radio, optical, and X-ray). The polarization of the observed electromagnetic radiation from the jet is typical of synchrotron radiation and supports the conclusion that the jet consists of relativistically moving particles transported from the nucleus to outer regions of the galaxy. The angle between the jet and our line of sight is not well known. While Bicknell & Begelman (1996) quote a jet angle of $i = (30 - 35)\degree$, Ly et al. (2007) assume a larger value of $i = (30 - 45)\degree$ and Acciari et al. (2009) a smaller value of $i = (15 - 25)\degree$. In our calculations, we test the cases $i = 20\degree$, $30\degree$, and $40\degree$. The gravitational radius of the black hole in M87 is

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4.1.2. Results

The optical depth has been calculated for three different inclinations ($i = 20\degree$, $30\degree$, and $40\degree$) and the two possible black hole masses ($m = 3.2 \times 10^9$ and $m = 6.4 \times 10^9$). In all calculations for M87 the bolometric luminosity is assumed to be $L_{\text{bol}} = 10^{42} \text{ erg s}^{-1}$.

In Figure 3 we set $m = 3.2 \times 10^9$ and $i = 20\degree$ and accordingly plot the optical depth $\tau_{\gamma\gamma}$ as a function of the production height $z_0$ of the TeV photon above the black hole in units of the gravitational radius. According to this value of the black hole mass, the TeV photon production should take place within $z_0 \approx 100 R_G$ above the black hole. Using this value for the production height, the optical depth exceeds unity only for photons with energy $E_\gamma \gtrsim 20 \text{ TeV}$. For lower photon energies the optical depth is $\ll 1$, implying no strong absorption. For $E_\gamma \lesssim 20 \text{ TeV}$ photons the optical depth is slightly smaller than one, so despite attenuation there should be no total absorption, and some of these photons should be able to leave the core region. Since the highest energy of the observed TeV photons in M87 is $E_\gamma \approx 20 \text{ TeV}$, our results are consistent with observations. Figure 4 shows the optical depth for the same parameters as Figure 3 with the exception of a higher inclination of $i = 30\degree$.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure3.png}
\caption{Optical depth for TeV radiation produced in M87 with $m = 3.2 \times 10^9$ and $i = 20\degree$. (A color version of this figure is available in the online journal.)}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure4.png}
\caption{Optical depth for TeV radiation produced in M87 with $m = 3.2 \times 10^9$ and $i = 30\degree$. (A color version of this figure is available in the online journal.)}
\end{figure}
For this inclination the optical depth is slightly higher than for $i = 20^\circ$, but the results do not change dramatically. Photons with $E_\gamma < 20$ TeV should be able to escape the production region, and even 20 TeV photons should not be totally absorbed. For an even higher inclination of $i = 40^\circ$, the optical depth reaches unity for just 7 TeV photons and reaches the value of $\approx 2$ for 15 TeV photons (cf. Figure 5), leading to an absorption of nearly 90% of the latter. For more energetic photons the optical depth is even higher and hence the probability for escaping the SSD photon field is very small.

If the mass of the M87 black hole has the higher value of $m = 6.4 \times 10^9$, the central region of M87 becomes less transparent for TeV photons, as can be seen in Figures 6–8 for inclinations of $i = 20^\circ$, $30^\circ$, and $40^\circ$, respectively. In this case the emission region should lie within the innermost $\sim 50 R_G$. For $i = 20^\circ$ photons up to $E_\gamma \sim 15$ TeV should escape their production region. An increase in inclination to $i = 30^\circ$ (cf. Figure 7) resp. $i = 40^\circ$ (cf. Figure 8) leads to an increase in the optical depth to a value of $\approx 2.5$ resp. $>3$ for $E_\gamma \approx 20$ TeV. Despite attenuation, it is still possible that for $i \lesssim 30^\circ$, some of these photons will not be absorbed.

To illustrate the absorption probability of the estimated production region, we plot the optical depth as a function of the TeV photon energy at the maximum possible production distance of $z_0 = 100 R_G$ for $m = 3.2 \times 10^9$ (cf. Figure 5) and $z_0 = 50 R_G$ for $m = 6.4 \times 10^9$ (cf. Figure 10). It can be seen that for $i = 20^\circ$, the optical depth for photons up to 20 TeV lies in the order of one. Even if the optical depth lies above one for the higher inclinations of $i = 30^\circ$ and $40^\circ$, there should be no total absorption, and a part of radiation with 20 TeV should be able to escape.

4.2. Cen A

4.2.1. Features

Cen A, the fifth-brightest system visible to earthbound observers, lies in the constellation Centaurus of the southern sky.
It is a nearby, lenticular radio galaxy at a distance of 3.8 Mpc (Harris et al. 2009). It is the closest recent merger, a trait that could increase $M$ and therefore, assuming the AGN is accretion-powered, contribute to very high energy (VHE; $E > 100$ GeV) radiation production (Martini & Ho 2004). Cen A is a very interesting case study since it is one of the few VHE sources that is not a blazar (Sreekumar et al. 1999) and was the first interesting case study since it is one of the few VHE sources.

**Figure 9.** Optical depth for TeV radiation produced in M87 for $z_0 = 100 R_G$. (A color version of this figure is available in the online journal.)

**Figure 10.** Optical depth for TeV radiation produced in M87 for $z_0 = 50 R_G$. (A color version of this figure is available in the online journal.)

(1998) quote an inclination of the inner jet of $i = (50 - 80)^\circ$. Based on this estimate we calculate the optical depth for the two inclinations $i = 50^\circ$ and $i = 80^\circ$. The spectrum of Cen A extends from radio wavelengths up to $\gamma$ rays with $E_\gamma \approx 10$ TeV, with which this paper is concerned. The SED of Cen A is double peaked, with one peak at $\sim 150$ keV due to synchrotron emission and a second peak at $\sim 1$ MeV (Steinle 2010). The gravitational radius of the Cen A black hole for the mass approximation used in this paper is

$$R_G \approx 7.375 \times 10^{12} \text{ cm} = 2.390 \times 10^{-6} \text{ pc}. \quad (22)$$

**Figure 11.** Optical depth for TeV radiation produced in Cen A with inclination $i = 80^\circ$. (A color version of this figure is available in the online journal.)

4.2.2. Results

Since we want to investigate if the observed $\gamma$ photons from Cen A can be produced in a similar way to the TeV photons from M87, we concentrate on the innermost 100 $R_G$ resp. 50 $R_G$, depending on the correct value of the M87 black hole mass. As can be seen from Figure 11, the optical depth for an inclination of $i = 50^\circ$ and photon energies between 0.25 and 30 TeV lies far above unity. An increase in inclination to $i = 80^\circ$ leads to an even stronger absorption of TeV photons (cf. Figure 12), so $\gamma$ radiation from 0.1 TeV up to (at least) 30 TeV should be completely absorbed. Figures 13 and 14 give the optical depth as a function of the photon energy for both inclinations at fixed production heights of 100 $R_G$ and 50 $R_G$, respectively. It can be seen that the optical depth is much larger than one over a wide range of TeV energies. Moreover, for both inclinations the maximum absorption occurs for photons with $E_\gamma \approx 1$ TeV. After this maximum the optical depth declines with increasing TeV photon energy but is still well above unity. Interestingly, this maximum value is more pronounced for $i = 80^\circ$ than for $i = 50^\circ$.

5. DISCUSSION

The results for Cen A are very different than for M87. Most notably, in Cen A the absorption of the TeV photons by disk photons is much higher than in M87. While the photon field produced by an SSD can be transparent for TeV photons produced in M87, the SSD photons in Cen A lead to a total absorption of photons between 0.25 and 30 TeV. Furthermore, for an emission distance of 100 $R_G$ resp. 50 $R_G$ the optical depth of...
Here, the influence of the term (mass, bolometric disk luminosity, and inclination of the object.

The results for the optical depth in M87 are consistent with observations: the SSD photon field can be transparent for TeV photons. Only for high inclinations would TeV photons produced inside M87 undergo a notable attenuation. Even in this extreme case a portion of them should still be able to escape. Moreover, the assumed disk luminosity is only an upper limit and can be one (or more) order(s) of magnitude lower, leading to a smaller optical depth, which favors our model. Since the influence of a change in the disk luminosity can be illustrated by a change in the mass of the black hole (cf. Section 3.3.3), we can simulate a decrease of the disk luminosity by an increase of the black hole mass. A change of m = 3.2 × 10^9 to m = 6.4 × 10^9 has a similar effect on the optical depth as a decrease of the disk luminosity to 75% of the original assumed value. This variable replacement simulation produces results that are consistent with the estimation of the disk luminosity. On the whole, we can say that the absorption of TeV photons produced around ∼100 R_G resp. ∼50 R_G above the black hole is so small that the observed γ radiation could come from the black hole vicinity.

On the other hand, it is not possible to observe TeV γ radiation produced within the innermost ∼100 R_G of Cen A. Thus, either the location of the production site is different than in M87 or a
low-luminosity SSD does not explain the accretion in LLAGNs appropriately.

In this paper, we assume a relatively low accretion rate. In a model by Blandford & Payne (1982), it is proposed that AGN jets are disk-driven. This model was, for instance, used in Bicknell & Wagner (2011) to estimate the optical depth for the blazar PKS 2155–304. Applying this model to M87 would predict a more luminous disk than assumed here, which would then be in contradiction to the detection of TeV emission within 100 $R_G$ of the central black hole of M87. Thus, the detection of TeV emission close to the black hole of M87 challenges the disk-driven jet model and favors other models such as the Blandford–Znajek mechanism (Blandford & Znajek 1977).

6. CONCLUSIONS AND OUTLOOK

We calculated the absorption probability for TeV photons produced in the vicinity of the supermassive black holes in LLAGNs M87 and Cen A by photons produced by the accretion flows around each black hole. Our model assumed that the accretion flow can be described by a low-luminosity SSD, where the luminosity is set to the observed (low) luminosities in both objects. The calculations show that the results are very different between the two LLAGNs. While for M87 the SSD photon field can be translucent for transversing TeV photons up to $\sim 15$ TeV produced not more than 100 $R_G$ (for a black hole mass of $m = 3.2 \times 10^9$) resp. 50 $R_G$ (for $m = 6.4 \times 10^9$) away from the black hole, TeV photons produced near the black hole in Cen A are absorbed heavily. This implies that the core region in M87 is detectable at TeV energies, whereas Cen A is not. Since both objects have been observed at TeV energies, our calculations imply either that the production mechanism and production site of the TeV photons are different between the sources or that the assumption of a low-luminosity SSD is not valid for accretion flows in LLAGNs. Our next step will be to carry out the calculations of the optical depth assuming different accretion models. An accretion disk model that does not depend so strongly on parameters like black hole mass and disk luminosity could produce similar results for both M87 and Cen A, thereby admitting TeV $\gamma$ production near the black holes in each galaxy. On the contrary, black hole mass and disk luminosity are essential parameters for most accretion models, so it is questionable whether they are in fact more insensitive to these two variables.

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