VHE γ-ray Emission from Passive Supermassive Black Holes: Constraints for NGC 1399

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ABSTRACT

Very high energy (VHE; >100 GeV) γ-rays are expected to be emitted from the vicinity of super-massive black holes (SMBH), irrespective of their activity state. In the magnetosphere of rotating SMBH, efficient acceleration of charged particles can take place through various processes. These particles could reach energies up to $E \sim 10^{19}$eV. VHE γ-ray emission from these particles is then feasible via leptonic or hadronic processes. Therefore passive systems, where the lack of a strong photon field allows the VHE γ-rays to escape, are expected to be detected by Cherenkov telescopes. We present results from recent VHE experiments on the passive SMBH in the nearby elliptical galaxy NGC 1399. No γ-ray signal has been found, neither by the H.E.S.S. experiment nor in the Fermi data analyzed here. We discuss possible implications for the physical characteristics of the system. We conclude that in a scenario where particles are accelerated in vacuum gaps in the magnetosphere, only a fraction ~ 0.3 of the gap is available for particle acceleration, indicating that the system is unlikely to be able to accelerate protons up to $E \sim 10^{19}$eV.

Subject headings: gamma rays, galaxies: individual (NGC 1399)

1. Introduction

Spheroidal systems (such as elliptical galaxies, lenticular galaxies, and early-type spiral galaxies with massive bulges) are commonly believed to host super-massive black holes with masses in the range $M_{\rm BH} = (10^6 - 10^9)\ M_\odot$ in their central region (e.g., Richstone et al. 1998; Ferrarese & Ford 2005). Many SMBH are *active* and give rise to emission over a wide range of frequencies. Some have been detected from radio to high energy γ-rays ($\sim$ 1 GeV). The SMBH is essential for the production and stability of relativistic jets. In many objects the inner, compact jets emit VHE γ-ray emission through various leptonic and/or hadronic processes. In blazar-type objects, where the jet is pointing towards the observer, VHE γ-ray emission is frequently observed (e.g., Hinton & Hofmann 2009; Weekes 2009). Often, this can be successfully modeled by non-thermal electrons upscattering either their own synchrotron radiation or upscattering an external photon field, although a hadronic origin (e.g., Aharonian 2000; Mücke & Protheroe 2001) cannot be excluded. In these cases the gamma-ray emission is released through the jets which in turn are powered by the SMBH.

VHE emission may also be indirectly related to SMBH independent of any electromagnetic activity. The presence of a SMBH steepens the po-

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tential well and hence the density profile of dark matter in the central regions of galaxies. The rate of annihilation of Dark Matter particles (e.g. Berezinsky et al. 1994) will thus be increased resulting in enhanced emission of the gamma-rays generated in the annihilation.

Several models for the direct production of γ-ray emission in the vicinity of SMBH have been proposed (see e.g., Aharonian et al. 1984; Mastichiadis & Protheroe 1990; Slane & Wagh 1990; Boldt & Gosh 1999; Levinson 2000; Neronov et al. 2004; Neronov & Aharonian 2007; Rieger & Aharonian 2008; Istomin & Sol 2009; Osmanov 2010; Levinson & Rieger 2011). Possibly, some of these mechanisms could also be responsible for acceleration of cosmic-rays to energies $E \sim 10^{19}$ eV and beyond. In order to avoid attenuation on circumnuclear fields, VHE photons could escape only if the SMBH does not produce too much low-energy radiation. The SMBH would have to be passive at low energies, i.e. most of the radiative losses would have to occur at high energies. In all cases a large mass of the central object is an important characteristic for generating a high VHE flux.

Correlations involving the SMBH masses and properties of their host galaxies have been investigated by many authors. In particular $M_{\rm BH}$ is found to be linked to the central stellar velocity dispersion (e.g., Gebhardt et al. 2000) or to the mass of the host galaxy bulge (e.g., Magorrian et al. 1998). These observational scaling laws, in addition to confirming the ubiquity of SMBH, have suggested that their activity is tightly linked to the evolution of their host galaxies (e.g. Ferrarese & Ford 2005). During the early stages of galaxy evolution SMBH accrete matter at high rates and are observed as bright QSO (Quasi-Stellar Objects). Even if such systems generate VHE gamma-rays, the dense photon fields associated with the Quasar phase would pair-absorb the VHE radiation. The average radiative output at low photon energies (e.g., in the optical band) decays from redshift $z > 3$ to $z = 0$ by almost 2 orders of magnitude. The majority of SMBH in the local universe are hosted in systems of low accretion rate and are therefore not embedded in dense radiation fields. In *passive* systems (i.e., SMBH hosted in nuclei without bright signatures of broad-band activity and very low luminosity in longer wavelengths). If VHE gamma-rays, if generated, can escape from the nuclear region without suffering from strong absorption via photon-photon pair absorption.

While the detection of VHE gamma-rays in blazar-type systems is facilitated by the superluminal motion (the apparent luminosity is boosted and the optical depth related to photon-photon absorption is reduced, see Schlickeiser (1996)), this is not the case for non-blazar systems. Hence, proximity and low luminosity in the IR/optical domain increase the possibility of a detection in the VHE band. Observations of passive systems can hence contribute to our understanding of the physics and properties of galactic nuclei. In addition they might give us an insight on Ultra High Energy Cosmic Ray (UHECR; $E > 4 \times 10^{18}$ eV) sources.

Here we present GeV limits and discuss observations of the passive SMBH in the core of NGC 1399, the central galaxy of the Fornax cluster, that were conducted with the H.E.S.S. Cherenkov telescope array (Pedaletti et al. 2007) and discuss its implications for gap-type particle acceleration and emission models.

2. The test object NGC 1399

The most massive black holes can be found in the large ellipticals at the center of galaxy groups and clusters. The nearest SMBH reside in the giant radio galaxy Centaurus A and in the central region of the Virgo cluster, especially in M87. These galactic nuclei have already been detected in VHE observations by, e.g., the H.E.S.S. experiment. The detected VHE emission might well be associated with features of their powerful inner jets (Aharonian et al. 2006, 2009a). Also SgrA*, in the galactic center, would be an obvious good candidate, despite its low black hole mass of $M_{\rm BH} \sim 4 \times 10^6 M_\odot$, thanks to its proximity. However, it is very close to other established Galactic gamma-ray emitting sources. Hence, these galaxies do no represent the best candidates for the studies described above.

The most nearby cluster visible from the southern hemisphere is the Fornax cluster. It was observed by H.E.S.S. (Pedaletti et al. 2007). The giant elliptical galaxy NGC 1399 is located in the central region of the Fornax cluster at a distance of 20.3 Mpc. A SMBH of $M_{\rm BH} = 5.1 \times 10^8 M_\odot$ resides in its central region (Gebhardt et al. 2007). The nucleus of this galaxy is well known for its low emissivity at all wavelengths, e.g., see O'Connell et al. (2005) and references therein.

The galaxy shows low-power antiparallel jets, with a luminosity of $\sim 10^{39}$erg s^{-1} between 10^7 Hz and 10^{10} Hz (Killeen et al. 1988). The outflows are confined in projection within the optical extension of the galaxy. The jets are initially transonic, then decelerate in the inter-stellar medium and end in lobe-like diffuse structure at ~ 9 kpc from the center (Killeen et al. 1988). X-ray images reveal cavities suggesting that the radio-emitting plasma is producing shocks in the hot X-ray emitting gas (Shurkin et al. 2008). The estimated jet power is $L_{\rm jet} \simeq 10^{42}$ erg s^{-1}.

Given the suggested low photon density at low energies, the high mass of the central SMBH, the absence of luminous jets and proximity of the galaxy, NGC 1399 emerges as the best candidate for a study of passive SMBH at very high energies.

3. Estimate of VHE luminosity from Passive SMBH

The expected luminosity and energy range of VHE γ-ray emission from magnetospheric processes in SMBH can be estimated as follows:

If the central black hole is spinning and accretes matter that carries magnetic flux, it will develop a rotating magnetosphere. This magnetosphere may be similar to those of neutron stars. Ambient charged particles can be accelerated to very high energies in the magnetosphere and radiative cooling will result in high energy radiation. A full treatment of the acceleration and of the resultant VHE γ-ray spectra requires detailed modelling of charged particle trajectories and interactions, as shown in, e.g., Neronov & Aharonian (2007).

It is however possible to estimate the expected VHE γ-ray luminosity based on some simple arguments:
The maximum available potential due to field line rotation is $\Delta V \simeq (a/2)\, r_H B$ (Thorne, Price & Macdonald 1986), where $a = J/J_{\rm max}$ (with $J_{\rm max} = GM^2/c$ the maximum angular momentum) is the black hole spin parameter, r_H denotes the radius of the event horizon and B the strength of the ordered magnetic field component. Provided a gap of size h exists, the effective potential for particle acceleration is (Levinson 2000)

$$\Delta V_e \simeq \Delta V (h/r_H)^2 \,. \qquad (1)$$

If particles are accelerated along the magnetic field lines, the primary radiative loss is curvature emission (note that photo-meson production is highly inefficient in low ambient radiation fields):

$$P_{\rm curv} = \frac{2}{3}\frac{q^2 c}{R_{\rm curv}^2}\gamma^4, \qquad (2)$$

with q the particle charge, $R_{\rm curv}$ the curvature radius and γ the Lorentz factor of the particle. Balancing acceleration in the gap by losses implies

$$q\ \Delta V_e = P_{curv} h/c \,. \qquad (3)$$

The expected emission spectrum from curvature radiation then extends up to VHE energies and the energy of the curvature photons does not depend on the mass of the emitting particle, i.e.,

$$E_{\gamma,\rm curv} = \frac{3\hbar c \gamma^3}{2R_{\rm curv}} \simeq 4.8\ a^{3/4} M_9^{1/2} B_4^{3/4} \times \left(\frac{h}{r_H}\right)^{3/4} \left(\frac{R_{\rm curv}}{r_g}\right)^{1/2} {\rm TeV}, \qquad (4)$$

where $M_9 = M_{\rm BH}/10^9 M_\odot$, $B_4 = B/10^4$ G, and $r_g = 1.5\times 10^{14} M_9$ cm is the gravitational radius. Hence, for realistic magnetic field strengths ($B >> 1$G), curvature emission is expected to peak in the Fermi and/or H.E.S.S. energy range. In the case of curvature-limited losses, an accelerated proton could reach (provided the potential is large enough) ultra-high energies of

$$E_{\rm p,curv} \simeq 2\times 10^{19} a^{1/4} M_9^{1/2} B_4^{1/4} \left(\frac{h R_{\rm curv}^2}{r_H^3}\right)^{1/4} {\rm eV}. \qquad (5)$$

In terms of the Goldreich-Julian number density $n_{\rm GJ} = \Omega B \cos\theta/(2\pi c q)$ (Goldreich & Julian 1969), the maximum VHE power of the gap for $(n_e/n_{\rm GJ}) \leq 1$ is given by

$$L_\gamma = \int n_e\ P_{\rm curv}\ dV \simeq \eta \left(\frac{n_e}{n_{\rm GJ}}\right) \frac{\Omega_H B}{2\pi q c}\ (q\Delta V_e)\ c r_H^2 \,, \qquad (6)$$

where $\Omega = a\ (c/2r_H)$ is the angular frequency of the black hole and $\eta \lesssim 1$ is a geometrical factor, and where the volume element has been approximated by $dV \simeq \pi h r_H^2$. Using Eq. (1) one finally obtains

$$L_\gamma \simeq \frac{\eta}{8} a^2 \left(\frac{n_e}{n_{\rm GJ}}\right) B^2 \left(\frac{h}{r_g}\right)^2 r_g^2 c$$
$$\simeq 8 \times 10^{45} \eta\, a^2 \left(\frac{n_e}{n_{\rm GJ}}\right) B_4^2\ M_9^2 \left(\frac{h}{r_g}\right)^2 \ {\rm erg\ s^{-1}}\,. \quad (7)$$

Note that for $n_e \sim n_{\rm GJ}$, L_γ is roughly a fraction $(h/r_g)^2$ of the maximum Blandford-Znajek jet power $L_{\rm BZ}$.

In the case of NGC 1399, the black hole mass is $M_9 \simeq 0.5$. The spin parameter a depends on the formation history of the black hole. If its growth is dominated by gas accretion and the accreted mass is of the order of the initial mass of the black hole, then it is possible to reach spins approaching $a \simeq 1$ (see e.g., Volonteri et al. 2007). This is believed to be true for the SMBH hosted in elliptical galaxies in the nearby universe, but might be violated if chaotic accretion occurs (King et al. 2008).
A lower limit on the magnetic field ($B \sim 10$ G) in the inner disk might be obtained by assuming equipartition with the observed radiation fields. However, as the radiative output is very low, the disk is unlikely to be of the standard-type. Thus, a more realistic value is given by equipartition with the accretion energy density, i.e., $B^2/8\pi = 1/2\rho(r_0)v_r^2(r_0)$, where ρ is the mass density and v_r is the radial infall velocity. The plasma density at the Schwarzschild radius is $\rho(r_s) \simeq 3 \times 10^{-16}$ g/cm^3, when extrapolated from the value at the accretion radius (Pellegrini 2005), assuming a free-fall profile. With $v_r(r_s) = c/\sqrt{2}$, this would suggest a field strength $B(r_s) \sim 1300$ G. A similar value is obtained if the inner disk would be of the ADAF/radiatively inefficient accretion flow-type (Narayan et al. 1998). In fact, due to its low overall luminosity NGC 1399 has become a prominent ADAF candidate source (e.g., Narayan 2002). One thus expects the accretion rate in NGC 1399 to be close to $\dot{m} \simeq 10^{-4}\dot{m}_{\rm Edd}$ (cf. Loewenstein et al. 2001; Narayan 2002) and the inner disk magnetic field to be close to $B_4 \simeq 0.1$. Note that these values are compatible with the requirement that the jet power ($L_{\rm jet} \simeq 10^{42}$ erg/s) is ultimately provided by a Blandford-Znajek-type process.

The above suggests that the VHE luminosity in NGC 1399 could be as high as

$$L_\gamma \simeq 10^{43} a^2 \left(\frac{n_e}{n_{\rm GJ}}\right) \left(\frac{h}{r_g}\right)^2 \quad {\rm erg\ s^{-1}}\,, \quad (8)$$

and hence high enough to be detectable by a VHE telescope array like the H.E.S.S. experiment.

4. Radiation Fields of NGC 1399

In constructing the spectral energy distribution (SED) of NGC 1399, observations were selected in order to consider only its nuclear region. To achieve this, at any wavelength only the observations taken with the smallest aperture reported in the literature were included (see Fig. 1). In most energy bands the smallest apertures exceed the projected linear scales considered above by several orders of magnitude. The measurements are hence to be considered as upper limits of the flux emitted from the vicinity of the SMBH.

4.1. Gamma-ray observations

In the VHE band NGC 1399 has been observed with the H.E.S.S. instrument (Pedaletti et al. 2007, 2008). The observations did not result in a detection of an unresolved source and an upper limit (99.9%) on the isotropic VHE γ-ray luminosity of

$$L_\gamma(> 200{\rm GeV}) < 9.6 \times 10^{40}\ {\rm erg\ s^{-1}}. \quad (9)$$

has been derived (Pedaletti et al. 2007). Extended emission would not be expected given that the angular resolution of H.E.S.S. exceeds the angular size of the host galaxy (∼7 arcmin, Jarrett et al. (2003)). The given upper limit assumes a spectral index of $\Gamma = -2.6$ for the photon spectrum.

While the H.E.S.S. upper limits refers to the integrated flux above 200 GeV, lower-energy gamma-ray emission can be studied using data obtained with the LAT instrument onboard Fermi. The data-set consists of 23 months of public Fermi data (04 August 2008 - 07 July 2010). The data set has been analyzed with the public software released by the Fermi Collaboration (ScienceTools-v9r15p2-fssc-20090808). Only events between 200 MeV and 100 GeV were considered and standard selection cuts for point-sources (as outlined in the Cicerone Fermi manual) were applied. The spectral analysis has been performed through an unbinned likelihood fit (gtlike tool in the public software). First a likelihood fit on the entire data range was made with a power law functional form $dN/dE = N_0(E/E_{\rm p})^{-\Gamma}$, where N_0 is the normalization at the pivot energy $E_{\rm p}$ and Γ is the spectral index. The object is not significant on the whole energy range (2.4σ). The background has been modelled as being composed from the sources in the first year Fermi Catalog and from two diffuse backgrounds. The diffuse backgrounds (both galactic and extragalactic) have been modelled from the ones supplied along with the public software. Upper limits have been derived at a 95% level for the three energy bins that are of most interest for the models investigated in this paper. The assumed spectral index for the upper limits is $\Gamma = 2$. The bins are 1-3GeV, 3-10GeV, 10-100GeV. Results are shown in Fig. 1.

4.2. Potential Absorption of VHE γ-rays

The absence of gamma-ray signals might, in principle, result from an annihilation of gamma-ray emission along the line-of-sight towards the observer. In the case of NGC 1399, however, any such absorption is unlikley: The cross section $\sigma_{\gamma\gamma}$ of this process depends on the product of the energies of the colliding photons. For VHE photons, the most effective interaction at the peak of the cross section is with background photons of energy

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

The optical depth resulting from this absorption, in a source of luminosity L and radius R, is given by

$$\tau\,(E,R) \simeq \frac{L\,(\epsilon)\,\sigma_{\gamma\gamma}}{4\pi R\epsilon c}. \qquad (10)$$

For NGC 1399, the visibility of a 200 GeV photon would require $L\,(\epsilon = 5\mathrm{eV}) < 4\times 10^{41}(R/100\ r_s)$ erg/s. This condition is satisfied (Fig. 1) since the flux measured within a small aperture is very low. If, instead, more energetic hard photons are considered, $E > 1$TeV, the constraints are placed by photons in the near-infrared regime ($\epsilon = 1$eV). In the absence of measurements with small apertures, (weak) constraints can only be derived from the fairly high near-infrared flux obtained with an aperture which is likely to be dominated by starlight. This would set a lower limit on the size of the emitting region of $R \sim 3\times 10^3 r_{\rm S}$ in order to allow VHE photons to escape.

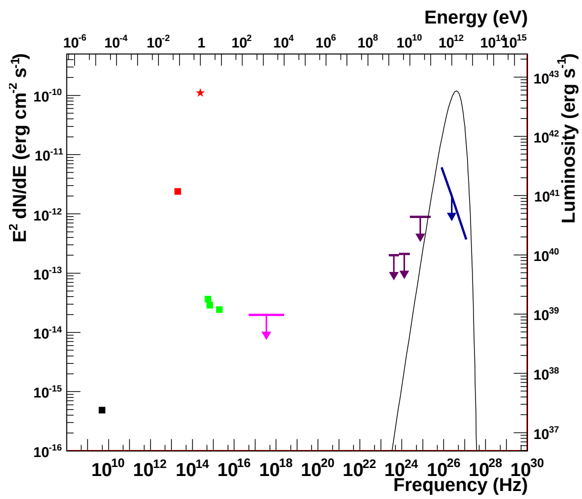

Fig. 1.— The SED of NGC 1399. All archival data are for the core region. The archival points are: VLA radio data (black; Sadler et al. (1989); core component <0.4"); 15μm ISO IR data (red square; Temi et al. (2005); 5" aperture, no host subtraction); 2MASS J-band data (red star; Skrutskie et al. (2006); 4" aperture, no host subtraction); HST optical data (green; O'Connell et al. (2005); 0.2" aperture), and Chandra X-ray upper limit (solid line; Loewenstein et al. (2001); 3" aperture). The purple upper limits (95%) are the Fermi data presented in this paper. The blue line is the H.E.S.S. spectrum 2σ upper limit (Pedaletti et al. 2007). The thin black line represents a toy curvature spectrum, i.e., a delta-function population with energy as in eq. (4) and with maximum luminosity from eq. (8) assuming a fully-developed gap.

An additional photon field that might possibly interact with VHE γ-rays produced near the SMBH is provided by synchrotron radiation emitted by pairs (Stawarz & Kirk 2007). However, the critical luminosity for this to occur is well above the estimated VHE output, so that this process is unlikely to limit the escape of VHE photons.

Lastly, absorption on the diffuse extragalactic background light does not cause any significant attenuation due to the proximity of NGC 1399.

We conclude that photon-photon pair absorption is expected to be low throughout the gamma-ray range considered here and should not significantly affect any potential VHE emission emitted from the vicinity of the SMBH of NGC 1399.

5. Discussion and Conclusion

If efficient gap-type particle acceleration and curvature emission occurs in NGC 1399, VHE γ-ray emission should have been detected by Fermi and/or H.E.S.S. According to eq. (8), the non-detection of NGC 1399 thus either suggests that (i) the strength of the ordered, magnetospheric field component is only a small fraction (≤ 0.1) of the disk magnetic field value estimated above, (ii) on average only a small fraction of the gap ($[h/r_g]^2 \ll 1$) is available for particle acceleration and/or (iii) the charge density n_e in the vicinity of the black hole is much smaller than the Goldreich-Julian density, i.e. $(n_e/n_{\rm GJ}) \ll 1$.

Option (i) would be incompatible with the jet power $L_{\rm jet} \simeq 10^{42}$ erg/s (Shurkin et al. 2008) being provided by a Blandford-Znajek-type process. Option (ii) would require that the charge density around the black hole exceeds the Goldreich-Julian density $n_{\rm GJ} \simeq 2 \times 10^{-3}(B/10^3{\rm G})$ cm^{-3}. This could be the case if efficient pair production occurs near to the black hole (e.g., Moscibrodzka et al. 2011; Levinson & Rieger 2011). The accretion rate for NGC 1399 inferred above (cf. also Narayan 2002) seems indeed close to the critical value $\dot{m}_c \simeq 2 \times 10^{-4}$ where annihilation of MeV photons in a two-temperature ADAF could lead to the injection of seed charges with density $n_e \geq n_{\rm GJ}$ (Levinson & Rieger 2011). If the accretion rate would be sufficiently high, i.e., $\dot{m} > \dot{m}_c$ ensuring $n_e > n_{\rm GJ}$, a substantial part of the gap is expected to be screened, suggesting $(h/r_g)^2 \ll 1$. This could make the anticipated VHE output, eq. (8), consistent with the VHE upper limits derived above. However, it would also imply that the available potential, eq. (1), is reduced down to a level where UHE proton acceleration will no longer be possible. On the other hand, if the accretion would be such that $\dot{m} < \dot{m}_c$, implying $n_e < n_{\rm GJ}$ (option [iii]), fully-developed gaps ($h \sim r_g$) may exist. This could again make L_γ consistent with the observationally inferred VHE upper limits. However, an additional plasma source would then be needed to establish the force-free outflow believed to be present on larger scales. One plausible scenario relates to pair cascade formation in charge-starved magnetospheric regions due to the absorption of inverse Compton up-scattered photons (Levinson & Rieger 2011). When applied to NGC 1399, the estimated multiplicity appears indeed sufficiently high ($M \gtrsim 10^3$) to allow the pair density to approach the Goldreich-Julian density. As the optical depth for pair production across the gap is larger than unity even if the gap is not fully restored (i.e., for $h < r_g$), cascade formation can occur on scales $< r_g$ and thereby limit the potential gap size. Detailed modelling would be required to self-consistently calculate the gap size and associated VHE emission. On the other hand, the estimated VHE γ-ray output L_γ is roughly a fraction $(h/r_g)^2$ of the maximum Blandford-Znajek jet power $L_{\rm BZ}$. Assuming $L_{\rm BZ} = L_{\rm jet}$, the VHE flux upper limits imply that $(h/r_g)^2 \lesssim 0.1$, again yielding conditions not conducive for efficient proton acceleration beyond 4×10^{18} eV.

Nearby, passive supermassive black holes are often believed to be prime candidates for magnetospheric, gap-type particle acceleration and emission scenarios. The non-detection of VHE gamma-ray emission in NGC 1399 by current VHE instruments now suggests that this object is unlikely to be an efficient UHECR proton accelerator.

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