Very High Energy Emission in the Vicinity of Supermassive Black Holes:

Stacking Analysis of Elliptical Galaxies with H.E.S.S. and its implications for Ultra High Energy Cosmic Rays

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***Abstract*. Very high energy (VHE; >100 GeV) γ-rays are expected to be produced in the vicinity of super-massive black holes (SMBH), irrespective of their activity state. In the magnetosphere of spinning SMBH efficient acceleration of particles can take place through various processes. These particles may reach energies of the order of $E \sim 10^{19}$eV. SMBH have hence been speculated to be accelerators of UHECRs, to be identified by their VHE gamma radiation. Predicted gamma-ray fluxes are presented and constraints on physical parameters are derived. Although the predicted fluxes exceed the sensitivity of present generation of Cherenkov telescopes, no emission was detected from the test candidate NGC 1399 with ∼20 hrs of H.E.S.S. observation. No short-term variability is expected from such systems. Therefore a stacking analysis, allowing a dramatic increase in livetime, is pursued. Different samples of galaxies are analyzed and stacked. Results and conclusions are presented.**

***Keywords*: stacking, SMBH, gamma**

I. Introduction

Super-massive black holes with masses in the range $M_{\rm BH} = 10^6 - 10^9 M_\odot$ are ubiquitously found in the central region of spheroidal systems (such as elliptical galaxies, lenticular galaxies, and early-type spiral galaxies with massive bulges).

Blazar-type Active Galactic Nuclei (AGN) are established emitter of VHE γ-rays [1]. In addition, VHE emission in the vicinity of SMBH in non-blazar galactic nuclei is also expected. A signal in the VHE domain is expected from passive super-massive Black Holes and both leptonic and hadronic models have been proposed in the previous years ([2], [3], [4], [5]).

The Pierre Auger Collaboration (PAC) claimed a correlation between the arrival direction of UHECR and a class of object whose spatial distribution follows that of local AGN [6]. A direct connection between AGN and UHECR is controversial up to date and it has to be kept in mind that nothing is known about UHECR sources, but the fact that they have to satisfy the so-called "Hillas criterion": the particles have to be confined in the acceleration region [7]. Galactic nuclei are considered among the possibilities because of the expected high magnetic field in their compact nuclear region; several authors explored already this possibility (see e.g. [8]). If these systems are indeed the sources of UHECR, there will be VHE γ-ray emission associated, the detection of which would uniquely pinpoint the source.

Furthermore, SMBH could be associated with VHE emission also in the case of radiogalaxies. Radiogalaxies are established VHE emitters since M87 [9] and CenA [10] were detected using Cherenkov telescopes. Interestingly, the radiogalaxy M87 also shows fast variability in the VHE domain of the order of few days [9], constraining the size of a non-relativistically moving emitting region down to few Schwarzschild radii ($R_{\rm S}$).

Local SMBH in non-blazar AGN can therefore be regarded as a prime candidate for VHE emission.

The same sample used by the PAC was investigated by the H.E.S.S. Collaboration, leading to no detection ([11]). Here we use an opposite approach, starting not from the position relative to the cosmic ray, but from a physically motivated sample.

II. Selection Criteria

A. The Test Candidate

The galaxy nearby large elliptical galaxy NGC 1399 was observed with the H.E.S.S. system of Cherenkov telescopes. The galaxy was chosen for the high mass of its SMBH and for the low emission detected in the NIR ($\sim$ 1 eV) as well as for its southern position. The data were reduced using the standard analysis tools and selection cuts (standard cuts, [12]) and the Reflected-Region method ([13]) for the estimation of the background.

No significant excess (-26 events, -1.1σ) is detected from NGC 1399 ($\sim$ 20 hrs observation). The upper limit (99% confidence level; [14]) on the integral flux above threshold is $I\,(>260\mathrm{GeV}) < 1.1\times10^{-12}$ cm^{-2}s^{-1}.

B. The Samples

If there is no variability, a dramatic increment in the livetime of the observations is needed to probe lower fluxes. Therefore a stacking analysis is performed using serendipitous data acquired by H.E.S.S. in other extragalactic fields. The stacking technique is a standard procedure used to study the statically averaged properties of a sample of object whose individual emission would otherwise be below detection threshold. The first requirement is a high mass of the central black hole in the corresponding galaxy. Therefore large ellipticals are selected from published catalogs.

It is necessary to avoid absorption of a potential emission, therefore these objects have to be in the nearby universe, in order to avoid EBL absorption, and to be not surrounded by a strong photon field. Three fields are presented here: the Virgo Cluster field, the Fornax Cluster field and the Coma Cluster field. They are all rich in large and low emitting ellipticals.

III. VHE Data Analysis

The data were reduced using the standard analysis tools and selection cuts ([12], standard cuts). The Reflected-Region method ([13]) was used for the estimation of the background. Regions of known VHE γ-ray emission and regions containing the galaxies in the sample are not considered in the estimation of the background. The significance of an excess for the whole sample is calculated following [15], knowing the on number of counts $\mathrm{N_{ON}}$ and off number of counts $\mathrm{N_{OFF}}$ and the parameter α (the ratio between exposure in the ON and OFF region). The number counts $\mathrm{N_{ON}}$ are extracted at the galaxy position and the size of the extraction region is $0.11°$. In the case of galaxies being closer than $0.2°$ to each other, only the first encountered galaxy is considered. In the case of no significant excess an upper limit is then calculated using the approach described in [14], assuming a photon index of Γ=2.6. Stacked values are derived for the entire sample.

IV. The cluster fields: Virgo, Fornax and Coma

A. The Binggeli sample in the Virgo cluster

The Virgo cluster field centered on M87 was observed for 54 hours (only 4 telescope data until 2008), leading to a total stacked exposure of $\sim$ 400 hours. The distribution of the 16 large ellipticals galaxies in the field is shown in Fig. 1, 9 of which are independent in position. These galaxies have been selected from the Virgo Cluster Catalog ([16]). Unfortunately no excess has been found at the position of any of the galaxies considered and the distribution of significances of the sample is consistent with an empty field even though the sample is limited and present an apparent shift to negative significances (cf. Fig. 1). Checks on the systematics are ongoing. Upper limits for the whole sample of 9 galaxies are given in Table I.

B. The Pierini sample in the Coma cluster

The Coma cluster field was observed for 7.3 hours (only 4 telescope data until 2008), leading to a total stacked exposure of $\sim$ 100 hours. The distribution of the 37 large ellipticals galaxies in the field is shown in Fig. 2, 16 of which are independent in position. These galaxies have been selected from the Galaxies morphology Catalog ([17]).

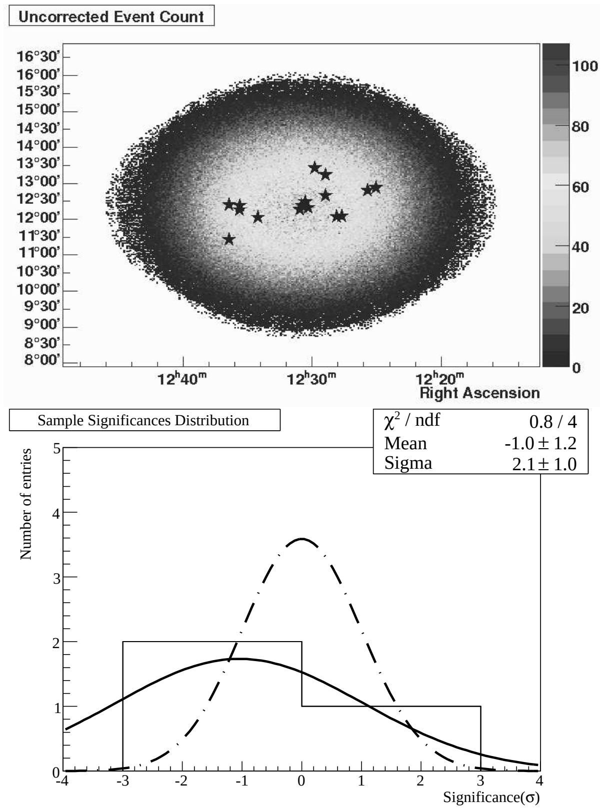

Fig. 1. *Top:* Position of the galaxies of the Binggeli catalog in the Virgo field. Only independent galaxies have been considered. *Bottom:* Distribution of significances for the Virgo sample. The solid curve is a gaussian fit to the histogram, while the doth-dashed curve is the expected distribution of significances for an empty field, for comparison.

None of the galaxies considered presented a significant excess and the distribution of significances of the sample is consistent with an empty field (cf. Fig. 2). Therefore upper limits for the whole sample of 16 galaxies are given in Table II.

C. The Ferguson sample in the Fornax cluster

The Fornax cluster field was observed for 15 hours (only 4 telescope data until 2008), leading to a total stacked exposure of $\sim$ 70 hours. The distribution of the 10 large ellipticals galaxies in the field is shown in Fig. 3, 8 of which are independent in position. These galaxies have been selected from the Galaxies in Fornax Cluster Catalog ([18]). None of the galaxies considered presented a significant excess and the distribution of significances of the sample is consistent with an empty field (cf. Fig. 3). Therefore upper limits for the whole sample of 8 galaxies are given in Table III.

N_{ON}	N_{OFF}	α (α_{range})	EXCESS	SIGNIFICANCE	LIVETIME hours	THRESHOLD TeV	UPPER LIMIT cm^{-2} s^{-1} (% C.U.)
22126	578850	0.04 (0.02÷0.06)	-311	-2.0σ	398.3	0.32	1.2×10^{-13} (0.1)

TABLE I
STACKING RESULTS FOR THE VIRGO SAMPLE. GIVEN ARE ALSO THE RANGE OF ALPHA IN THE SAMPLE. THE PERCENTAGE OF THE CRAB FLUX (C.U) IS CALCULATED ABOVE THE SAME THRESHOLD.

N_{ON}	N_{OFF}	α (α_{range})	EXCESS	SIGNIFICANCE	LIVETIME hours	THRESHOLD TeV	UPPER LIMIT cm^{-2} s^{-1} (% C.U.)
4350	59864	0.07 (0.05÷0.15)	-9.9	-0.1σ	104.1	0.67	2.8×10^{-13} (0.7)

TABLE II
STACKING RESULTS FOR THE COMA SAMPLE. QUANTITIES AS IN TABLE I.

N_{ON}	N_{OFF}	α (α_{range})	EXCESS	SIGNIFICANCE	LIVETIME hours	THRESHOLD TeV	UPPER LIMIT cm^{-2} s^{-1} (% C.U.)
3856	94683	0.04 (0.02÷0.07)	-36	-0.6σ	74.7	0.3	6.5×10^{-13} (0.5)

TABLE III
STACKING RESULTS FOR THE FORNAX SAMPLE. QUANTITIES AS IN TABLE I.

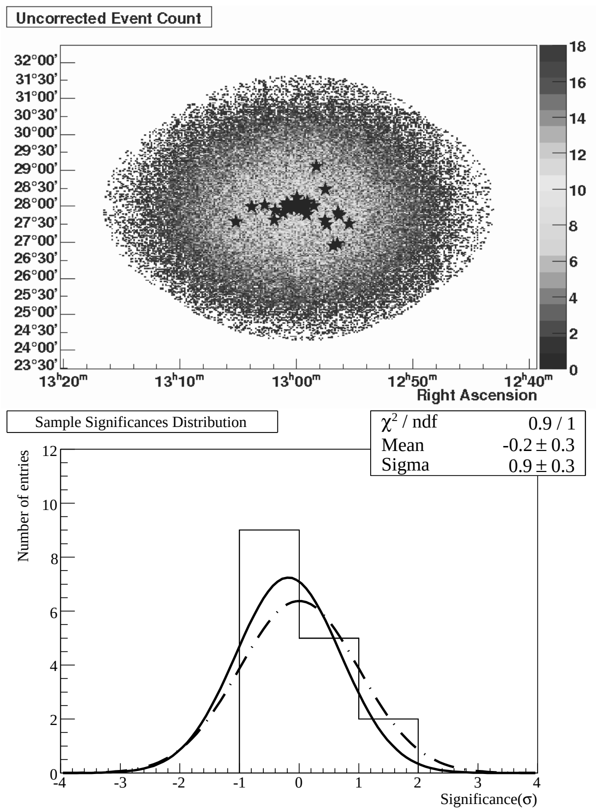

Fig. 2. *Top:* Position of the galaxies of the Pierini catalog in the Coma field. Only independent galaxies have been considered. *Bottom:* Distribution of significances for the Coma sample, curves as in Fig. 1.

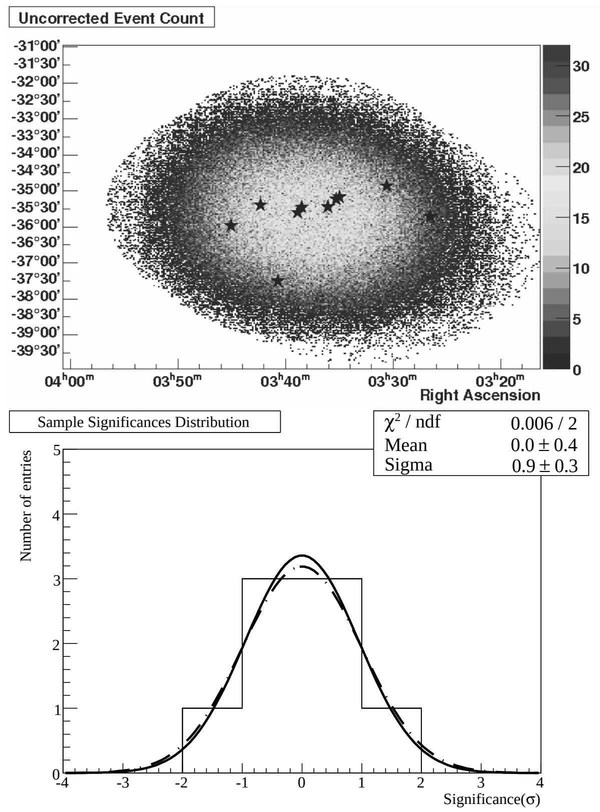

Fig. 3. *Top:* Position of the galaxies of the Pierini catalog in the Fornax field. Only independent galaxies have been considered. *Bottom:* Distribution of significances for the Fornax sample, curves as in Fig. 1

V. IMPLICATIONS FOR UHECR

Recently there have been claims by the Auger collaboration of correlation between Ultra High Energy Cosmic Rays arrival direction and AGN spatial distribution ([6], on the same sample in VHE γ-ray see [11]). This is suggesting AGN as the sources of these events. If this conjecture is correct we would expect VHE γ-ray emission associated with these objects. The stacking analysis presented here can therefore be used to constrain this hypothesis. Knowing the stacked γ-ray luminosity allows to estimate the typical luminosity of a UHECR emitter and the relative CR density.

If therefore one assumes that the large ellipticals of the samples investigated here could be related to

UHECR acceleration, one would need to conclude that the associate γ-ray luminosity (in the energy range $E = (0.7 - 100)$ TeV) is small, of the order of

$$L_\gamma \sim 1.41 \times 10^{41} \left(\frac{D}{50\mathrm{Mpc}}\right)^2 \text{ erg s}^{-1}$$

, where D is the distance of the putative emitter.

This estimation comes from the stacking of the three samples, weighted for the distance of every field, leading to an upper limit of $I\,(> 0.7 \text{ TeV}) < 1.7 \times 10^{-13}$ cm^{-2}s^{-1}.

VI. Conclusions

VHE emission is expected from the vicinity of SMBH present at the center of spheroidal galaxies. Data acquired by the H.E.S.S. system of telescopes in the Virgo, Coma and Fornax cluster field have been used in order to detect such signal. No excess has been found at the position of any of the galaxies considered. Morover a stacking analysis has been performed on the entire sample, resulting in no excess. Assuming that the three samples are homogeneous a part from the distance D to the observer, we can stack all the three fields and obtain a final upper limit of $I\,(> 0.7 \text{ TeV}) < 1.7 \times 10^{-13}$ cm^{-2}s^{-1} for 33 galaxies. This is consistent with the scaling of sensitivity with time [12].

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