Observation of Radio Galaxies and Clusters of Galaxies with VERITAS

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***Abstract*. Radio galaxies are the only non-blazar extragalactic objects detected in the VHE ($E >$ 100 GeV) band. These objects enable the investigation of the main substructures of the AGN, in particular the core, the jet and its interaction with the intergalactic environment. Clusters of galaxies, instead, have not been detected by γ-ray observatories. These objects are collections of up to thousands of galaxies and are the densest large-scale structures in the universe. Galaxy clusters consist of up to 85% dark matter, that could reveal its presence through self-annihilation and VHE γ-ray emission. The observation of non-thermal diffuse radio emission in galaxy clusters suggests the presence of accelerated particles and high magnetic fields that can also produce VHE emission. Results from the VERTIAS observations of radio galaxies and galaxy clusters will be presented.**

***Keywords*: VERITAS extra-galactic TeV**

I. Introduction

Radio galaxies are currently the only non-blazar extragalactic objects detected at very high energies (VHE: $E > 100$ GeV). In the unified model of Active Galactic Nuclei (AGN), the various classifications of AGN are strongly dependent on the orientation of the galaxy toward the observer's line of sight. Blazars are AGN which contain relativistic plasma jets aligned within a few degrees to our line of sight, causing the observed radiation to be highly Doppler-boosted. For radio galaxies this is generally not the case due to wider jet viewing angles, making these objects more challenging to detect at VHE. Nevertheless, the discoveries of VHE emission from the radio galaxy M 87 by the HEGRA collaboration [1], and more recently by VERITAS [2], as well as the discovery of NGC 5128 (Centaurus A) at VHE by the HESS collaboration [3] have opened new possibilities into investigating non-thermal processes in the large-scale structures of AGN.

Radio galaxies are preferentially located in clusters when compared to other galaxies of comparable mass [4]. Their powerful jets energize the intra-cluster medium through termination shocks accompanied by particle acceleration and magnetic field amplification. Large scale AGN jets and clusters of galaxies are believed to be potential accelerators of cosmic rays [5], and are therefore of particular interest for the cosmic-ray community. According to the Fanroff & Riley (FR) classification, radio galaxies can be classified into two main families [6]. In FR I objects, the radio emission peaks in the central core and diminishes along the jets, while in FR II objects the outer part of the jets (lobes) are brighter in the radio than the central core of the galaxy. FR I radio galaxies are in general found at low redshifts and have a typical radio power at 178 MHz less than 1025 W Hz^{-1} sr^{-1}. Above this radio power nearly all radio galaxies are FR II objects. Further distinction between the two classes can be found in their discrete spectral properties, i.e. in their excitation emission lines [7]. An interesting aspect of this classification is the large number of shared features between FR I type radio galaxies and BL-Lac type blazars. A possible unification of the two sub-classes of AGN is suggested [8], in which FR I radio-galaxies are BL-Lac objects observed at larger jet viewing angles. Evidence of synchrotron emission at radio to X-ray energies from the extended structures and the core of radio-galaxies is well explained by relativistic electrons moving in a beamed relativistic jet [9]. A possible mechanism for HE-VHE radiation is the Synchrotron-Self-Compton (SSC) process [10], where the optical and UV synchrotron photons are up-scattered by the same relativistic electrons in the jet. Predictions have long been established for the γ-ray emission [11] and frequency dependent variability [12]. Besides leptonic scenarios, several models also consider a hadronic origin for the non-thermal emission in jets. Accelerated protons can initiate electromagnetic cascades or photomeson processes [13], or directly emit synchrotron radiation with consequent X-ray emission and Inverse Compton (IC) up-scattering of photons by secondary electrons [14].

Modelling the jet emission with an homogeneus SSC mechanism may imply typical Lorentz factors particularly high $\Gamma > 50$ with consequent high Doppler factors and small beaming angles $\theta \simeq 1^\circ$ [15]. This is in conflict with the unification scheme according to which FR I radio galaxies and BL-Lac objects are the same kind of object observed at different viewing angle. Moreover, these high values for the Doppler factor are in disagreement with the small apparent velocities observed in the sub-parsec region of the TeV BL-Lac objects Mrk 421 and Mrk 501 [16]. These considerations suggest a decelerating flow in the jet with a consequent gradient in the Lorentz factor of the accelerated particles and in average smaller values for it [17]. The first consequence, in fact, is that the fast upstream particles "see" the downstream produced seed photons with an amplified energy density because of the Doppler boost due to the relative Lorentz factor $\Gamma_{\rm rel}$. The IC process is then favoured requiring less extreme values for the Lorentz factor and allowing larger values for the beaming angle. In a similar way, a spine-sheath structure in the jet consisting of a faster internal spine surrounded by a slower layer has been also suggested for the broadband non-thermal emission of VHE BL-Lac objects [18]. This model is supported by radio maps which show a limb brightened morphology [19] and can explain the HE-VHE emission observed in radio galaxies at larger angles ($\theta_{\rm layer} = 1/\Gamma_{\rm layer} \simeq 20°$). The model well describes the emission in both radio galaxies and "classical" BL-Lac objects. Observation of the VHE component from radio galaxies is therefore signicant for the multi-structured jet modeling, as it can be related to the external lower structure of the jet itself.

Galaxy clusters are also potentially of strong interest to TeV observations. Galaxy clusters are collections of hundreds to thousands of galaxies and are the densest large-scale structure in the universe. They are also the largest ($\sim 10^{15}$ solar mass, ~10 Mpc diameter) gravitationally-bound objects. However, the velocities of individual galaxies within a cluster often exceed the cluster's escape velocity, implying the presence of either an an additional attractive force besides gravity or an additional invisible mass component (i.e. dark matter). Galaxy clusters also contain large amounts of very hot ($\sim 10^8$ K) X-ray-emitting intergalactic gas. Although the gas is about twice as massive as the galaxies, it is also not enough to contain the galaxies in the cluster. Assuming this gas is in hydrostatic equilibrium with the cluster's gravitational field, the total cluster mass is calculated to be several times larger than the mass of the galaxies and the hot gas. The mass of a typical cluster consists of ~85% dark matter, 5% galaxies, and ~10% intergalactic gas. Given the large mass and high-density of dark matter, galaxy clusters may be detectable in VHE gamma-rays via the self-annihilation of dark matter particles. Non-thermal diffuse radio emission, e.g. radio halos and relics, is also observed in galaxy clusters and is direct evidence that galaxy clusters are also sites of relativistic particle acceleration and high magnetic fields that can produce VHE γ-rays [23][24][25][26]. Galaxy clusters are one of the few prominent candidate classes of γ-ray sources which have not yet been detected by satellite- (e.g. the Fermi γ-ray Space Telescope) or ground-based γ-ray observatories (e.g. VERITAS). The significance of such detection for the theoretical understanding of non-thermal phenomena in cosmology cannot be overstated. For example it could be used to measure the mass of a potential dark matter particle, as well as give indications of its distribution on cosmological scales. Such observations could also completely unfold the morphology of non-thermal particles and fields in a cluster.

II. VERITAS Observations

VERITAS (the very energetic radiation imaging telescope array system) is an array of four 12 m aperture imaging atmospheric Cherenkov telescopes (IACT) [20] [21], operating at the Whipple Observatory in southern Arizona. By indirect detection of showers produced by γ-rays interacting in the atmosphere, VERITAS can achieve a very large effective area, e.g. 20000 m^2 at 300 GeV. The showers are reconstructed from the images of the Cherenkov light they produce, as recorded in the $3.5°$ field of view cameras of at least two of the four telescopes. At zenith, the energy threshold for spectral reconstruction is about 150 GeV, and the energy resolution for individual γ-rays is 15-20%. The 68% containment radius for reconstructed γ-ray directions decreases with increasing energy, ranging from $0.1°$ to $0.2°$. VERITAS can detect a γ-ray source with 5% of the Crab Nebula flux in 2.5 hours.

In this work we present three sources observed by VERITAS, two radio galaxies and a cluster of galaxies.

A. NGC 1275

NGC 1275 (Perseus A, 3C 84) is a radio galaxy located in the center of the Perseus cluster and is one of the most unusual early-type galaxies in the nearby universe (z = 0.018). Its radio emission is core dominated, but it presents also strong emission lines. In addition, the emission line system shows a double structure, a high velocity and a low velocity system. The puzzling nature of NGC 1275 is still under debate and makes it difficult to definitely classify it in a standard AGN sub-class. Its spectral energy distribution (SED) extends from radio to γ-rays, although at VHE only upper limits have been presented so far [30]. A source coincident with NGC 1275 at high confidence has been recently detected at high energy (HE) γ-rays by Fermi [28] reporting an average flux between August and December 2008 described by a simple power law in the energy range from 100 MeV to 25 GeV with a photon spectral index -2.17. The source was already present in the Fermi bright sources list [27] that reported a preliminary average integral flux and a preliminary average spectral index. Fermi result is compatible with a detection by VERITAS by mean of a simple extrapolation.

VERITAS observed the source between January and February 2009 at a zenith angle range between $15°$ and $30°$. All data taken under bad weather or with technical problems have been excluded. A total amount of 8 hours has remained for analysis purposes.

B. 3C 111

The radio galaxy 3C 111 has been suggested as a counterpart for the unidentified EGRET γ-ray source 3EG J0416+3650 [29]. Due to the large uncertainty on the EGRET γ-ray source position, 12 X-ray and radio sources can be found inside the $3\,\sigma$ confinement error box. Nevertheless, the radio galaxy 3C 111 is among the 12 sources the only object that is known to emit

TABLE I: Observed sources. The five columns represent: the source name; the source type (RG = radio galaxy; CoG = cluster of galaxies); the period of observation; the zenith angle range; the total observation time in hours; the flux upper limit in Crab units (tbp = to be presented at the conference).

Source	Type	Period	ZA	observation time	flux U.L.
NGC 1275	RG	01/09 – 02/09	$15° - 30°$	8 h	1%
3C 111	RG	10/08 – 12/08	$15° - 30°$	11 h	tbp
Coma cluster	CoG	03/08 – 05/08	$9° - 20°$	19 h	3%

both in radio and X-rays. The $5.3\,\sigma$ detection reported by EGRET with an average flux above 100 MeV of 1.3×10^{-7} cm^{-2} s^{-1} with a simple power-law photon index -2.59 makes this γ-ray source interesting for an instrument like VERITAS. If detected, given its higher angular resolution, VERITAS would be able to definitely identify the γ-ray emitter with the underlying object.

Data have been taken during fall 2008 at a zenith angle range between $15°$ and $30°$. All data taken under bad weather conditions or with technical problems have been discharged. Finally, a total amount of about 11 hours has remained for analysis purposes.

C. Coma Cluster

Observation of galaxy clusters is done unavoidly during the observation of many radio galaxies. This is the case for NGC 1275 and M 87 where the Perseus and Virgo clusters respectively are observed during the radio galaxy observation. However, a dedicated study on the cluster itself has been done only on the Coma cluster up to now. The Coma cluster is a nearby cluster of galaxies which is well studied at all wavelengths [31] [32]. It is at a distance of 100 Mpc (z=0.023) and has a mass of $2 \times 10^{15}\,M_{\odot}$. Its X-ray and radio features suggest the presence of accelerated electrons in the inter-galactic medium emitting non-thermal radiation. Beside relativistic electrons, there might be a population of highly energetic protons. Both high energy electrons and protons are known to be able to produce VHE photons. A detection by a sensitive instrument like VERITAS would considerably improve our understanding of the acceleration processes of the intra-cluster medium.

Data have been recorded between March and May 2008. As for the other sources, data taken with technical problems or under non-optimal weather conditions have been excluded. A total amount of 19 hours spanning a zenith-angle range of $9°$ to $20°$ have been used for analysis purposes.

III. Data Analysis

The data have been analyzed using the VERITAS standard VEGAS analysis package, with background rejection cuts optimized on a Crab-like spectrum. The direction and impact point of each shower is reconstructed from the positions and orientations of the shower images in the cameras. Candidate γ-ray showers are required to have images with length and width consistent with expectations from simulated showers of the corresponding size and distance from each telescope, allowing a large fraction of the background proton showers to be rejected. Proton showers typically have longer and wider images.

Analysis on the radio galaxy 3C 111 is still in progress and will be presented at the conference. A preliminary analysis on NGC 1275 reveals no signal and the excess events distribution over the sky map of the VERITAS FoV is compatible with a Gaussian distribution of average 0. An integral upper limit is calculated at the 99% confidence level using the method described by [22] assuming a Poissonian background and a 20% uncertainty on the efficiency. A preliminary result above 250 GeV yields an integral upper limit of 2.58×10^{-12} erg cm^{-2} s^{-1}.

The analysis of the Coma cluster showed no evidence for point-source emission within the field of view and a preliminary upper limit of $\sim$ 3% of the Crab flux is given for a moderately extended region centered on the core [33].

All results are summarized in Table I.

IV. Conclusions

During the last observation cycle VERITAS observed two radio galaxies, NGC 1275 and 3C 111. In addition, VERITAS observed the Coma cluster of galaxies. All observations resulted in a null detection. A preliminary analysis on the radio galaxy NGC 1275 and on the Coma cluster of galaxies resulted in upper limits and a final result will be reported at the conference. Analysis on the 3C 111 radio galaxy is still in progress and will be reported at the conference.

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