VERITAS Observations of Radio Galaxies

N. Galante, for the VERITAS Collaboration
Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA

Radio galaxies are the only non-blazar AGN 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. VERITAS observations have included exposures on a number of radio galaxies. Recently, the discovery by Fermi of GeV emission from the radio galaxy NGC 1275 triggered VERITAS observations of this source. Results from the VERITAS observations of radio galaxies and future plans are presented.

1. INTRODUCTION

The search for γ-rays from radio galaxies is important for the understanding of the dynamics and structure of jets in active galactic nuclei (AGN). Even though radio galaxies are AGN with jets, their jet is not oriented toward the observer and therefore the radiation produced by the jet is not Doppler-boosted towards higher energies and luminosities, making them more challenging to detect in the very high energy (VHE: E > 100 GeV) regime. The discovery of VHE γ-rays from the radio galaxy M 87 by the HEGRA collaboration [1], detected later by VERITAS [2], and from NGC 5128 (Centaurus A) by the HESS collaboration [3] has shown that non-blazar AGN can produce very energetic photons from non-thermal processes.

Radio galaxies are classified into two main families based on the morphology of their radio emission [4], whether it is core dominated (FR I) or lobe dominated (FR II), with differences in the radio energetics and in the discrete spectral properties [5]. The large number of features that FR I radio galaxies share with BL Lac type blazars suggests a possible unification between the two sub-classes of AGN, in which FR I radio galaxies are BL Lac objects observed at larger jet viewing angles [6].

Evidence for synchrotron emission in radio to X-ray energies from both the extended structures and the core is well explained by relativistic particles moving in a beamed relativistic jet [7]. A commonly considered mechanism for HE-VHE (HE: high energy, 100 MeV < E < 100 GeV) radiation is the synchrotron-self-Compton (SSC) process [8], where the optical and UV synchrotron photons are up-scattered by the same relativistic electrons in the jet. Predictions concerning the inverse Compton (IC) component have long been established for the γ-ray emission [9] and frequency-dependent variability [10]. Besides leptonic scenarios, several models also consider a hadronic origin for non-thermal emission in jets. Accelerated protons can initiate electromagnetic cascades or photomeson processes [11], or directly emit synchrotron radiation [12, 13] and produce γ-rays through collisions with ambient gas [14, 15].

Modelling the blazar jet emission with a homogeneous SSC mechanism may imply particularly high Lorentz factors, Γ > 50, with consequent high Doppler factors and small beaming angles θ ≃ 1° [16]. Such a small beaming angle 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 angles. 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 [17]. These considerations suggest a more complicated geometry, for example a decelerating flow in the jet with a consequent gradient in the Lorentz factor of the accelerated particles and a smaller average Γ [18]. As a result of this gradient, the fast upstream particles interact with the downstream seed photons with an amplified energy density, because of the Doppler boost due to the relative Lorentz factor Γrel. The IC process then requires less extreme values for the Lorentz factor and allows larger values for the beaming angle. In a similar way, a jet spine-sheath structure 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 [19]. An inhomogeneous jet with a slow component may explain the HE-VHE emission observed in radio galaxies at larger angles (θlayer = 1/Γlayer ∼ 20°). Observation of the VHE component from radio galaxies is therefore significant for the AGN jet modeling. In this work an overview of the observations of radio galaxies by VERITAS is presented.

2. OBSERVATIONS

2.1. NGC 1275

NGC 1275 (Perseus A, 3C 84) is a nearby (z = 0.018) radio galaxy located in the center of the Perseus cluster. It is one of the most unusual early-type galaxies in the nearby Universe. Its radio emission is core dominated, but it also has strong emission lines. In addition, the emission line system shows...
a double structure, corresponding to both a high-velocity and a low-velocity system. The puzzling nature of NGC 1275 makes it difficult to definitively classify it in a standard AGN sub-class. It has been recently detected in high energy $\gamma$-rays by Fermi [20], with a flux between 100 MeV and 25 GeV described by a power law with photon index $-2.17$.

VERITAS observed the source between January and February 2009 for a total amount of good-quality data of 7.8 hours. Additional Fermi-LAT data simultaneous to the VERITAS observational campaign have been analyzed, reporting a lower flux by a factor of 1.37 and a similar photon index $-2.15$ compared to the 2008 published Fermi-LAT spectrum. A differential upper limit at the decorrelation energy of 340 GeV is calculated and is incompatible ($P(\chi^2) = 3.6 \times 10^{-6}$) with an extrapolation of the Fermi measured spectrum (fig. 1). A deviation from the power-law regime is therefore a likely explanation. Three possible models have been considered: a power law with an exponential cutoff, with a sub-exponential cutoff respectively, and a double power law. The estimated cutoff energies are

$$E_{\text{exp}} \approx 20 \text{ GeV} \quad \text{and} \quad E_{\text{subexp}} \approx 120 \text{ GeV}$$

in the case of an exponential and sub-exponential cutoff respectively, and $E_b \approx 16 \text{ GeV}$ in the case of a broken power law. For details of the analysis see [35].

The result of the observation is rather interesting. It shows, for the first time, that there can be a deviation from the power-law regime in a radio-galaxy spectrum at an energy of the order of 100 GeV or lower. This is the first example of a scientific result obtained by VERITAS in conjunction with Fermi.

### 2.2. 3C 111

3C 111 is a near ($z = 0.0485$) FR-II radio source whose central component is coincident with a broad-line Seyfert 1 galaxy. The radio morphology shows a double-lobe/single-jet structure with the jet emerging at an angle of $\sim 63^\circ$ [22]. The central component is variable on time scales of a few months. Hints of superluminal behaviour are observed [23, 24]. The radio spectrum is flat with an index of $-0.3$ between 6 cm and 80 cm [25]. Strong emission is detected in the mm and infra-red bands too [26, 27]. In the X-ray band, 3C 111 has been detected by many instruments with a long-term variability within a factor of 5 [28]. The broadband spectral energy distribution (SED) shows a double-peaked structure (see fig. 2 right) with typical blazar-like features and the source has been suggested to be a misaligned blazar [29].

The radio galaxy 3C 111 has been suggested as a counterpart for the unidentified EGRET $\gamma$-ray source 3EG J0416+3650 [30]. This is a $\gamma$-ray source located at $\ell = 162.2^\circ$ $b = 9.97^\circ$, i.e. close to the galactic plane, with a 95% confidence error radius of 38.2'. However, since the optical position of the radio galaxy is outside the 99% confidence level contour of the EGRET $\gamma$-ray source ($\sim 76$ arcmin separation), the probability of the association between the two sources is rather low ($P = 0.019$) [31].

However, additional hint supporting the association between 3C 111 and 3EG J0416+3650 can be found in [29]. Due to the large uncertainty on the EGRET $\gamma$-ray source position, 12 X-ray and radio sources can be found inside the 3$\sigma$ confinement error box (see fig. 2 left). Nevertheless, the radio galaxy 3C 111 is among the 12 sources the only object that is known to emit both in radio and X-rays, with the hardest and strongest X-ray flux.

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

VERITAS observed the radio galaxy 3C 111 during fall 2008 at a zenith angle range between 15$^\circ$ and 30$^\circ$. 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. No VHE signal has been detected, a 99% confidence level upper limit above the analysis threshold of 300 GeV has been derived. The result is reported in table II.

### 2.3. M 87

M 87 is a radio galaxy located in the Virgo cluster at a distance of 16 Mpc [32]. Originally detected at TeV energies at 4 sigma significance by HEGRA [1], and later detected above 5 sigma by HESS [33], it has been later detected also by VERITAS [2]. The substructures of the jet are well studied in the X-ray, optical and radio wavelengths [34], with an estimated angle of $20^\circ \sim 40^\circ$ toward the line of sight. Its proximity and spatially-resolved structures at all wavelengths make M 87 a unique laboratory to study the jet physics, especially for the related mechanisms to the VHE $\gamma$-ray production. Given its peculiarity, an extensive VERITAS-led coordinated multi-wavelength observational campaign, involving all major imaging air Cherenkov telescopes (IACT) currently operating, VERITAS, MAGIC and HESS, and other X-ray and radio instruments, namely Chandra and VLBA, has been performed in 2008. Correlation studies of this broad-band observational campaign resulted in the
Figure 1: NGC 1275 spectrum and the VERITAS upper limit on the differential flux at the decorrelation energy 338 GeV (standard cuts). The solid circles with error bars are the measurement by the Fermi γ-ray space telescope during the VERITAS observation campaign. Empty circles with error bars are the measurement presented in [20] from the energy-binned analysis. The solid line is the power-law fit to the Fermi data. The dashed line is the extrapolation of the power-law. The dotted-dashed line is the fit of a power law with an exponential cutoff at 18 GeV. The double-dotted dashed line is the fit of a power law with a sub-exponential cutoff at 120 GeV and the dotted line is the smooth broken power law fit of a break energy at 16 GeV. All fits are done on the Fermi data analyzed in this work (solid circles).

Figure 2: (left) The BeppoSAX-MECS (2-10 keV) image superimposed on the EGRET γ-ray probability contours at 50%, 68%, 95%, 99% and 99.9% confidence level. Crosses: ROSAT faint sources; diamonds: ESS sources; plusses: NVSS radio sources; squares: GBT radio sources. (right) Broadband SED of 3C 111. Open circles: radio; open squares: mm-band; filled triangles: IRAS; filled circles: optical; open pentagons: infra red (2MASS); filled squares: BeppoSAX; open triangles: EGRET; arrows: 2σ upper limits by COMPTEL. Both figures from [29].

3. CONCLUSIONS

VERITAS observed three radio galaxies during the last two years. Only in one case, the already-known γ-ray emitter M 87, the observation resulted in a VHE γ-ray emission detection. Given the peculiarity of the identification of the region responsible for the origin of the γ-ray emission [35]. A dedicated contribution has been therefore presented at this Symposium [36].
Table I VERITAS upper limits on the observed radio galaxies VHE flux. The five columns represent: the source name; the period of observation; the energy threshold for that specific analysis; the total observation time of good quality data; the 99% confidence level integral flux upper limit in cm$^{-2}$ s$^{-1}$.

| Source   | Obs. Period | $E_{th}$ | $T_{obs}$ | Flux U.L. |
|----------|-------------|----------|-----------|-----------|
| 3C 111   | 10/08 - 12/08 | 300 GeV | 11 hr     | $3.5 \times 10^{-12}$ |
| NGC 1275 | 01/09 - 02/09 | 190 GeV | 8 hr      | $5.11 \times 10^{-12}$ |
| M 87     |             |          |           | See [36]   |

radio galaxy M 87, that makes it a unique laboratory for the study of the blazar astrophysics, in particular for the jet-related processes, VERITAS coordinated an observational campaign together with the major IACT partners and other X-ray and radio partners. The broad-band observational campaign resulted in the discovery of the region responsible of the $\gamma$-ray emission.

The observation of other two radio galaxies, 3C 111 and NGC 1275, did not result in a VHE detection. However, a joint work together with Fermi-LAT on NGC 1275 resulted in the identification of a variation from the power-law regime at an energy of the order of $\approx 100$ GeV or lower, a previously unknown feature of radio-galaxies $\gamma$-ray component.

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