The VERITAS Extragalactic Science Program

N. Galante  
*Harvard-Smithsonian Center for Astrophysics*  
for the VERITAS Collaboration  
http://veritas.sao.arizona.edu

VERITAS is an array of four 12-m diameter imaging atmospheric-Cherenkov telescopes located in southern Arizona. Its aim is to study the very high energy (VHE; \( E > 100 \text{ GeV} \)) \( \gamma \)-ray emission from astrophysical objects. The study of Active Galactic Nuclei (AGN) is intensively pursued through the VERITAS blazar key science project, but also through the large MWL observational campaigns on radio galaxies. The successful VERITAS AGN research program has provided insights to the jet inner structures and started a more detailed classification of blazars. Moreover, the synergy between Fermi and VERITAS on blazar observations resulted in important constraints on the extragalactic background light (EBL) through \( \gamma \)-ray observations, and on the cataloguing of the several AGN sub-classes. VERITAS discovered also the first extragalactic non-AGN \( \gamma \)-ray source. The discovery of gamma-ray emission from the starburst galaxy M 82 by VERITAS and Fermi provides important clues on possible mechanisms for accelerating cosmic rays.

I. INTRODUCTION

The largest population of VHE-detected \( \gamma \)-ray sources are blazars, a sub-category of AGNs in which the ultra-relativistic jet, produced by the accretion of matter around a super-massive black hole, is aligned within a few degrees to the observer’s line of sight \([1]\). The most commonly accepted model to account for the \( \gamma \)-ray emission from the jet of AGNs is inverse-Compton scattering of the synchrotron photons produced by shock-accelerated electrons and positrons within the jet itself \([2]\). In these aligned sources relativistic beaming substantially boosts the apparent flux. Non-blazar AGNs are typically oriented at larger angles from the observer’s line of sight, becoming much more challenging. However, the misalignment enables imaging of the jet’s structure, crucial to identifying the emission regions and probing models of the acceleration mechanism. Given the typical angular resolution of the order of several arcminutes in \( \gamma \)-ray instruments, jet substructures are not resolved in the \( \gamma \)-ray energy band, but they are in other wavelengths. Correlation studies through coordinated multi-wavelength (MWL) observational campaigns on radio galaxies are a viable strategy to investigate the physical processes at work in the substructures of the jet. A dedicated contribution about radio galaxies is presented in these proceedings.

The advantage of observing radio galaxies is that it is possible to study also the rich environment in which they are typically located. It has been seen that radio galaxies are preferentially located in cluster of galaxies \([3]\). Their powerful jets energize the intra-cluster medium through the termination shocks accompanied by particle acceleration and magnetic field amplification. Large scale AGN jets and cluster of galaxies are believed to be potential accelerator for cosmic rays \([4]\), therefore the modeling of the dynamics of both populations is of particular interest for the cosmic-ray community.

Beside AGN-related environments, starburst galaxies are also good candidates as ultra-high energy cosmic rays accelerators. The active regions of starburst galaxies have a star formation rate about 10 times larger than the rate in normal galaxies of similar mass, with a consequent higher rate of novae and supernovae. The cosmic rays produced in the formation, life, and death of their massive stars are expected to eventually produce diffuse gamma-ray emission via their interactions with interstellar gas and radiation.

Finally, globular clusters are the closest extragalactic structures whose physics is interesting to the \( \gamma \)-ray community. They can host hundreds of millisecond pulsars which can accelerate leptons at the shock waves originating in collisions of the pulsar winds and/or inside the pulsar magnetospheres. Energetic leptons diffuse gradually through the globular cluster. Comptonization of stellar and microwave background radiation is therefore expected to be responsible of \( \gamma \)-ray emission.

The indirect search for dark matter (DM) candidates, is also part of the VERITAS extragalactic non-blazar program. A dedicated contribution on the VERITAS DM program is presented in a separate proceeding. Highlights on the research topics and results of the VERITAS extragalactic non-blazar science program are here presented.

II. THE EXTRAGALACTIC SCIENCE PROGRAM

A. Blazars

Since the beginning of its operations in October 2007, VERITAS observation of blazars averaged ~
410 hr per year, resulting in the detection of 20 blazars (15 HBL and all 5 known IBL), including 10 discoveries.

Mrk 421 is the longest-known VHE blazar, and generally has the brightest VHE flux. It is easily the best-studied HBL at VHE, and VERITAS has acquired nearly 80 hr on this blazar since 2007, largely during flaring states identified with the Whipple 10-m telescope. A total of 47 hrs of VERITAS and 96 hrs of Whipple 10-m data taken between 2006 and 2008 are presented in 12. VERITAS monitoring of the VHE flux from Mrk 421 in 2009-10 reveals an elevated state presented in 5. VERITAS monitoring of the VHE Whipple 10-m data taken between 2006 and 2008 are scheduled. A total of 47 hrs of VERITAS and 96 hrs of flaring states identified with the Whipple 10-m telescope. An extreme flare was observed on February 17, 2010, and showed variations on timescales of approximately 5-10 minutes [8]. Figure 1 shows the seasonal light curve with a zoom on the night of the flare. Variability on the time scale of few minutes is visible. Figure 2 shows a preliminary spectral analysis for two different flux levels: the flare happened on February 17, 2010, and the rest of the season 2009-2010. Clear evolution of the spectral parameters can be seen.

H 1426+428 was first detected during an outburst in 2001 6. This HBL was observed by VERITAS for 22 hr quality-selected live time between 2007 and 2011. A weak excess, 5.2σ, is observed in these data, marking the first time H 1426+428 is detected since 2002. The observed flux is 2% Crab, well below the value (13% Crab) reported during its VHE discovery, and also below any other published VHE flux or limit from this source.

PG 1553+113 is a hard-spectrum (Γ_{LAT} \sim -1.66) Fermi-LAT blazar 7. It is likely the most distant HBL detected at VHE (see z > 0.43 from [3]). It was observed by VERITAS for 60 h of quality-selected live time between May 2010 and May 2011. These data result in the most significant VHE detection (39σ) of this HBL. The time-averaged VHE ux is 10% Crab above 200 GeV, higher than the archival VHE measurements, and the photon spectrum is well described between 175 GeV and 500 GeV by a powerlaw function with photon index Γ = -4.41 \pm 0.14. The VHE spectrum can be used to set an upper limit on the redshift of z < 0.5.

1ES 0229+200 is one of the hardest-spectrum VHE blazars known (Γ_{HESS} = -2.5; [18]). It was observed by VERITAS as part of an intense MWL observation campaign for 46 h live time from 2009-11. A strong signal is detected (∼ 600 γ-rays, 9.0σ) in these observations corresponding to an average VHE flux of ∼ 2% Crab above 300 GeV. The VERITAS flux is variable in a timescale of months, and the preliminary VHE spectrum measured between 220 GeV and 15 TeV has photon index Γ = -2.44 \pm 0.11. The results of the MWL campaign are in preparation. It is interesting to note that 1ES 0229+200 is the only VERITAS-detected blazar not included in the 1FGL catalog 13.

1ES 0414+009 is the most distant VHE HBL with a well-measured redshift (z = 0.287). It was observed by VERITAS for 55 h of quality-selected live time from January 2008 to February 2011. An excess of VHE γ-rays is detected (∼ 7σ) from this Fermi-LAT source (Γ_{LAT} = -1.94; 7). The observed VERITAS spectrum between 230 GeV and 1.8 TeV is relatively hard (Γ = 3.4 \pm 0.5) considering EBL-related effects, and consistent with that observed during the HESS discovery [19]. The observed VERITAS flux is somewhat higher (1.6% Crab) than measured by HESS (0.6% Crab above 200 GeV), although the large datasets used by both experiments are not simultaneous. Results from a contemporaneous MWL observation campaign are in preparation.

B2 1215+30, an IBL discovered at VHE during a flare in January 2011 8, was observed for 55 h of quality-selected live time between December 2008 and April 2011. The measured excess of ∼ 240 γ-rays (6.3σ) corresponds to a VHE flux of ∼ 1% Crab. There is a weak indication that the flux observed by VERITAS in 2011 may be higher than seen from 2008-10. The VERITAS flux is consistent with that (2 ± 1% Crab) reported during the MAGIC discovery.

B. Radio Galaxies

Radio galaxies observed by VERITAS include M 87, 3C 111 and NGC 1275. A dedicated contribution on M 87 is presented in these proceedings. A preliminary analysis of 11 hr of quality-selected data of 3C 111 results in a flux upper limit of ∼ 3% Crab flux above 200 GeV. NGC 1275 is an unusual early-type galaxy located in the center of the Perseus cluster. Its radio emission is core dominated, but emission lines are also seen, making it difficult to classify it according to the Faranhoff & Riley (FR) classification 12. In Fall 2008 the Fermi γ-ray space telescope reported the detection of γ-ray emission from a position consistent with the core of NGC 1275. VERITAS observed the core region of NGC 1275 for about 11 hr between 2009 January 15 and February 26, resulting in 7.8 hr of quality-selected live time. No γ-ray emission is detected above the analysis energy threshold of ∼190 GeV, resulting in a flux upper limit incompatible with the extrapolation of the Fermi-LAT spectrum. Under the assumption of a SSC emission mechanism, the VERITAS result suggests the presence of a cutoff in the sub-VHE energy range 13. The detection in Summer 2010 of VHE γ-ray emission by MAGIC 14 has eventually included NGC 1275 among the few interesting radio galaxies for future VHE investigation.
FIG. 1: Nightly lightcurve of Markarian 421 during the VERITAS 2009-2010 monitoring campaign. The source is detected at an average flux level of approximatively 2 Crab units over the entire season. On February 17, 2010 the source is observed in flaring state at a flux level of \(~\sim\) 8 Crab units. A zoom of the intra-night 2-minute bins lightcurve of the flaring event is shown. During the flaring event the source and intra-night variability is seen.

C. Clusters of Galaxies

Observation of clusters of galaxies 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, up to now a dedicated study of the clusters themselves has been done only on the Coma cluster. The Coma cluster is a nearby cluster of galaxies which is well studied at all wavelengths [16]. 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 intergalactic medium emitting non-thermal radiation. Beside relativistic electrons, there may also be a population of highly energetic protons. Both high energy electrons and protons are known to be able to produce VHE photons. A total of 19 hr of data have been recorded between March and May 2008. No evidence for point-source emission was observed 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 [17].

D. Starburst Galaxies

M 82 a prototype small starburst galaxy, located approximately 3.7 Mpc from Earth, in the direction of the Ursa Major constellation. M 82 is gravitationally interacting with its nearby companion M 81. This interaction has deformed M 82 in such a way that an active starburst region in its center with a diameter of \(~\sim\)1000 light years has been developed [21, 22]. Throughout this compact region stars are being formed at a rate approximately 10 times faster than in entire “normal” galaxies like the Milky Way. Hence the supernovae rate is 0.1 to 0.3 per year [23, 24]. The high star formation rate in M 82 implies the presence of numerous shock waves in supernova remnants and around massive young stars. Similar shock waves are known to accelerate electrons to very high energies, and possibly ions too. The intense radio-synchrotron emission observed in the central region of M 82 suggests a very high cosmic-ray energy density, about two orders of magnitude higher than in the Milky Way [25]. Acceleration and propagation of cosmic rays in the starburst core are thus expected to be responsible for VHE \(\gamma\)-ray emission. Theoretical predictions include significant contributions from both leptonic and hadronic particle interactions. Cosmic-ray ions create VHE gamma rays through collisions with interstellar matter, producing \(\pi^0\) which decay into \(\gamma\)-rays. Alternatively, accelerated cosmic-ray electrons may inverse-Compton scatter ambient X-ray photons up to the VHE range [22, 26, 27, 28].

VERITAS observed M 82 for a total of 137 hours of quality-selected live time between January 2008 and April 2009 at a mean zenith angle of 39\(^\circ\). An excess of 91 gamma-ray-like events \((\sim 0.7 \text{ photons per...})\).
hour) are detected for a total 4.8σ statistical post-trials significance above 700 GeV. The observed differential VHE gamma-ray spectrum is best fitted using a power-law function with a photon index \( \Gamma = 2.5 \pm 0.1^{\text{stat}} \pm 0.2^{\text{sys}} \). Comparison of the VERITAS VHE spectrum with predictions of the theoretical models supports a hadronic scenario as the dominant process responsible for the VHE emission \[29\].

**III. CONCLUSIONS**

The VERITAS extragalactic science program is well established. The study of the AGN physics develops through two complementary observational programs of blazars and non-blazar (radio galaxies) AGN. Several blazars have been detected or discovered, and a new catalog of a sub-class of AGN, the IBL catalog, was started by VERITAS. The VHE-IBL catalog consists entirely in VERITAS-discovered blazars. Distant blazars are also studied, resulting in significant measurements for the EBL characterization. Non-AGN sources are also investigated. A dedicated VHE study on the Coma cluster of galaxies resulted in a flux upper limit on the extended region centered on the core. The first detection of \( \gamma \)-ray emission from a starburst galaxy established a connection between cosmic-ray acceleration and star formation.

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