The VERITAS Extragalactic non-Blazar Program

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Abstract: 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: $E > 100$ GeV) $\gamma$-ray emission from astrophysical objects. In addition to the study of blazars, the VERITAS extragalactic science program develops a comprehensive observational program of extragalactic non-blazar sources. The study of Active Galactic Nuclei (AGN) is intensively pursued through the large MWL observational campaign on non-blazar radio galaxies. The success of these MWL campaigns has for the first time provided insights to the inner structures of jets responsible for $\gamma$-ray emission. The problem of the origin and acceleration of ultra-high energy cosmic rays is pursued through the observation of the starburst galaxy M 82, whose detection at VHE delivers important insights on the possible acceleration mechanisms. Finally, investigation of globular clusters places important limits on the millisecond pulsar contribution to their addressed $\gamma$-ray emission. The VERITAS extragalactic non-blazar science program and its results are presented.

Keywords: IACT Cherenkov TeV extragalactic

1 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 \cite{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 \cite{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.

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 \cite{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 \cite{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.

2 The VERITAS Instrument

The VERITAS detector is an array of four 12-m diameter imaging atmospheric Cherenkov telescopes located in southern Arizona [5]. Designed to detect emission from astrophysical objects in the energy range from 100 GeV to greater than 30 TeV, VERITAS has an energy resolution of \( \sim 15\% \) and an angular resolution (68% containment) of \( \sim 0.1^\circ \) per event at 1 TeV. A source with a flux of 1% of the Crab Nebula flux is detected in \( \sim 25 \) hours of observations, while a 5% Crab Nebula flux source is detected in less than 2 hours. The field of view of the VERITAS telescopes is 3.5°. For more details on the VERITAS instrument and the imaging atmospheric-Cherenkov technique, see [6].

3 The Extragalactic non-Blazar Science Program

3.1 Radio Galaxies

Most of the VERITAS observations of radio galaxies are on the radio galaxy M 87. This AGN is located in the center of the Virgo cluster at a distance of \( \sim 16 \) Mpc and is currently the brightest detected VHE radio galaxy. M 87 was originally detected with marginal significance by HEGRA at TeV energies [7], and later also by HESS [8], VERITAS [9] and MAGIC [13]. This giant radio galaxy has always been of particular interest because its jet lies at \( \sim 20^\circ \) respect to the line of sight and its core and the structure of the jet are spatially resolved in X-ray, optical and radio observations, thus it is an ideal candidate for correlated MWL studies [16].

In 2008 VERITAS coordinated an observational campaign with two other major VHE observatories (MAGIC, HESS), overlapping with VLBA radio observations [17]. Three Chandra X-ray pointed observations have also been performed during the first half of 2008. Multiple flares at VHE have been detected. In X-rays, the inner-most knot in the jet (HST-1) was found in low state, while the core region was in high state since 2000. Progressive brightening of the core region in radio was also seen along the VHE flare development. This is an indication that the \( \gamma \)-ray emission originates from a region close to the core rather than from more distant regions.

In April 2010, during the seasonal monitoring of M 87, VERITAS detected another flare with peak flux of \( \sim 20\% \) of the Crab Nebula flux. During the six-month observation period, M 87 was detected at a level of 25.6σ above the background, with an average flux above 350 GeV equivalent to 5% of the Crab Nebula flux. Dedicated analysis in 20-minute bins has been performed on the April 2010 flaring episode. A spectral analysis has been done on three different phases of the flaring episode: the rising phase, the peak and the falling phase. A power-law fit has been applied to each phase, showing a hint of spectral variability: \( \Gamma_{\text{rise}} = 2.60 \pm 0.31 \), \( \Gamma_{\text{peak}} = 2.19 \pm 0.07 \), \( \Gamma_{\text{fall}} = 2.62 \pm 0.18 \).

Other radio galaxies observed by VERITAS include 3C 111 and NGC 1275. A preliminary analysis of 11 hr of quality-selected data of 3C 111 results in a flux upper limit of \( \sim 3\% \) 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 [10]. In Fall 2008 the Fermi \( \gamma \)-ray space telescope reported the detection of \( \gamma \)-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 \( \gamma \)-ray emission is detected above the analysis energy threshold of \( \sim 190 \) 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 [11].
eventually included NGC 1275 among the few interesting radio galaxies for future VHE investigation.

3.2 Clusters of Galaxies

Observation of clusters of galaxies is done unavoidably 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 [14]. 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 [15].

3.3 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 [19][20]. 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 [21][22]. 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 [23]. 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 [20][24][25][26]. 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°. An excess of 91 gamma-ray-like events ($\sim 0.7$ photons per hour) are detected for a total $4.8\sigma$ 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 $\Gamma = 2.5 \pm 0.6_{stat} \pm 0.2_{syst}$. The VERITAS flux upper limit (99% confidence level [29]) shown at 6.6 TeV is above the extrapolation of the fitted power-law function at these energies. The thin lines represent a recent model [25] for the $\gamma$-ray emission from M 82. The thin solid line is the total emission predicted. The dashed lines represent components from $\pi^0$ decay, and from radiation from cosmic-ray electrons through IC scattering and Bremsstrahlung. The markedly different spectral slopes of these dominant components should be noted.

3.4 Globular Clusters

M 15 (aka NGC 7078) is a very compact ($R_c = 0.19$ pc) globular cluster located at a distance of 9.4 kpc. It belongs to the class of “core-collapsed” globular clusters and is thought to contain a $\sim 2000 M_\odot$ black hole in its center. M 15 contains 7 known millisecond pulsars and a low-mass X-ray binary (LMXB) system. That are expected to emit $\gamma$-rays. Pulsars produce relativistic strongly magnetized winds which, when colliding with other winds, create relativistic shocks. Models presented in [28] consider the case of relativistic leptons injected by the pulsar in such relativistic shocks with a power-law energy distribution. VERITAS observed the globular cluster M 15 between June 10 and June 21, 2010 for a total of 6.2 hours of good-
provides constraints on predictions of γ-ray emission from ms pulsars.

This research is supported by grants from the US Department of Energy, the US National Science Foundation, and the Smithsonian Institution, by NSERC in Canada, by Science Foundation Ireland, and by STFC in the UK. We acknowledge the excellent work of the technical support staff at the FLWO and at the collaborating institutions in the construction and operation of the instrument.

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