

VERITAS contributions to CF6-A: Cosmic Rays, Gamma Rays and Neutrinos

The VERITAS Collaboration

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Introduction

VERITAS, located at the Fred Lawrence Whipple Observatory in southern Arizona, is one of three major imaging atmospheric Cherenkov telescope facilities in operation worldwide. It consists of an array of four, 12-meter diameter telescopes, providing a $< 1\%$ Crab-flux sensitivity in the energy range between 100 GeV and 50 TeV. The array has been operating since 2007 and has detected 42 objects from ~ 10 different source classes, including many new discoveries [1].

In 2012, the VERITAS collaboration established a long-term plan describing a scientific strategy for operations. Many of the goals outlined address problems relevant to the charge of the CF6 subgroup. An additional white paper describing the VERITAS indirect dark matter detection program has been submitted to subgroup CF2 [2]. A prerequisite for achieving these goals was the success of a major upgrade to the array which was completed, with no disruption to the array operations, in the summer of 2012. The upgrade involved the installation of a new trigger system, and the replacement of all of the photodetectors with super-bialkali photomultiplier tubes. This has resulted in an increase of at least 35% in photon collection efficiency. VERITAS will remain the premier VHE facility in the Northern Hemisphere for some time, while the next-generation Cherenkov Telescope Array (CTA) project is under development. The contemporaneous overlap of VERITAS operations with Fermi-LAT, HAWC, IceCube and Auger will be of critical importance to many of the science goals described here.

Cosmic Particle Acceleration as Signal and Background

VERITAS has made significant contributions to the study of Galactic particle accelerators, including pulsars and their nebulae, gamma-ray binary systems and supernova remnants. Highlight results include the detection of > 100 GeV emission from the Crab pulsar [3], and the first TeV detection of Tycho's SNR [4]. The Crab pulsar result can only be easily explained by a new emission mechanism, or an additional component at high energies. The Tycho detection, combined with results from the Fermi-LAT, provides compelling evidence for hadronic particle acceleration in SNR. Complementary evidence for a link between cosmic ray production and star formation activity was provided by the discovery of gamma-ray emission from the starburst galaxy M82 [5].

HAWC [6] will soon begin observations, and will provide a complete TeV map of the northern sky. Follow-up observations with high sensitivity and better angular and energy resolution will be performed by VERITAS. In particular, this is key to determining the nature of unidentified 'dark accelerators', as already demonstrated by VERITAS observations of Milagro sources. The resolution of gamma-ray emission in the region of MGRO J2019+37 and the Cygnus OB1 association into at least two distinct sources, one clearly associated with the pulsar wind nebula CTB 87, demonstrates the importance of the excellent angular resolution provided by the imaging technique. Contemporaneous operation of VERITAS and HAWC will also allow a rapid response to transient events, such as blazar flares and gamma-ray bursts.

The study of VHE gamma-ray emission from particle accelerators is, of course, interesting from a purely astrophysical perspective. It is also critical to understand the nature and properties of astrophysical backgrounds in searches for new physical effects (this issue is addressed in detail in a separate CF6 white paper [7]). The interpretation of indirect dark matter searches, Lorentz Invariance Violation (LIV) tests, studies of gamma-ray and anti-matter backgrounds and searches for axion-like particles all rely on an accurate knowledge of the potential astrophysical backgrounds and their spectral, morphological and temporal properties. A classic example of this is the case of the Galactic Center, which has the highest local concentration of dark matter, but also hosts multiple known and potential astrophysical TeV sources, both point-like and extended [2]. VERITAS observations of the Galactic Center are ongoing as part of our long-term observing plan. For this southern source, the observations take place at low elevation angles, resulting in a high energy threshold but providing an increase in the effective collection area at high energies. This allows us to probe the end point of the spectrum of the Galactic Center gamma-ray emission, which may hold the key to resolving the nature of the source.

Probing Fundamental Physics

VERITAS is a mature experiment, and has moved beyond the initial source discovery phase. Fundamental physics topics now play an increasingly important role in the observing plan. The success of these studies, which often require long and technically challenging exposures, relies on stable operation and a thorough knowledge of the detector performance, calibration and associated Monte Carlo simulations. After five years of operations, all of these aspects of VERITAS are very well understood. Indirect dark matter searches are described elsewhere [2]. Other topics which we plan to investigate with VERITAS in the coming years include:

- **Antimatter studies:** The rising positron fraction identified by PAMELA [10] and confirmed by Fermi [11, 12] up to a few hundred GeV is an intriguing result. It may be explained by a contribution from local astrophysical sources, or possibly by annihilating dark matter. First results from AMS-02 confirm that the positron fraction continues to rise up to at least 250 GeV, at which point it appears to flatten [13]. A measurement of the positron fraction at higher energies would provide a key discriminant between the competing explanations. VERITAS is attempting to make such a measurement by observing the shadow of the Moon in both electrons and positrons, as proposed by Colin [14]. This is technically challenging, due to the optical sky brightness close

to the Moon, and the limited amount of observing time available at high elevations. We have developed short-wavelength optical filter plates for the telescope cameras to enable us to observe close to the Moon, and the results of preliminary test observations are encouraging. Observations over the next few years should allow us to build up the necessary exposure required for this unique measurement.

- **Primordial Black Holes:** In addition, or as an alternative to, particle dark matter, primordial black holes (PBHs) formed during the early universe can serve as a viable candidate for cosmological dark matter (see [16]). PBHs can evaporate through Hawking radiation, where the evaporation rate is directly coupled to their mass. Consequently, during the final seconds of their lifetime, PBHs can release a large flux of gamma rays within the sensitivity range of VERITAS. Dedicated searches for these PBH signals have already commenced with VERITAS [17], and an evaporation rate limit of $\rho_{PBH} < 1.29 \times 10^5 \text{ pc}^{-3} \text{ yr}^{-1}$ has been placed using only 700 hours of VERITAS observations. This limit is already an order of magnitude below previous limits. VERITAS accrues approximately 800 hours of Moonless observations each year, so a significant refinement of the result can be expected.
- **Cosmological measurements using the EBL and IGMF:** The gamma-ray spectra of blazars are modified by interactions with intergalactic radiation fields through pair-production and subsequent cascade processes. As a result, these spectra contain an imprint of the extragalactic background light (EBL) and the intergalactic magnetic field (IGMF). The EBL comprises the combined flux of all extragalactic sources integrated over the history of the Universe, and carries unique information regarding the epoch of galaxy formation and the history of galaxy evolution. This topic is discussed in detail in a related white paper [15]. The IGMF strength is only weakly constrained, and impossible to measure directly. VERITAS observations of the spectra, angular distribution and arrival times of gamma-rays from distant blazars will provide constraints to, or a measurement of, the IGMF strength which is not accessible to other techniques. A positive measurement would be important, possibly implying the existence of a primordial field produced in the early Universe. Both EBL and IGMF measurements require deep, multi-year exposures of numerous blazars over a range of redshifts out to $z \sim 0.5$, as envisaged in our long-term observing plan.
- **Tests of Lorentz Invariance Violation (LIV):** Blazar observations provide the most stringent tests of LIV for VERITAS, thanks to their large distance and rapid timescale of variability. Four bright, high-energy peaked BL Lac objects have been identified for deep monitoring exposures of ≥ 100 hours in our long-term plan. An additional target-of-opportunity program allows us to respond rapidly to alerts of enhanced emission from instruments at other wavelengths. The detection of VHE emission from the Crab pulsar also raises the possibility of using pulsar time profiles to constrain LIV [9], and we plan to substantially augment our already extensive Crab pulsar dataset over the coming years, as well as to search for pulsed emission from other candidate sources. The energy threshold reduction provided by the 2012 upgrade will be particularly important in this regard.

UHECRs and Neutrino Astrophysics

VERITAS observations impact the related fields of ultra-high energy cosmic rays (UHECRs) and neutrino astrophysics. The UHECRs are most likely extragalactic in origin, with active galactic nuclei (AGN) among the best candidates for the accelerators. Gamma-ray observations in the GeV-TeV range are essential to constrain models of particle acceleration and gamma-ray/ neutrino emission in these sources (see [18] for more details). Our long-term plan calls for regular monitoring of most of the northern hemisphere VHE blazar population over the next five years, allowing us to accumulate deep exposures of the sources in various emission states, and maximizing our chances of detecting bright VHE flares. Observations of the nearby radio galaxy M87 will also continue, and will be complemented by high resolution X-ray and radio observations in the event of a flare. A clear correlation between morphological changes in the jet structure and the VHE emission state could help to finally pin down the particle acceleration and photon emission region in AGN jets.

VERITAS can also act as a flare alert system for the UHECR and neutrino observatories, and provide rapid, high sensitivity follow-up observations. In response to the early Auger reports of a correlation between ultra-high energy cosmic rays and AGN, VERITAS was the first instrument to provide follow-up TeV gamma-ray observations [19]. No gamma-ray emission was seen, and the evidence for a correlation has diminished over time, but the observations demonstrate the substantial overlap between the two instruments, despite their locations in different hemispheres. IceCube, conversely, can easily view the northern sky, and VERITAS and IceCube are very well-matched in energy range (IceCube has a minimum neutrino energy threshold of 50-100GeV, and an optimal response above 1 TeV [20]). Numerous predictions of measurable neutrino fluxes associated with astrophysical particle accelerators exist in the literature, including both Galactic (SNRs, binary systems, unidentified TeV sources and pulsar wind nebulae [21, 22]) and extragalactic (GRBs, active and starburst galaxies [23]) objects. VERITAS is the best instrument to search for and characterize the electromagnetic signatures of particle interactions in these objects, which will be necessary to assess the relative contributions of leptonic and hadronic particle populations. We will perform follow-up gamma-ray observations of any reported neutrino sources, and have established a memorandum of understanding between VERITAS and IceCube which allows us to rapidly trigger observations of any transient neutrino excess. IceCube and Auger will be at their most productive over the coming five years, and VERITAS observations will both complement and augment their results.

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