Recent Results from VERITAS

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VERITAS is an array of four imaging atmospheric Cherenkov telescopes, located in southern Arizona, for γ-ray astronomy above 100 GeV. VERITAS has been fully operational since September 2007 but was reconfigured in 2009 through the relocation of a telescope to provide enhanced sensitivity. To date, VERITAS has detected 33 sources of TeV γ rays including active galactic nuclei, shell-type supernova remnants, pulsar wind nebulae, a binary system, a starburst galaxy, and several unidentified sources. This paper provides a status update on VERITAS and its science results as of September 2010, with emphasis on recent discoveries.

Keywords: gamma ray; atmospheric Cherenkov telescopes; active galactic nuclei; starburst galaxies; supernova remnants; dark matter.

1. Introduction

Very high energy (VHE, $\gtrsim$ 100 GeV) γ rays are signatures of non-thermal relativistic processes in the Universe and may be used to probe sites of particle acceleration and environments associated with the production of cosmic rays. VERITAS (the Very Energetic Radiation Imaging Telescope Array System, fig. 1) is an array of four 12 m diameter imaging atmospheric Cherenkov technique[1] (IACT) telescopes for VHE γ-ray astronomy, located at the Fred Lawrence Whipple Observatory in Arizona, that has been fully operational since Autumn 2007. The VERITAS collaboration consists of approximately 90 scientists from 22 institutions in four countries (Canada, Ireland, U.K., U.S.A.), plus associate and non-affiliated members from Argentina, Finland, Germany and the U.S.A. The collaboration operates a strong scientific observing program that encompasses both Galactic and extragalactic science, with emphasis on new source discovery and detailed studies of established sources. The success of this program has been demonstrated by the detection of 33 VHE sources with VERITAS, in addition to sensitive limits being placed on the emission levels of many other objects of interest.

2. VERITAS Technical Details, Performance and Upgrades

VERITAS consists of four 12 m diameter IACT telescopes, each equipped with a 499-pixel photomultiplier-tube (PMT) camera. The array employs a sophisticated three-level trigger system, with the PMT pulses digitised by a 500 MS/s Flash-ADC system. Image cleaning and parameterisation techniques are applied to characterise the images, and stereoscopic 'cuts' based on Monte Carlo simulations of extensive air showers are applied to select candidate γ-ray events and reject background cosmic ray events.

Fig. 1. The VERITAS Array at the base camp of the Fred Lawrence Whipple Observatory.

The telescopes are currently arranged with a typical baseline of $\sim$100 m. The array was changed to this configuration in summer 2009 to provide an optimum baseline as previously telescopes 1 and 4 had been close together with a separation of $\sim$30 m. Simultaneous with the move of telescope 1, a new mirror facet alignment system[2] was implemented to give better image definition. The result of these changes is that VERITAS has improved its flux sensitivity and has decreased the time it takes to detect a 1% Crab Nebula source from $\lesssim$ 50 hrs to $\lesssim$ 30 hrs (fig. 2). VERITAS has an angular resolution (68% containment) of $< 0.1°$, a pointing accuracy of < 50 arc-secs, an energy range of 100 GeV-50 TeV, and an energy resolution (above 200 GeV) of 15-20%. Future planned upgrades of VERITAS include replacement of the camera PMTs with high quantum efficiency PMTs, an improved array-level trigger, improved atmospheric monitoring with a LI-

DAR system, and a possible drive replacement to improve slew speed.

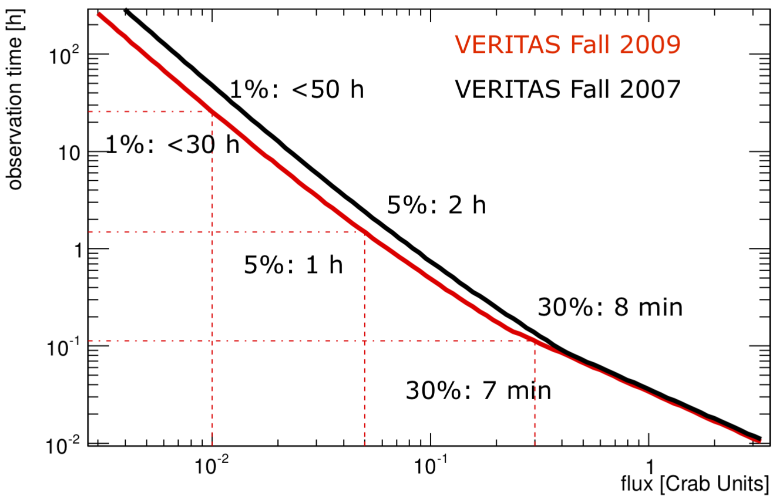

Fig. 2. VERITAS sensitivity before and after the move of telescope 1 and implementation of an improved mirror-alignment tool..

3. VERITAS Science Program and Results

The VERITAS collaboration has key science projects that receive guaranteed observing time as well as a competitive time allocation program where collaboration members, and scientists from outside the collaboration who collaborate with VERITAS scientists, can submit proposals for observing time on objects of interest. In addition, the collaboration has a γ-ray burst program where follow-up observations are made as soon as possible after notification of a suitable burst from the GCN network. VERITAS typically obtains ~800 hours of good-quality dark-time observations per year, plus ~200 hours under moonlight conditions. VERITAS science results to date are discussed below with emphasis on the most recent.

3.1. *Starburst Galaxies*

VERITAS detected >700 GeV γ-ray emission from the starburst galaxy M82 through 137 hours of observations made in 2008 & 2009.[3] The significance of the detection was 4.8σ (post-trials) with a γ-ray rate of 0.7 photons per hour, making it one of the weakest VHE sources so-far detected. The VHE γ-ray emission is believed to be produced by the interaction of cosmic rays with interstellar dust and gas, and the flux is in agreement with theoretical predictions. The VERITAS detection implies a cosmic ray density of 250 eV cm^{-3} in M82, almost 500 times that of our own galaxy.

3.2. *Radio Galaxies*

M87 is one of only three radio galaxies detected in VHE γ-rays, the others being Centaurus A[4] and IC 310 (ATEL#2510). M87 exhibits flaring episodes across the electromagnetic spectrum and detailed analysis of the VERITAS observations, including a 4-day flare observed in February 2008 with peak flux ∼8% of the Crab Nebula flux have recently been published.[5] A joint multi-wavelength monitoring campaign in 2008 revealed that the TeV emission is associated with the core and not features in the jet.[6] VERITAS observations of other radio galaxies, including NGC 1275[7] and 3C 111 have yielded upper limits.

3.3. *Blazars*

Blazars are the subset of radio-loud AGN that happen by chance to have their jets oriented towards the Earth and are the most prominent extragalactic objects in the γ-ray sky. The study of blazars is one of VERITAS's key science projects, and has four components: a VHE blazar discover program, a target-of-opportunity program for flaring blazars, multi-wavelength studies of VHE blazars, studies of distant blazars to constrain the extragalactic background light.

To date, VERITAS has detected 17 VHE blazars, of which 10 have been discoveries, with two additional unidentified objects that are probably blazars (table 1). All discoveries are announced by ATEL and have accompanying multi-wavelength data. Of the 17, four are classified as intermediate BL Lac (IBL) objects while the remainder are classified as high-energy-peaked BL Lac objects (HBL).The successful VHE blazar discoveries of PKS 1424+240,[8] 1ES 0502+675, VER J0521+211, RX J0648.8+1516 and 1ES 1440+122 were motivated by results from Fermi/LAT, but RGB J0710[9] was the first Fermi/LAT source found after first being identified by a VHE instrument.

Multi-wavelength studies of the VERITAS VHE blazars have revealed that the synchrotron self-Compton (SSC) models fit the HBL broadband spectra well, including flare states (e.g. RGB J0710+591,[9] 1ES2344+514[10]).

Table 1. VHE blazars detected by VERITAS.

Name	Class	Redshift	ATEL #
Markarian 421	HBL	0.030	
Markarian 501	HBL	0.034	
1ES2344+514	HBL	0.044	
1ES1959+650	HBL	0.047	
W Comae	IBL	0.102	1422
RGB J0710+591	HBL	0.125	1941
H 1426+428	HBL	0.129	
1ES 0806+524	HBL	0.138	1415
1ES 0229+200	HBL	0.139	
1ES 1440+122	IBL	0.162	2786
1ES 1218+304	HBL	0.182	
RBS 0413	HBL	0.190	2272
1ES 0414+113	HBL	0.287	
PG 1553+113	HBL	0.34 - 0.47	
1ES 0502+675	HBL	?	2301
3C 66A	IBL	?	1753
PKS 1424+240	IBL	?	2084
VER J0521+211	?	?	2260, 2309
VER J0648.7+152	?	?	2486

Monitoring of Markarian 421 with the Whipple 10 m telescope and VERITAS revealed large flares in 2008 and 2010 (ATEL #2443) which initiated multi-wavelength campaigns. Variability on 5-10 min. time-scales was observed during a massive flare on 17th February 2010 and detailed multi-wavelength spectra were obtained for a variety of different flux levels. Modeling of the broadband spectra again reveals that the SSC model works well.[11,12] However, the SSC model does not appear to work quite as well for IBLs, and suggests that an inverse-Compton model where additional photons that originate external to the jet might be needed (e.g. W Comae,[13,14] 3C 66A[15,16]).

3.4. *Indirect Dark Matter Search Results*

Indirect dark matter searches with ground-based γ-ray observatories provide an alternative for identifying the particle nature of dark matter that is complementary to that of direct searches or accelerator production experiments. As part of the VERITAS Dark Matter key science project, four dwarf spheroidal galaxies (Draco, Ursa Minor, Boötes 1 and Willman 1) were selected as targets based on proximity to Earth and favorable estimates for the dark matter density profile based on stellar kinematic data. No significant γ-ray excess was observed from any of the four targets and the derived γ-ray flux upper limits were used to constrain $< \sigma v >$ (the thermally averaged product of the total self-annihilation cross section and the velocity of the WIMP) for neutralino pair annihilation as a function of neutralino mass to be $\lesssim 10^{-23}$ cm^3 s^{-1} for neutralino masses $M_\chi \gtrsim$300 GeV.[17] The derived limits are well above generic predictions for minimal supersymmetric Standard Model (MSSM) models.

3.5. *Survey of the Cygnus Region*

Between April 2007 and December 2008 VERITAS conducted a survey for sources of VHE γ-ray emission in the Cygnus region of the Galactic plane between 67° and 82° in Galactic longitude and -1° and 5° in Galactic latitude. 112 hours of quality observations were made in the base survey with an additional 56 hours in followup observations. The survey analysis had four pre-defined sets of cuts to provide optimum sensitivity to hard and soft point-like and moderately extended sources. A sensitivity of ∼3% of the Crab Nebula flux for point-like sources was achieved. The survey led to the rediscovery of the unidentified source TeV J2032+4130 and the discovery of a new source, VER J2019+407. Further observations of VER J2019+407 have confirmed at the 7.5σ level a source with flux level ∼3% of the Crab Nebula and an extension of $\sim 0.2°$. VER J2019 is located in the northwest side of the γ-Cygni supernova remnant and could be associated with the nearby Fermi pulsar PSR J2021+4026, or be possible shock/molecular cloud interaction.

3.6. *Supernova Remnants and Pulsar Wind Nebulae*

In addition to the Crab Nebula, VERITAS has detected five SNR/PWN systems as VHE γ-ray sources: Tycho, G54.1+0.3,[18] Cassiopeia A,[19] IC443[20] and Boomerang (G106.3+2.7).[23] The three most recent results are discussed below.

3.6.1. *Tycho*

Tycho's SNR is the historical shell-type remnant of the Type Ia supernova observed in 1572. VERITAS observations taken in 2008 to 2010 provided 67 hours of data which result in a detection of Tycho with a pre-trials significance of 5.8σ. The emission is weak, at $\sim$ 1% of the Crab Nebula flux above 1 TeV, and peaks somewhat to the north of the remnant, overlapping a region with enhanced CO emission (fig. 3). Detailed studies of multiwavelength morphology and γ-ray emission mechanisms are currently under way.

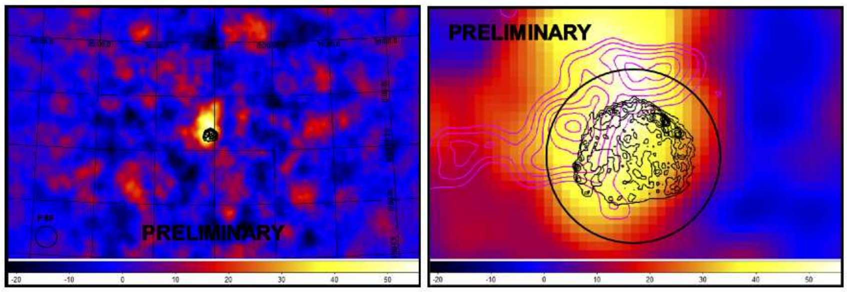

Fig. 3. Preliminary VERITAS excess maps of Tycho, full map (left) and zoomed map (right). Black contours are the Chandra ACIS[21] and magenta contours are ^{12}CO data from the FCRAO Survey.[22]

3.6.2. *G54.1+0.3*

The SNR G54.1+0.3 is a young ($\sim$3 kyr) X-ray PWN which, by virtue of its similarities to that object, has been called a "cousin to the Crab".[24] VERITAS observed G54.1+0.3 for $\sim$36 hours in 2008/2009, after partial-moonlight observations in 2007 revealed a hint of signal. These observations resulted in a 7σ detection of a point-like object, centered on the PWN location. The integral flux of the source above 1 TeV is 2.5% of the Crab Nebula flux, and the energy spectrum follows a power-law with index $2.39 \pm 0.23_{stat} \pm 0.3_{sys}$.

3.6.3. *Cassiopeia A*

Cassiopeia A (Cas A) is a compact young shell-type remnant of a massive star, located 3.4 kpc away, and is the brightest radio source in the sky with a synchrotron spectrum which extends all the way up to hard X-rays. Cas A had been previously detected in VHE γ-rays by HEGRA[25] and MAGIC.[26] VERITAS observed Cas A for 22 hours, resulting in an 8.3σ detection. The source, which has a flux of $\sim$3% that of the Crab Nebula above 200 GeV, shows no evidence for extension beyond the VERITAS point spread function, and has an energy spectrum which is well fit by a power-law of index $2.61 \pm 0.24_{stat} \pm 0.2_{sys}$. The Fermi/LAT team has modeled the high-energy emission from Cas A and finds that a hadronic emission model with a hard proton population (spectral index = 2.1) and a cutoff energy of 10 TeV fits the combined GeV/TeV excess well.[27]

3.7. *Binary Systems*

Binary systems are the Galactic VHE γ-ray sources that exhibit the greatest degree of variability and there are now four binary systems detected in VHE γ rays: Cygnus X-1,[28] LS 5039,[29] LS I +61 303,[30] and PSR B1259-63.[31] Of these, VERITAS has detected LS I +61 303.[32] In addition, it has been suggested that variable point source HESS J0632+057,[33] which has recently been detected by VERITAS after previous observations failed to detect it,[34] is possibly a binary system.[35]

3.7.1. *LS I +61 303*

LS I +61 303 is a high-mass X-ray binary system consisting of a compact object, either black hole or neutron star, orbiting a B0Ve companion with a mass of $\sim$12.5 $M_\odot$ and a circumstellar disk. VERITAS has made continued observations of LS I +61 303 in 2008, 2009 and 2010, having previously detected it with a statistical significance of 8.4σ with clear orbital modulation of the flux and peak emission near apastron.[36] LS I +61 303 has not been detected in the recent VERITAS observations but it has been detected by Fermi/LAT which showed emission peaks near periastron and a cut-off in the spectrum at 6 GeV. However, since a 40% increase in the Fermi/LAT-measured flux in March 2010, there is no evidence for orbital modulation of the flux. Detailed simultaneous multi-wavelength observations of this object are needed to gain an insight into the γ-ray emission mechanism.

4. Summary and Conclusions

VERITAS, especially after the recent move of Telescope 1, has excellent sensitivity and is performing very well. The scientific program is a mixture of discovery and deep observations of established sources, and has proved highly successful with the detection of 33 VHE sources. With the planned upgrades of VERITAS in the coming years we expect the scientific output to continue to flourish.

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