VERITAS Very High Energy Gamma-ray Observations of Galaxies

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Abstract. Remarkable progress has been made in very high energy (VHE; E ≥ 100 GeV) gamma-ray astrophysics in the last decade. The VHE source catalog has increased tenfold, with a wide variety of source classes, and includes more than 45 extragalactic objects. Currently, the Very Energetic Radiation Imaging Telescope Array System (VERITAS) has made observations of numerous source candidates, both galactic and extragalactic, including more than 100 galaxies. The last 18 months of observations are especially noteworthy as they have been completed in a new array configuration, following the relocation of one of the four 12-meter telescopes. This new configuration has yielded a significant increase in the VERITAS sensitivity to gamma-ray sources above 100 GeV, resulting in several new source detections in the first few months of operations alone. To date, the VERITAS extragalactic source catalog includes various blazars, the radio galaxy M87 and the starburst galaxy M82. Highlights from the VERITAS extragalactic observation program are summarized here.

1. The VERITAS Instrument
VERITAS comprises four imaging atmospheric Cherenkov telescopes. The VERITAS array is located in southern Arizona at 1268 meters above sea level and is sensitive to gamma rays between ~100 GeV and ~30 TeV with an energy resolution of 15%. These telescopes are 12-meter dishes which reflect the light produced through cosmic-ray and gamma-ray interaction with the atmosphere onto a pixelated camera composed of 499 photomultiplier tubes. These very brief air shower events are promptly digitized, allowing moment and timing analysis for background rejection. The array has been in full operation since September of 2007 and has been used to observe very-high-energy (VHE) events from astrophysical targets with an angular resolution of ~0.1 degrees. In the current configuration, the array is capable of detecting a 1% Crab source in 28 hours. See [1] and [2] for a more general overview of the instrument.

2. The VERITAS Extragalactic Catalog
VERITAS has detected three types of extragalactic objects. BL–Lac–type blazars, specifically high-frequency-peaked (HBL), are the most commonly VHE detected galaxy type, with 14 having been detected by VERITAS at the time of this publication. Additionally, 5 intermediate-frequency-peaked (IBL) BL Lacs have been detected by VERITAS. The historically typical VHE class of BL Lac blazars is joined by the VERITAS detection of the radio galaxy M87 and the starburst galaxy M82, pertinent discoveries with regards to long posed questions about TeV gamma-ray and Galactic cosmic-ray production.
2.1. Blazars

The VERITAS catalog of detected blazars is continually expanding with 20 detected thus far. These blazars are summarized in Table 1. The VERITAS blazar observation program currently splits the available time each year between discovery and long term monitoring observations. This observation program hopes to increase both the number and type of blazars available for study with VHE instruments as well as catch previously detected VHE emitting blazars in both quiescent and flaring states. Organizing VHE observations to be coincident with other wavebands is a high priority for VERITAS and allows for a more complete view of blazar emission states, while at the same time accumulating deep exposures. Only a small selection of these multiwavelength observations will be summarized here.

Table 1. VERITAS blazar detections shown along with BL Lac type. The table is organized in order of increasing redshift. VERITAS discoveries are shown in bold.

| AGN          | Type | Redshift |
|--------------|------|----------|
| Mrk 421      | HBL  | 0.030    |
| Mrk 501      | HBL  | 0.034    |
| 1ES 2344+514 | HBL  | 0.044    |
| 1ES 1959+650 | HBL  | 0.102    |
| W Comae      | IBL  | 0.102    |
| RGB J0710+591| HBL  | 0.125    |
| H 1426+428   | HBL  | 0.129    |
| 1ES 0806+524 | HBL  | 0.138    |
| 1ES 0229+200 | HBL  | 0.139    |
| 1ES 1440+122 | IBL  | 0.16     |
| RX J0648.7+1516 | HBL | 0.179 |
| 1ES 1218+304 | HBL  | 0.182    |
| RBS 0413     | HBL  | 0.190    |
| 1ES0414+009  | HBL  | 0.287    |
| PG 1553+113  | HBL  | 0.43 ≤ z ≤ 0.47 |
| 1ES 0502+675 | HBL  | 0.341?   |
| 3C 66A       | IBL  | 0.444?   |
| PKS 1424+240 | IBL  | ?        |
| VER J0521+211| ?    | ?        |
| B2 1215+30   | IBL  | ?        |

2.1.1. Detected Blazars  RGB J0710+591 is an “extreme” HBL, with its synchrotron peak near 10^{19} Hz. This historically promising VHE candidate, as indicated by its hard X-ray spectrum, is a relatively low redshift (z=0.14), hard-spectrum VHE blazar. This target was the first VHE-led Fermi-LAT discovery. Upon detection of VHE emission by VERITAS [3], observations by instruments in other wavebands were encouraged. The collections of these data allow for the synchrotron self-Compton (SSC) modeling of the quasi-simultaneous broadband data, as can be seen in Figure 1. As is often the case for TeV emitting HBLs, a SSC model adequately describes the observed emission. More information on the multiwavelength observations and modeling can be found in [4].

1 Full TeV publication history available through the TeV Online Catalog TeVCat: http://tevcat.uchicago.edu/
PKS 1424+240 was the first Fermi-LAT motivated VHE discovery, which prompted simultaneous observations of the target at other wavelengths. This blazar has no determined redshift and is bordering on the IBL/HBL split with the synchrotron peak occurring at $10^{16}$ Hz during these observations, as can be seen by its SED in Figure 2. A SSC model is applied to the SED data for redshifts ranging from 0.05 to 0.7. This broadband SED modeling favors a redshift of less than 0.1. An upper limit on the redshift can be produced with the simple assumption that all softening of the spectrum observed between the high energy and the VHE regimes is due solely to the absorption of VHE photons on the EBL. Using the Fermi high-energy spectrum extended up to the VHE band and absorbing the fit with the EBL models from [5,6,7] until the spectrum matches that measured by VERITAS for a range of redshifts suggests a redshift of less than 0.66, although a lower redshift is likely, as can be reasoned from the soft X-ray spectrum observed with the Swift-XRT. More information on the VHE discovery, redshift constraint and SSC modeling of PKS 1424+240 can be found in [8].

RX J0648.7+1516 (1FGL J0648.8+1516) was another Fermi-LAT motivated VHE discovery. This target was selected as a promising VHE candidate through the inspection of localized groups of photons collected by Fermi-LAT with energy greater than 50 GeV. At the time of VHE detection by VERITAS, this object was an unidentified source 6 degrees off the Galactic Center.
plane with no redshift measurement. The angular resolution of VERITAS enabled the previously unidentified Fermi source to be associated with the X-ray source RX J0648.7+1516. Follow-up spectroscopic measurements made at the Lick Observatory identified the object as a BL--Lac--type object with a redshift of 0.179. The optical spectrum can be seen in Figure 3. Additionally, the concurrent multiwavelength data gathered in response to the TeV detection allows the HBL sub-classification of the blazar. The photon spectrum above 200 GeV is well fit by a power law \( \frac{dN}{dE} = F_0 \left( \frac{E}{E_0} \right)^{-\Gamma} \) with a photon index \( \Gamma = 4.4 \pm 0.8_{\text{stat}} \pm 0.3_{\text{syst}} \) and a flux normalization \( F_0 = (2.3 \pm 0.5_{\text{stat}} \pm 1.2_{\text{syst}}) \times 10^{-11} \text{ TeV}^{-1}\text{cm}^{-2}\text{s}^{-1} \) at \( E_0 = 300 \text{ GeV} \) (see Figure 4). This soft spectrum offers no constraint on the EBL density and no VHE variability is detected during the VERITAS observations between 4 March and 15 April 2010.

In addition to the newly detected Fermi-LAT blazars PKS 1424+240 and RX J0648.7+1516 summarized above, RBS 0413, 1ES 0502+675, VER J0521+21 and 1ES 1440+122 are also new additions to the VERITAS extragalactic catalog [9,10,11,12]. Additionally, VERITAS has recently detected VHE emission from a few previously detected TeV blazars, including 1ES 0414+009, B2 1215+30 and H1426+428. The details of the types of blazars and redshifts are given in Table 1. Continued VERITAS observations of these historical TeV blazars allows valuable insight into the variable nature of the gamma-ray emission, as in the case of 1ES 1218+304.

Figure 3. Spectrum of RX J0648.7+1516 showing the Ca H+K, G-band, Na I and Mg I spectral features indicating a redshift of \( z = 0.179 \). Since the G-band arises in stellar atmospheres, we interpret this as the redshift for the host galaxy and not an intervening absorber. The blazar was observed at Lick Observatory using the 3-meter Shane Telescope on UT night of 6 November 2010.

In early 2009, VERITAS monitoring observations of the TeV-emitting HBL 1ES 1218+304 [13] detected a short flare with a variability timescale of a single day. The light curve of VERITAS observations can be seen in Figure 5. The VHE flux was seen to increase from \( \sim 7 \) to \( \sim 20 \) percent of the Crab Nebula with no spectral change. The power law fit to the low and high states of the blazar are shown in relation to the Crab Nebula in Figure 6. The fast variability timescale detected challenges the kiloparsec jet model of hard spectrum emission, as proposed in [14]. More details on the variable nature of 1ES 1218+304 can be found in [15].
Figure 4. The differential photon spectrum of RX J0648.7+1516 between 200 and 650 GeV measured by VERITAS between 4 March and 15 April 2010 (MJD 55259–55301). The solid line shows a power-law fit to the measured flux derived with four equally log-spaced bins and a final bin boundary at 650 GeV, above which there are few on-source photons. A 99% confidence upper limit evaluated between 650 GeV and 5 TeV assuming a photon index of 4.4 is also shown. The shaded region shows the systematic uncertainty of the fit, which is dominated by 20% uncertainty on the energy scale.

Figure 5. Light curve of the VERITAS observations of the hard-spectrum HBL 1ES 1218+304 above 200 GeV. The flaring region is highlighted, with a corresponding zoomed plot showing the day-scale flux variations (from [15]).

Figure 6. Spectra for the HBL 1ES 1218+304 in both the flaring and quiescent state as compared to the Crab Nebula. The hard spectrum of the blazar is seen to remain constant during both the high and low emission states (from [15]).

2.1.2. Nondetected Blazars The small field of view of the imaging atmospheric Cherenkov telescopes (IACTs) makes new source discovery from a large-scale sky survey difficult, and the
hunt for VHE emitting objects has historically been guided by X-ray and high energy gamma-ray experiments such as EGRET onboard the Compton Gamma Ray Observatory [16], Swift [17], ROSAT [18] and now the Fermi-LAT [19].

The distribution summarizing the observation of 47 blazars selected as promising VHE candidates prior to the launch of Fermi is shown in Figure 7. These candidates, each observed between one and twenty hours, are mainly hard X-ray, low redshift blazars that were observed with VERITAS between 2007 and 2011. Stacking the result from the observation of these blazars results in a 4.1 standard deviation excess. These exposures often provide the best VHE upper limits to date on these targets. A similar stacking analysis for MAGIC observations of BL Lacs [20] yielded a similar result.

A significance distribution can also be seen for 21 high flux, hard-spectrum Fermi-motivated TeV candidate blazars, which were not confined solely to those with known redshifts. Each candidate had between 5 and 10 hours of VERITAS exposure, which again provide some of the best VHE upper limits to date. There is no hint of a stacked excess seen from these observations.

![Figure 7. Significance distribution of VHE blazar candidates selected before the Fermi launch, restricted to blazars with known redshift.](image1)

![Figure 8. Significance distribution of VHE blazar candidates selected from the Fermi data, including blazars with no known redshift.](image2)

2.2. Non-Blazar Galaxies

2.2.1. M82

M82 is a prototypical starburst galaxy at a distance of nearly 3.9 megaparsecs in the direction of Ursa Major [21]. This close proximity makes the absorption of gamma rays by the EBL negligible. The galaxy diameter on the sky is one arcmin, which is small enough to appear as a point source for VERITAS. The central supermassive black hole is less than $3 \times 10^7$ solar masses, showing no evidence for an active nucleus [22].

The tidal forces resulting from the gravitational interaction with nearby M81 result in an active starburst region with a diameter of approximately 1000 light years [23]. Imaging from the Hubble Space Telescope shows this region to contain more than 200 massive star clusters, suggesting a star formation rate nearly 10 times that of the Milky Way Galaxy. The galaxy’s high star formation rate is paired with a high supernova rate of between one and three supernovae every 10 years [24, 25].

Observations by VERITAS during the 2007 through 2009 observing seasons (totaling 137 hours of live time) resulted in the detection of 91 excess gamma-ray events above the threshold of 700 GeV [26]. This high threshold results from the average angle of VERITAS observations being 39 degrees from zenith. The sky map of the VERITAS observations is shown in Figure 9. This detection represents a 4.8 standard deviation post-trials result with a chance probability of $7.7 \times 10^{-7}$. The subsequent Fermi-LAT detection of high-energy gamma-ray events shows good agreement with the VERITAS result [27]. The VERITAS spectrum and power law fit can be seen in Figure 10.
The VHE emission can be explained through the production of high-energy cosmic-ray hadrons by supernovae in the active starburst region. These cosmic-ray hadrons interact with gas to produce pions which in turn produce VHE gamma rays. Cosmic ray electrons can interact with ambient photons within the galaxy to directly produce gamma-rays. A model representing these processes is also shown to be in good agreement with the VERITAS data in Figure 10. These results are also in agreement with those found through TeV detection from starburst galaxy NGC 253 by HESS [28].

Figure 9. Sky map showing a VHE point source excess coincident with the M82 position, denoted by the black star (from [26]).

Figure 10. M82 spectrum above 700 GeV shown together with emission model lines for non-thermal gamma-ray production methods thought to be responsible for VHE emission in the starburst galaxy (from [26]).

2.2.2. M87 M87 is an active galactic nucleus with a jet oriented slightly off the Earth line of sight. This radio galaxy offers a unique laboratory for the study of jet and jet substructure physics. One unknown in the field of extragalactic gamma-ray astronomy is where the origin of the gamma-ray emission is located within the active galactic nucleus. This question is complicated by the fact that extragalactic objects appear as no more than point sources for IACTs. Imaging from radio, optical and X-ray instruments shows the M87 jet to contain a bright location at the core (near the base of the jet) and a bright knot farther out from the core, referred to as HST-1.

Simultaneous VHE and X-ray observations of this flaring TeV source in 2005 suggest that both the VHE and X-ray emission increased in the HST-1 region of the jet at the same time. This behavior is shown through the Chandra X-ray observation of increased 2-10 keV flux from the HST-1 region contemporaneous with a TeV flare, detected by HESS. The Chandra observations of the core during the same timeline show no variability. More details on this multiwavelength campaign can be found in [29]. This same variability trend was not observed with more recent multiwavelength observations of M87 flaring events, suggesting that the core is capable of emitting VHE gamma rays during flaring episodes.

Multiwavelength efforts in early 2008 including radio observations from VLBA show correlated variability across the radio, X-ray and TeV bands for the core emission. Results from
these observations can be seen in Figure 11. These observations resulted from a well organized multiwavelength campaign involving monitoring by the very high energy gamma-ray instruments VERITAS, HESS and MAGIC, X-ray observations from Chandra and radio observations from VLBA. As can be seen in the figure, an increase in flux from the core region is apparent in both radio and X-ray observations coincident with a TeV flaring episode. More information on this flare can be found in [30].

Additionally, as is detailed in a proceedings by M. Raue, over 50 hours of monitoring shared between VERITAS, HESS and MAGIC resulted in the most detailed observation to date of a fast flare from M87 in April of 2010. In addition to the X-ray and radio observations triggered by these observations, this flare marks the first TeV flare from M87 with Fermi-LAT monitoring.

Figure 11. A light curve of the multiwavelength observations of a flare from M87. The top panel contains the VHE integral flux observed by the IACTs VERITAS, MAGIC and HESS, with the window of the flare highlighted. A zoomed plot of the flaring TeV activity is shown. The middle panel shows Chandra 2-10 keV X-ray observations of both the M87 HST-1 and core regions. An increase in flux coincident with the TeV flare can be seen from the nucleus, while the HST-1 emission remains constant. The bottom panel shows the VLBA 43 GHz radio observations of the nucleus, which exhibits an increase in flux coincident with the flaring activity observed in the other wavebands. The radio observations of the jet without the nucleus are also shown, which do not follow the increasing flux observed for the nucleus alone (from [30]).

3. Conclusions

Discoveries of TeV emission from the starburst galaxies M82 by VERITAS and NGC 253 by HESS, the radio galaxy M87 as well as blazars have led to exciting new insights regarding the origin of Galactic cosmic-rays and the particle populations responsible for the gamma-ray emission, but even with these new discoveries questions still remain. What is the nature of the blazar sequence? Do blazars go through an evolutionary process? What are the constituent particles that are responsible for the non-thermal emission observed? Is this a blazar-specific question? With continued monitoring and discovery observations of galaxies by IACTs such as VERITAS, HESS and MAGIC, even more targets and a larger set of variable states will be collected. As can be seen from the observations reported above, these observations are most
enlightening when simultaneous observations are made across the entire broadband spectrum, allowing a complete view of the galaxy emission. It is evident that TeV extragalactic astronomy is changing from a single-instrument’s agenda to a well organized and collaborative effort. The observations that have and will be made from these efforts will help address some of the remaining questions about gamma-ray emission from galaxies.

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