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Highlights from the VERITAS AGN Observation Program

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VERITAS is one of the world's most sensitive detectors of astrophysical VHE (Very High Energy; E $>$ 100 GeV) γ-rays. This array of four 12-m imaging atmospheric-Cherenkov telescopes has operated for $\sim$10 years, and nearly 5000 hours of observations have been targeted on active galactic nuclei (AGN). These studies of blazars and radio galaxies have resulted in 36 detections. Most of these detections are accompanied by contemporaneous, broadband observations, which enable detailed studies of the underlying jet-powered processes. Recent highlights from the VERITAS AGN observation program and scientific results are presented.

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1. Introduction

AGN are the most numerous class of identified VHE γ-ray emitter. They comprise $\sim$35% of the VHE sky catalog with 70 AGN VHE detected as of *ICRC2017* [1]. These luminous objects emit non-thermal radiation across the entire broadband spectrum and the VHE band is generally located above the high-energy peak of their signature double-humped spectral energy distribution (SED). All VHE AGN possess jets, and their γ-ray emission is believed to be produced in a compact region within these accretion-powered jets, near the AGN's central supermassive black hole. Although four nearby ($z < 0.06$) FR-I radio galaxies are VHE detected, most ($\sim$94%) VHE AGN are blazars, a class of AGN with jets pointed along the line-of-sight to the observer. The VHE blazar population includes four subclasses: 47 high-frequency-peaked BL Lac objects (HBLs), 8 intermediate-frequency-peaked BL Lac objects (IBLs), 2 low-frequency-peaked BL Lac objects (LBLs), and 6 flat-spectrum radio quasars (FSRQs), as well as 3 objects whose blazar sub-classifications are uncertain. The VHE blazar catalog covers a redshift range from $z = 0.030$ to $z = 0.944$, noting that $\sim$80% of the objects have either $z < 0.3$ or uncertain redshift. The general proximity of these objects is due to a combination of energetics requirements and the effects of the extragalactic background light (EBL) which attenuates VHE photons in an energy- and distance-dependent manner.

There are two empirical qualities that generally describe VHE AGN: their observed VHE photon spectra are often soft ($\Gamma_{obs} \sim 3-5$) and their observed VHE flux is almost always variable. In most cases, the harder the VHE spectrum is the more interesting the target becomes scientifically, noting that very few VHE AGN are detected above 1 TeV. While flux variability is common, and about a third of VHE AGN are only detected during flares, most VHE AGN only show a factor of 2-3 in VHE flux variations with notable episodes (see, e.g., [5]) of rapid (minute-scale), large-scale (factor of 100) flux variations being very rare. It is worth noting that the observed time scales for these smaller variations (days to years) often depends on brightness of the objects in the VHE band, with shorter-duration variations only seen during isolated flaring episodes or for only the brightest objects. This could be a sensitivity effect, as many of the VHE AGN require long integration times for detection with current instruments.

The VERITAS AGN (radio galaxy and blazar) program focuses on making precision measurements of their VHE spectra and variability patterns, while leveraging contemporaneous multi-wavelength (MWL) observations from both ground- and space-based facilities. Its main component is a long-term study of the existing VHE AGN population in a manner that emphasizes the regular search for, and intense observation of, major flaring episodes. Independent of any successful flare identification, the regular sampling of each VHE AGN aims to build high-statistics data sets to enable fully-constrained modeling of each VHE AGN's SED (see, e.g., [7]). The long-term MWL light curves should also allow for flux and spectral correlation studies that may indicate commonalities in the origin of each AGN's emission. VERITAS AGN studies are also useful for a variety of cosmological measurements and have been used to to constrain the strength of the intergalactic magnetic field [11] and the density of the EBL [19].

2. VERITAS AGN Program

VERITAS [2] is located at the F.L. Whipple Observatory in southern Arizona, USA (31° 40'

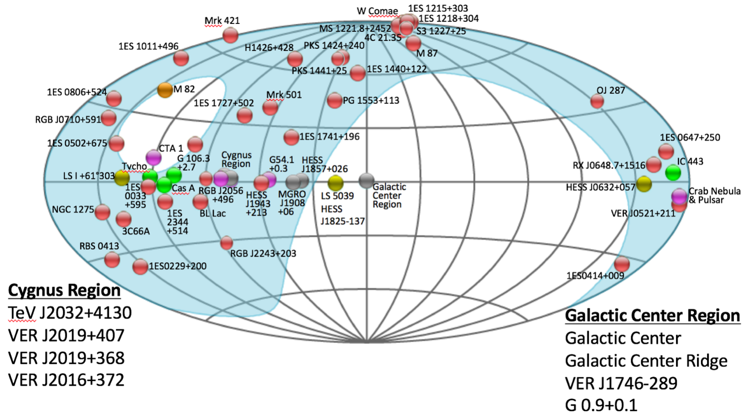

Figure 1: The VERITAS sky catalog in Galactic coordinates. Different astrophysical classes are shown with different colored markers. The red circles are AGN. The blue region is the sky visible to VERITAS in normal observing modes.

N, 110° 57’ W, 1.3 km a.s.l.). It is most sensitive between ∼85 GeV and ∼30 TeV and the full array has been used to regularly observe the Northern sky each season (September – July) since 2007. Following the completion of a series of upgrades in Summer 2012, the observatory can detect an object with flux equal to 1% Crab Nebula flux (1% Crab) in ∼25 hours, and spectral reconstruction of observed signals can be performed above ∼100 GeV. The typical systematic errors reported for scientific quantities are ∼20% on the flux and 0.1 on the photon index (Γ).

Over the past decade, VERITAS has acquired an average of ∼950 h of good-weather observations each season during “dark time” (moon illumination <30%). The collaboration also has the capability to observe during periods of “bright moonlight” (i.e. >30% illumination) [12]. One of the bright-moon techniques has comparable sensitivity to the normal observing mode and only slightly higher threshold (e.g. 250 GeV). Since 2012, it is a regular component of VERITAS data taking, adding another ∼30% to overall good-weather data yield. VERITAS has successfully detected several blazars during these observations (see, e.g., [9]).

AGN observations are a significant component of VERITAS data taking (∼50% since 2007). As of June 2017, they comprise a total of ∼4240h (∼425 h per year) of good-weather dark time and ∼840h (∼170 h per year) of good-weather, bright-moon time. The dark time is split ∼90% to blazars, primarily BL Lac objects, and ∼10% to radio-galaxies, primarily M 87. The bright-moon time is almost entirely observations of BL Lac objects, with observationssplit ∼35% to hard-spectrum VHE blazars and ∼65% to candidates for new VHE discoveries during the past two seasons. AGN comprise 62% of the VERITAS source catalog (shown in Figure 1), and a table listing 34 of the 36 AGN detected by VERITAS can be found in [14]; the two newest detections (RGB J2056+496 and OJ 287) are described below.

Conceptually, much of the VERITAS AGN program is based on regular (∼weekly) monitoring observations of the entire Northern VHE catalog when the targets are best visible to self-identify relatively long-term VHE flaring episodes. These monitoring observations are supplemented with coordinated data at lower energy, so that long-term contemporaneous MWL data sets exist for all Northern VHE AGN. When interesting flaring events are observed in any of these monitoring programs, intense MWL target-of-opportunity (ToO) observations are immediately scheduled. The monitoring program is designed such that the minimum cadence will detect a 10% Crab flux. Over a period of many years, even the lowest level monitoring significantly increases the data set for each object, and for ∼10 particularly interesting targets longer-duration monitoring is scheduled to generate very deep, legacy exposures.

While the philosophy of the AGN program is largely based on exploiting the existing catalog via deep / timely measurements of the known sources, ∼30% of the AGN program was devoted to the discovery and follow-up observations of new VHE AGN during the past two seasons. Most discovery observations are taken on targets from a list of selected candidates during bright-moon time, or ToO observations triggered by MWL partners. Recently, our selected discovery candidates have focused on a comprehensive list of Northern objects including all the hardest ($\Gamma_{2FHL} < 2.8$) AGN in the *Fermi*-LAT 2FHL (>50 GeV) catalog [4], and the X-ray brightest HBLs in the 2WHSP catalog (i.e. objects with a "TeV Figure of Merit" > 1.0) [15].

Regardless of whether their focus is the discovery and/or follow-up observation of a new VHE source, or exploiting the potential of bright flares in known VHE blazars, ToO observations are a key component of the VERITAS AGN program. These data average ∼25% of the AGN yield each season. Indeed it is notable that aside from some low-level monitoring, nearly all VERITAS FSRQ data are taken via ToO observations.

3. Recent Highlights

RGB J2056+496 is one of the brightest, hard-spectrum ($\Gamma_{2FHL} \sim 2.3$) objects in the *Fermi*-LAT 2FHL (>50 GeV) catalog [4] not directly observed prior to the 2016-17 season by VERITAS. This blazar, of unknown redshift, is also a XMM-Newton source and a Swift-BAT source. It was observed with the array for 9.0 h of good-quality live time between October 10, 2016 and November 9, 2016. A preliminary analysis of these observations yields an excess of 120 events above the background at the position of the blazar, corresponding to a statistical significance of 6.3 standard deviations (σ). The VERITAS collaboration is interpreting this excess as the discovery of VHE γ-ray emission from the blazar, noting that the blazar is only ∼13 arc-seconds from the micro-quasar candidate LS III +49 13, and the two objects are effectively co-located for VERITAS. The observed VHE spectrum from RGB J2056+496 is shown in Figure 2. The observed integral flux is F(>300 GeV) = $(4.00 \pm 0.77_{\rm stat} \pm 0.80_{\rm syst}) \times 10^{-12}$ cm^{-2} s^{-1}, or about 2.9% Crab above the same threshold. The nightly VHE light curve shown in Figure 3, and the flux in November 2016 is well fit by a constant (χ^2 = 0.22, NDF = 4). Four Swift XRT / UVOT observations were taken simultaneous with the November VERITAS observations of this blazar, which comprise ∼85% of the data set. While SED modeling will be possible, we note the brightness of LS III +49 13 (V ∼ 8.8) makes optical photometry and spectroscopy of the AGN very difficult.

OJ 287 is an optically-bright blazar at redshift $z = 0.306$. It has unusual optical behavior, displaying regular outbursts with a overall period of ∼12 years, but also significant divergences from this period. This quasi-periodicity has often been explained and predicted by the presence of a binary black hole system at the core of OJ 287. Its SED has shown HBL-like features suggesting it is an appropriate target for VHE observatories [16]. The extrapolation of its *Fermi*-LAT 3FGL spectrum ($\Gamma_{3FGL} \sim 2.1$) to the VHE band is also favorable (∼10% Crab), but OJ 287 is not in the 2FHL (>50 GeV) catalog [4]. In December 2007, during an anticipated phase of optical brightness, VERITAS observed OJ 287 for ∼10 h live time, yielding an upper limit of ∼2.6% Crab above 180

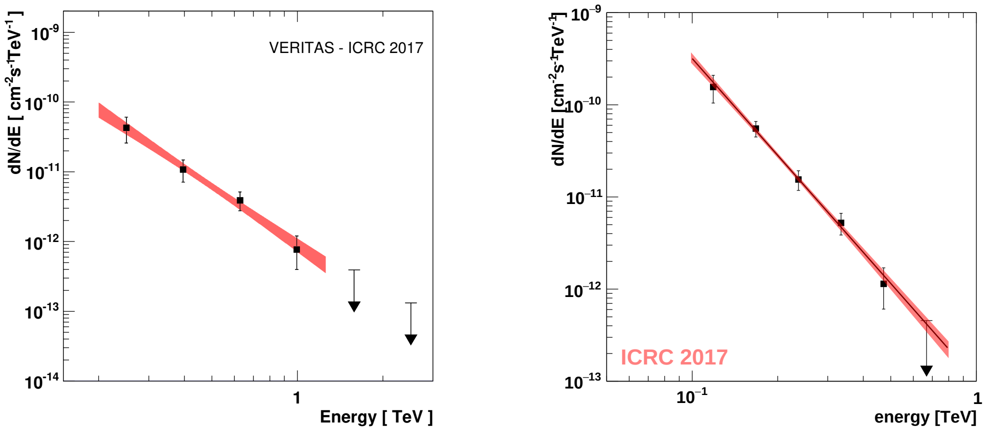

Figure 2: Left) The preliminary VHE spectrum measured from the direction of RGB J2056+496. The best fit (χ^2 = 0.46, NDF = 2) of a power law $dN/dE = I_o \times (E/E_o)^{-\Gamma}$ to these data has photon index $\Gamma = 2.77 \pm 0.40_{\rm stat} \pm 0.10_{\rm syst}$, $I_o = (1.15 \pm 0.23_{\rm stat} \pm 0.23_{\rm syst}) \times 10^{-11}$ cm^{-2} s^{-1} TeV^{-1}, and E_o = 400 GeV. Right) The preliminary VHE spectrum measured from OJ 287 [18]. The best fit of a power law yields photon index $\Gamma = 3.49 \pm 0.28_{\rm stat} \pm 0.10_{\rm syst}$.

GeV [10]. Following the observation of long-lasting, enhanced X-ray activity from OJ 287 by Swift in late-2016, VERITAS began a series of ToO observations of the blazar. In February 2017, these observations resulted in the successful discovery of VHE emission from OJ 287 (ATel #10051) which coincided with the brightest state yet observed with the Swift XRT (ATel #10043). The VHE discovery and bright X-ray state led to an intense VERITAS and MWL observation campaign though March 2017. A total of ∼50 h of quality-selected live time were acquired on OJ 287 with the VERITAS array. During these observations a point-like excess of 556 γ-rays is detected from OJ 287, corresponding to a statistical significance of 9.7σ. The VHE flux observed by VERITAS is variable, with a time-average of F(>150 GeV) = $(4.61 \pm 0.61_{\rm stat} \pm 0.92_{\rm syst}) \times 10^{-12}$ cm^{-2} s^{-1}, or about 1.3% Crab above the same threshold. The observed VHE spectrum is shown in Figure 2. An early look at the copious MWL data from this campaign suggests a shift of the high-frequency SED peak to higher energies during the VHE detection. More details on the VERITAS and MWL observations can be found in these proceedings [18].

BL Lacertae ($z = 0.069$) was initially discovered as a weak (3% Crab) VHE emitter during a flare in August 2005 [6]. Since 2010, it has been regularly monitored with the VERITAS array yielding a total exposure of nearly 70 h of good-weather data including ToO observations. This long-term monitoring has shown BL Lacertae is not normally detectable in the VHE band, however, there have been 4 flares detected by VERITAS. The first was a brief flare in June 2011, that peaked at a VHE flux of ∼125% Crab [8]. This flare had a rapid exponential decay ($\tau = 13 \pm 4$ min) and was associated with the appearance of a superluminal radio knot . Two smaller flares of ∼16% Crab and ∼9% Crab were recorded on the nights of June 21, 2015 and November 30, 2015, respectively [3]. An exceptional flare was detected with VERITAS during routine monitoring on October 5, 2016, triggering immediate ToO observations. A total exposure of 2.6 h good-quality live time was acquired, yielding a strong detection (∼71σ). The light curve from this event is shown in Figure 3. The flare peaks at ∼180% Crab when binned on 4-minute time scales (or ∼125% Crab when binned on 30-minute scales) and it is characterized by a slow rise (t ∼ 140^{+25}_{-11} min) followed

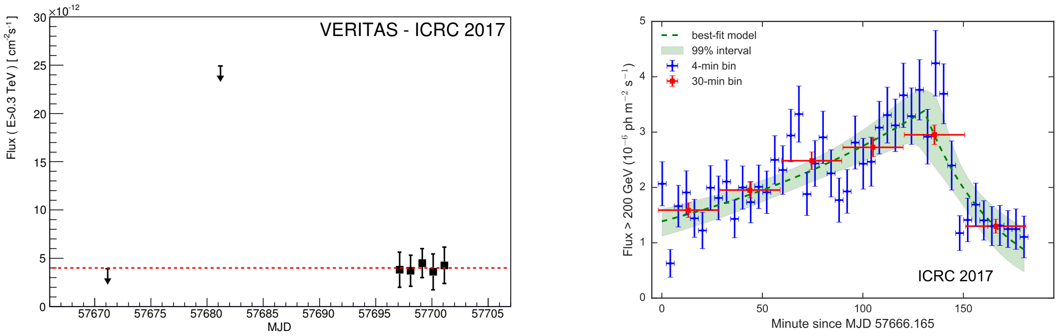

Figure 3: Left) The preliminary VHE light curve measured from the position of RGB J2056+496 in 2016. The dashed line is the best fit of a constant to the data. Right) The preliminary VHE light curve measured from BL Lac on October 5, 2016, in 4-minute (blue dots) and 30-minute (red squares) bins. The dashed line and shaded region show the best fit mode and its 99% confidence interval, respectively.

by a more rapid fall (t $\sim 36^{+8}_{-7}$ min). Similar to the 2011 event, this VHE flare is also associated with the appearance of a candidate superluminal radio knot. More details regarding the VERITAS flare as well as interpretation of contemporaneous VLBA, optical (photometry and polarization), Swift, and *Fermi*-LAT data can be found in these proceedings [17].

1ES 1959+650 is a well-known, nearby ($z = 0.047$) HBL that has been relatively inactive since a possible "orphan flare" in 2002. During the 2015-16 season, the X-ray and MeV-GeV fluxes were the highest seen from this blazar since the start of the *Swift* and *Fermi*-LAT missions. VHE flaring was also observed by VERITAS during deep observations in both Fall 2015, and in Spring 2016 ($>$15 h each, $>80\sigma$ detections). The peak flux observed during each of the events was $\sim$200% Crab and $\sim$300% Crab, respectively. More details on the significant MWL coverage and the VERITAS observations can be found in these proceedings [20].

Mrk 421 ($z = 0.030$) is the most well-studied VHE blazar and VERITAS has acquired more than 300 h of good-weather data on this object. These studies include data taken during both low-states and exceptionally bright states, and nearly all data have been taken contemporaneously with a wide assortment of MWL partners. In 2013, VERITAS embarked on a deep, season-long MWL observing campaign on Mrk 421 that was unprecedented due to its hard X-ray coverage from the NuStar satellite. While relatively low fluxes were recorded by VERITAS and other TeV partners for from January to March 2013 [13], exceptional flaring activity was recorded by VERITAS and MAGIC in April 2013 (ATel #4976). This led to $\sim$12 h / night of uninterrupted VHE coverage with MAGIC and VERITAS, as well as near continuous NuStar coverage, pointed *Fermi*-LAT observations, numerous Swift pointings, and copious coverage at optical and longer wavelengths for several nights. A total of 21.8 h of good-quality live time were acquired by VERITAS between April 11 and April 16, 2013. The VERITAS light curve from these observations is shown in Figure 4. A summary of results from the data is given in Table 1.

Over the past two seasons VERITAS has devoted approximately 90 hours toward observing radio galaxies. A particular highlight of these observations is the detection of two bright flares (ATel #9690 and ATel #9931) from **NGC 1275**. The first flare on October 30, 2016, was $\sim$15% Crab flux and the second flare on January 2, 2017, was $\sim$65% Crab flux. Both detections were at least an

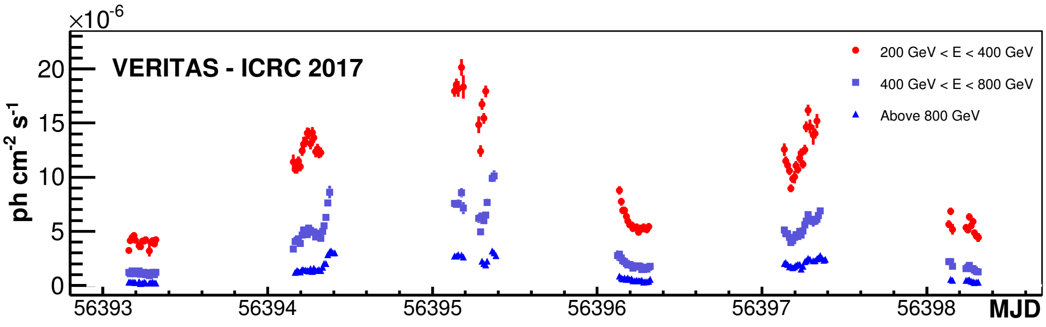

Figure 4: The light curve measured from Mrk 421 in April 2013. The integral fluxes are shown for three separate energy ranges: 200 GeV $<$ E $<$ 400 GeV, 400 GeV $<$ E $<$ 800 GeV, and E $>$ 800 GeV. The fluxes are provided at the VERITAS public web page: https://veritas.sao.arizona.edu/.

Date	Live Time [h]	F(>280 GeV) [cm^{-2} s^{-1}]	F(>280 GeV) [Crab]	Γ	E_{cut} [TeV]
April 11	2.7	$(2.67\pm0.07)\times10^{-10}$	1.87	2.09 ± 0.11	0.81 ± 0.13
April 12	5.0	$(8.16\pm0.09)\times10^{-10}$	5.70	2.04 ± 0.03	2.27 ± 0.14
April 13	2.1	$(10.83\pm0.14)\times10^{-10}$	7.57	2.03 ± 0.05	1.96 ± 0.17
April 14	3.9	$(4.04\pm0.07)\times10^{-10}$	2.82	2.18 ± 0.06	1.24 ± 0.16
April 15	5.1	$(8.86\pm0.09)\times10^{-10}$	6.19	2.06 ± 0.02	4.58 ± 0.34
April 16	2.0	$(3.65\pm0.09)\times10^{-10}$	2.55	2.44 ± 0.11	1.75 ± 0.46

Table 1: VERITAS results from Mrk 421 in April 2013. For each night's observation, the average integral flux above 280 GeV, and key parameters from the best fit of a power law with an exponential cutoff to the spectra are shown.

order of magnitude brighter than previous flare detections (∼1% Crab; see, e.g., [14]). Another recent highlight is our participation in an international MWL campaign on M 87 in March-April 2017. Here we coordinated our observations with the new Event Horizon Telescope to test if any high-energy flickering in the low-emission state is related with any new phenomena near the core of M 87. The VHE flux during our ∼25 h of observations was consistent with the low state and our total exposure on M 87 is now ∼290 h. Although it had been nearly five years since any VERITAS observations were taken with the goal of discovering new radio galaxies, ∼15 h exposures were taken in 2016-17 on each of 3C 303 and 3C 264. No significant excesses were found in these data.

4. Conclusion

VERITAS has now acquired more than 10,000 hours of good-weather, scientific observations, including more than 5,000 hours targeted on AGN. The array continues to run well with >1250 h of observations acquired in each of the two most recent seasons, including >1100 h of good-weather data taken on AGN since *ICRC2015*. These most recent AGN observations have resulted in the VHE discoveries of 2 BL Lac objects, and several interesting VHE flares. The VERITAS AGN catalog now includes 32 BL Lac objects, 2 FSRQs and 2 FR I radio galaxies. The VERITAS collaboration plans to operate the telescope array through at least 2019, and has correspondingly organized a strategy to guide the AGN program through this time (see [14] for more details). This program is heavily focused on regular VHE and MWL monitoring of all known VHE AGN in the Northern Hemisphere, and emphasizes immediate and intense ToO follow-up of interesting flaring events. Although the VERITAS collaboration has published upper limits on more than 100 AGN

[10], and has observed nearly 100 other AGN since, we maintain a strong program focused on the discovery of new VHE blazars. Here we are using ToO observations of interesting VHE candidates during dark time and non-ToO observations of selected targets with limited existing exposures during bright-moon time. As AGN observations remain a priority for the VERITAS collaboration, we expect our long tradition of producing exciting results to continue.

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