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WHIPPLE-VERITAS: A STATUS REPORT

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Abstract

Recent results from the Whipple 10 m gamma-ray telescope are presented including a tentative detection of the Galactic Center, a confirmation of the TeV unidentified source TeV J2032+4130 and an update on measurements of bazar spectra. Furthermore, we give a status report of the VERITAS project: we discuss the successful test of a prototype telescope and the rapid construction of a 4-telescope array on Kitt Peak, Arizona.

1 Introduction

The imaging atmospheric Cherenkov technique has rapidly advanced since the pioneering detection of the first TeV gamma-ray source, the Crab Nebula, by the Whipple collaboration in the late 1980s [23]. Although the Whipple 10 m gamma-ray telescope is now 36 years old, it still provides good sensitivity for gamma-ray observations in the northern hemisphere and it will be retired in the VERITAS era. We report science results from its most recent observations.

Stereoscopic imaging of air showers has been widely recognized as a key technique for providing better sensitivity for next generation ground-based based gamma-ray telescopes [9]. The VERITAS (Very Energetic Radiation Imaging Telescope Array System) collaboration is currently constructing VERITAS-4, an array of four imaging telescopes on Kitt Peak, located in southern Arizona. While VERITAS-4 is in the construction phase we report here first results on the performance of a prototype of the individual elements of VERITAS, showing that the design and technical specifications have been met.

2 Galactic Sources

2.1 Galactic Center

Observations of the Galactic Center have been pursued with the Whipple 10 m telescope over the time period of 1995 through 2003 ([3],[11]). The Galactic Center culminates at an elevation of 29^o in the southern Arizona sky, therefore observations were taken at large zenith angles. This observing mode increases the energy threshold of the detector to 2.8 TeV. However, as shown previously for the Whipple 10 m telescope ([13],[17]), observations at large zenith angles also increase the collection area, yielding good sensitivity at multi-TeV energies as demonstrated for the Crab Nebula [13]. For sources with energy spectra harder than the Crab (dN/dE $\propto E^{-2.5}$), large zenith angle observations are even more sensitive, because the ratio of source counts over cosmic-ray events increases with energy.

Since the Galactic Center data were taken over an extended period of time involving 3 different camera configurations, it was necessary to develop a new analysis method that allows the combination of data from eight years. Taking into account the different pixelations used in the camera and improvements of the point spread function of the telescope optics, it was possible to use scaled values of the image parameters for the analysis [12]. A total of 26 hours of on-source exposure have been used for this analysis.

Figure 1 shows the sky map of the excess events of gamma-ray events in the direction of the Galactic Center. An excess with a significance of 3.7 σ is present and coincides with the position of the Galactic Center. Since the region around the Galactic Center is relatively bright, related systematic effects from the different sky brightness between ON and OFF source runs were corrected in the analysis. However, remaining uncertainties could have effects on the number of excess events and the significance of the signal. The Galactic Center has been convincingly detected by the HESS collaboration [2] and has also been reported by the CANGAROO-II collaboration [22]. Further observations are underway to confirm the detection with the Whipple 10 m instrument and the VERITAS telescope array. The flux level at 2.8 TeV corresponds to 0.4 Crab, which is a factor of 3 higher than the corresponding flux point in the energy spectrum published by the HESS collaboration [2]. However, given the marginal significance of the Whipple detection of the Galactic Center, this result is not inconsistent with the HESS results.

2.2 TeV Unidentified Sources

The fortuitous detection of a gamma-ray source in the Cygnus region by the HEGRA collaboration [1] indicates the discovery of the first unidentified TeV source in the sky, TeV J2032+4130. The initial result is based on an extensive exposure time of 121 hours, raising the concern of possible systematic effects above what is usually expected from short exposures for which instrumental effects are better understood. Therefore, independent confirmation with another instrument is deemed important. The HEGRA collaboration was able to confirm the initial result by follow-up observations with now a total of 279 hours of observation time [20] yielding a significance of $\approx 7\sigma$. The integral flux of TeV J2032+4130 above 1 TeV is just 3% of the Crab which is at the sensitivity limit of second generation imaging atmospheric Cherenkov telescopes. Interestingly, the energy spectrum is rather hard with a differential spectral index of $1.9 \pm 0.3_{\mathrm{stat}} \pm 0.3_{\mathrm{syst}}$. The detection of this new source was unexpected; it was a result of a 2-dimensional analysis of the camera field of view around the direction of Cygnus X-3, which is just 0.6^o south of TeV J2032+4130.

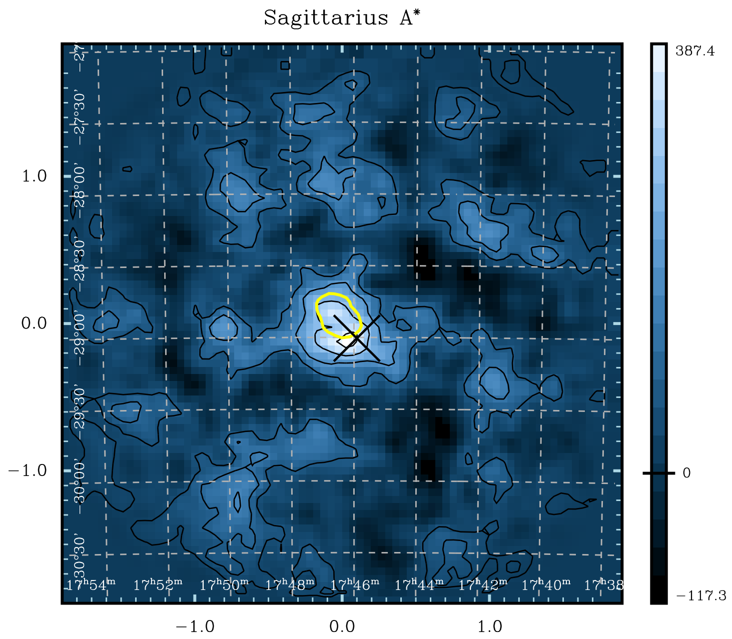

Figure 1: Showing the two dimensional distribution of the gamma-ray excess counts in the direction of the Galactic Center. The dark contour lines indicate the significance levels in steps of 1 σ. Also shown is the 99% confidence region for EGRET observations according to a recent analysis by Hooper et al. [10], however, for an earlier analysis see [16].

Archival data from the Whipple collaboration from the time period 1989/1990 in the direction of Cygnus X-3 allowed us to independently verify the reported source detection by HEGRA [1] . A total of 50.4 hours of observing time of Cygnus X-3 was used to search for the HEGRA source.

Figure 2 shows the excess significance of the skymap centered on the direction of Cygnus X-3 based on the Whipple observations [15]. A 4 σ excess is present near the HEGRA source location approximately 0.6^o north of Cygnus X-3. Accounting properly for the number of trial factors introduced by searching around the HEGRA position, the total significance is reduced to 3.5 σ. The excess appears in both years of observations, hence no variability is indicated by the data. Due to the relatively low significance of the detection it is not possible to determine the angular size of the source.

In summary, the first unidentified TeV gamma-ray source, TeV J2032+4130 has been confirmed by the Whipple 10 m telescope, although with marginal

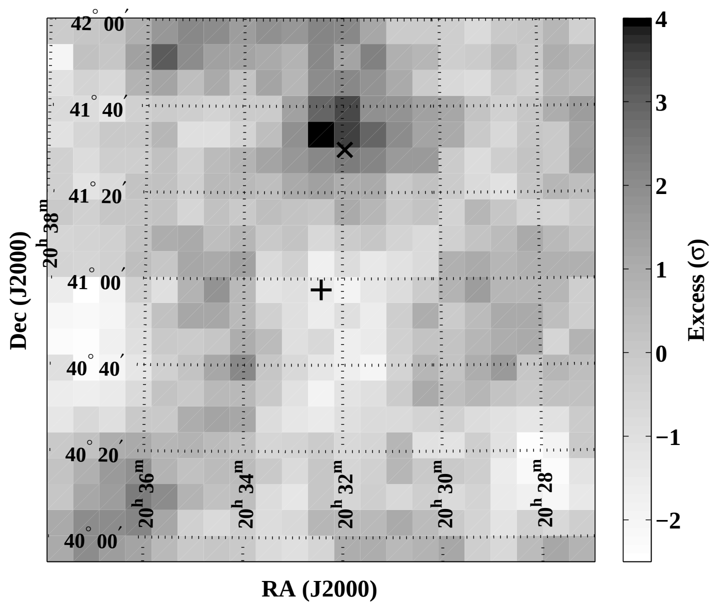

Figure 2: The skymap of the Cygnus X-3 region is shown in units of standard deviations of gamma-ray excess events. An excess with a significance of 3.3 σ is coincides with the position of TeV J2032+4130 as reported by the HEGRA collaboration. The cross nearby the excess corresponds to the HEGRA position, whereas the cross in the center indicates the position of Cygnus X-3.

significance. Observations with a next generation instrument, e.g., VERITAS-4 or MAGIC [5] are required to solve the origin of TeV J2032+4130 as a gamma-ray source and provide accurate identification with a counterpart at other wavelengths.

3 Extragalactic Sources: Gamma Ray Blazars

The Whipple 10 m telescope was used in an extensive survey searching for low redshift TeV gamma-ray blazars and was initially guided by the first EGRET catalog [8] of blazars at GeV energies. This led to the discovery of the first active galaxy, Mrk 421 in TeV gamma rays [19] . More refined search strategies selecting X-ray bright BL Lacs led to a number of detections of low redshift blazars (Mrk 501, 1ES2344+514, H1426+428 and 1ES1959+650) ranging from z=0.03 to 0.129. A major interest in blazar observations at TeV energies is to test particle acceleration models and gamma-ray emission models in jets of active galactic nuclei. A recent overview describing properties of TeV blazars constraining gamma-ray production models in jets can be found in these proceedings in the paper by J. Buckley. The emphasis of this section will be the interaction of TeV gamma-ray beams with cosmological radiation fields, the cosmic near-IR and mid-IR background.

3.1 Gamma Ray Blazar Energy Spectra

TeV blazar observations can also be used to provide constraints to the intervening medium, in particular the diffuse extragalactic background light (EBL). A TeV photon can interact with a near-infrared photon of the EBL via pairproduction; the energy dependent cross section for a 1 TeV photon is maximal when interacting with a $\approx 1\mu$m soft photon. Because of the energy and distance dependence of this gamma-ray absorption effect, the observed energy spectra of blazars at various distances are attenuated by a different magnitude. In addition the shape of the imprinted absorption feature in the observed gamma-ray spectra also depends on the energy distribution of the EBL; its double-peak structure is well established. However, direct measurements of the EBL in the 5-60 μm wavelength regime are hampered by foreground emission from interplanetary dust, the EBL is largely uncertain in this wavelength regime. In fact, unfolding of TeV gamma-ray spectra of blazars at various redshifts may be the most promising method to gain information about the mid-IR part of the EBL spectrum.

Figure 3 shows the Whipple power spectra of the two nearby blazars Mrk 421 and Mrk 501, both at a redshift of ≈ 0.03, the more distant blazar 1ES1959+650 at a redshift of 0.048 and the most distant blazar H1426+428 at a redshift of 0.129. It is apparent that the two nearest blazars exhibit a hard spectrum (dN/dE $\propto E^{-1.95\pm0.07}$ and dN/dE $\propto E^{-2.14\pm0.03}$) terminated by a cutoff at approximately 4 TeV. The spectrum of 1ES1959+650 is steeper (dN/dE $\propto E^{-2.8\pm0.3}$) but statistics do not allow the unraveling of structure other than a power law. The energy spectrum of H1426+428 is even steeper (dN/dE $\propto E^{-3.5\pm0.6}$), again limited statistics prevent statements about the detailed spectral shape.

Although suggestive for EBL absorption, the energy spectra of Mrk 421 and Mrk 501 with the same characteristic cutoff energy, could present the intrinsic spectral shape of the two TeV gamma-ray sources. For example, Dwek & Krennrich [7] explore a wide range of EBL scenarios, which are allowed based on currently available direct measurements and limits, and reconstruct the absorption-corrected spectra of Mrk 421 and Mrk 501. These absorption-corrected spectra show that the source spectra could differ very little from the observed spectra except in the absolute flux level, which is almost certainly effected [7]. On the other hand, in case of EBL scenarios with a high energy density in the mid-IR, the observed cutoffs are mostly caused by the EBL. The

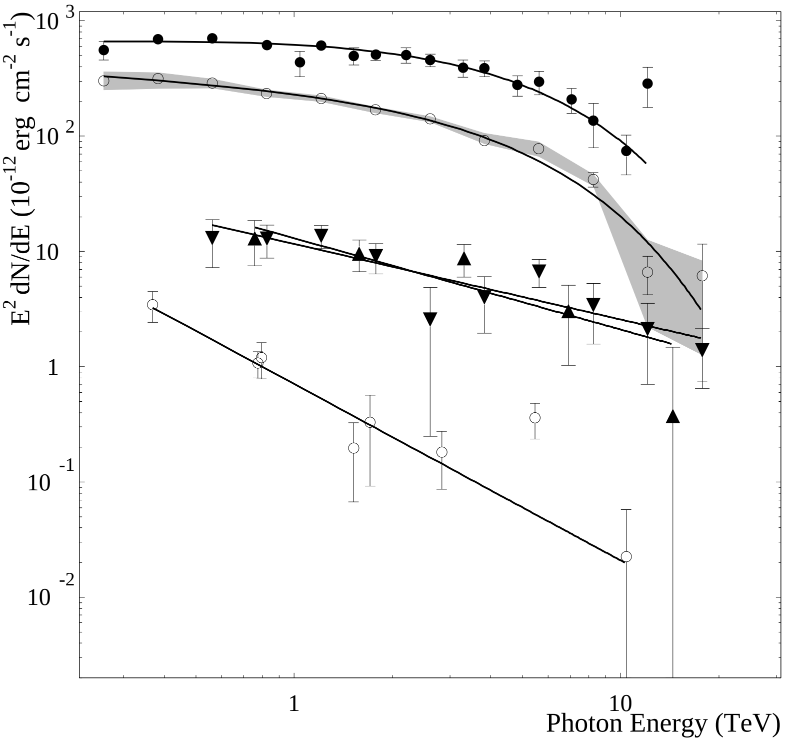

Figure 3: The energy spectra of Mrk 501 (filled circles) [21] , Mrk 421 (empty circles) [14] , 1ES1959+650 (triangles) [6] and H1426+428 (empty circles at bottom) [18] are shown.

absorption-corrected energy spectra of the TeV blazars Mrk 421 and Mrk 501 do show a limited range of luminosity peak energies between 0.5 TeV - 2 TeV, indicating that the power output of both objects peaks in the TeV range [7].

Limits to the EBL in the mid-IR have been derived from TeV observations, however, the ultimate goal of measuring the EBL over a range of 0.1 μm to 30 μm is still in its infancy and can likely be achieved with next generation imaging atmospheric Cherenkov telescopes.

Figure 4: A photomontage of the VERITAS telescope array currently under construction on Kitt Peak.

4 The VERITAS Project

VERITAS-4 is the next generation ground-based gamma-ray observatory in the U.S. and will be located in Horsehoe Canyon on Kitt Peak, in southern Arizona. The main objective of the design is to reach maximum sensitivity at 100 GeV - 10 TeV, providing excellent angular resolution (0.1^o to 0.03^o at 100 GeV and above 1 TeV, respectively) and good energy resolution (15% and 10% at 100 GeV and above 1 TeV, respectively). This can be achieved by stereoscopic imaging of air showers with 12 m diameter optical reflectors and imaging cameras with 499 photomultipliers in the focal plane. The field of view of each camera is 3.5° across.

The VERITAS-4 design consists of four 12 m diameter imaging Cherenkov telescopes, with three spaced on the corners of a triangle and one at the center with a distance of 80 m from the others. The mirror area of $100\,\mathrm{m}^2$ for each telescope allows, e.g., for a total mirror area of $300\,\mathrm{m}^2$ when three telescopes located in the Cherenkov light pool participate in a true array trigger. A true array trigger is possible by the use of a flash-adc system [4] with $8\,\mu$s memory depth, providing enough delay time for reaching a trigger decision based on Cherenkov light detected in each telescope. Utilizing the combined mirror area is essential for achieving the lowest possible trigger threshold and energy threshold.

The VERITAS collaboration has constructed and tested a prototype telescope at the basecamp of Whipple observatory. The prototype will become the first element of four telescopes forming the array. The reflector of the prototype telescope had been equipped with 80 mirrors (360 for a complete single VERITAS element) and a half camera in the focal plane. This prototype setup has allowed us to test the largely custom designed electronics (frontend, flash-adcs, discriminators and pattern trigger) and the optics of the VERITAS telescopes and verify performance specifications.

Figure 5: The prototype telescope for the VERITAS-4 telescopes.

The optics of the prototype meets expectations with a point spread function of 0.04° F.W.H.M., consistent with ray-tracing calculations of the prototype reflector. The optical support structure (OSS) with its quadrapot bypass structure, a design that passes the load from the telescope arms and camera to a the positioner circumventing the OSS, meets our specifications.

The VERITAS-4 array is designed to use stereoscopic imaging and at the same time record the pulse shapes from the Cherenkov light flashes using a 500 MHz sampling rate flash-adc system. Imaging combined with timing is promising for the best possible shower reconstruction.

First results from observations of Mrk 421 in spring 2004 are reflected in Figure 6. Initiated by Whipple 10 m observations we were able to observe Mrk 421 in a high flaring state and carried out observations with the prototype telescope as well. In 19.2 hours an excess with a significance of 20.5σ has been detected. This demonstrates that the prototype is working well, although it contained only a half camera, less than a quarter of the mirror area and no light concentrators.

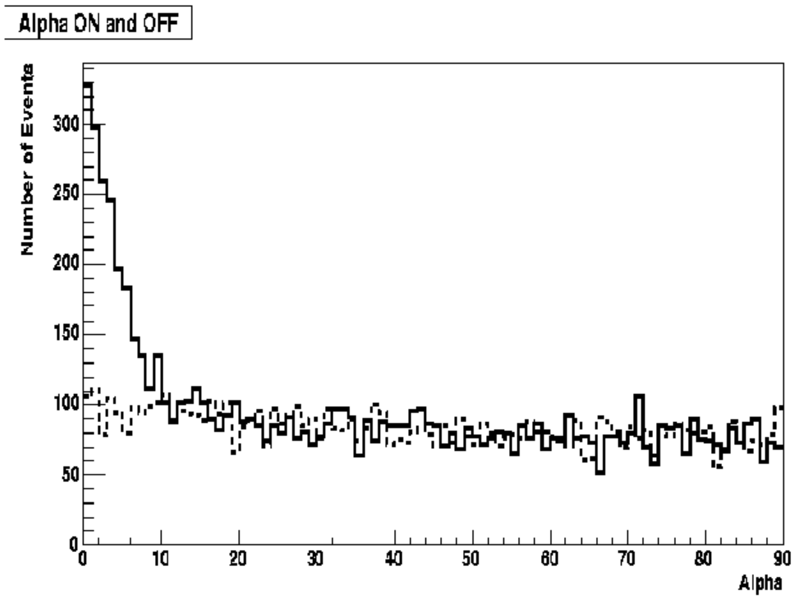

Figure 6: The alpha distribution of Mrk 421 observations (ON) and background events (OFF) showing an excess of 20.5 σ from19.2 hours of observations.

5 Summary

TeV gamma-ray observations with imaging atmospheric Cherenkov telescopes have reached a significant milestone for any astronomical technique: the development of an order of magnitude more sensitive instruments and the discovery of unexpected sources of radiation occurring in the field of view. Whipple archival data has confirmed the detection of the first TeV unidentified source discovered by the HEGRA collaboration, a second generation instrument operated at its sensitivity limit.

Also at the sensitivity limit of the Whipple 10 m telescope is the Galactic Center, now unambiguously detected by the HESS collaboration; over a time period of 8 years and 26 hours of observations, a tentative detection with a significance the 3.7σ has been reported by the Whipple collaboration.

Furthermore, we give an update on the measurement of energy spectra of gamma-ray blazars with the 10 m telescope. There are several energy spectra available measured by the Whipple collaboration: Mrk 421 and Mrk 501 which exhibit a hard spectrum with a cutoff at 4 TeV, H1426+428 with a very steep spectrum and 1ES1959+650 with a spectral index between that of Mrk 421 and that of H1426+428. As to whether or not the cutoff for Mrk 421 and Mrk 501 is due to the EBL cannot be unambiguously decided. Recent studies of a wide range of EBL scenarios clearly show that an intrinsic cutoff as well as a cutoff due to the EBL are viable possibilities. However, all EBL scenarios imply substantial absorption above 0.5 TeV for the Mrk 421 and Mrk 501, indicating that the energy spectra of 1ES1959+650 and H1426+428 are strongly absorbed in that energy regime.

Finally, we show results from the construction of a prototype telescope that will be the basis for the elements of VERITAS-4. Tests of the optical support structure and point spread function indicate that the optics of the telescope is of excellent quality. Also the test of the mostly custom built electronics proved to be successful. A front-to-end test is given by a strong detection (20.5 σ) of Mrk 421 in 19 hours of observation. VERITAS-4 is currently under constructed at Kitt Peak and is expected to start operating as a four telescope array in 2006.

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