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First results from VERITAS

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Abstract

VERITAS is an array of four, 12-m-diameter, Cherenkov telescopes, designed to explore the very-high-energy gamma-ray sky in the energy band between 100 GeV and 50 TeV. Its construction and commissioning have occurred over the past two years and the array has been taking scientific data with three or more telescopes since November 2006. We present results from observations made with VERITAS during the past observing season, including new results on the distant blazar 1ES1218 + 304, the active galaxy M87 and the high-mass X-ray binary system LS I +61 303. We also describe the plans in place for the coming observing seasons.

Keywords: Gamma-ray astronomy; Active galaxies; Blazars; X-ray binaries

1. Introduction

The field of very-high-energy (VHE) gamma-ray astronomy, where VHE refers to energies above about 100 GeV, can be said to have started with the detection of gamma rays from the Crab Nebula in the late 1980s [1]. This result was made possible by the use of the imaging atmospheric Cherenkov technique wherein a highly pixellated camera, mounted at the focal point of a large, steerable reflector, records images of the extensive air showers produced by energetic gamma rays impacting the upper atmosphere. The Whipple 10-m telescope [2] was the first such instrument.

A later development in VHE astronomy was the HEGRA [3] array of imaging telescopes which demonstrated that multiple, independent views of the same shower made with several telescopes could result in similar sensitivity using smaller reflectors.

VHE astronomy is now being carried out with a new set of detectors which are arrays of large reflectors with highly pixellated cameras; the HESS array in Namibia [4] the MAGIC detector in the Canary Islands [5] and CANGAROO-III [6] in Australia all began operations within the last few years. The latest member of this group is the VERITAS array in Arizona which has recently been completed.

In this contribution we will describe some of the technical details of the VERITAS instrument and will present results obtained from data taken during the last observing season. Plans for future observations will be outlined at the end of the article.

2. The VERITAS telescopes

VERITAS consists of an array of four identical telescopes installed at the basecamp of the Fred Lawrence Whipple Observatory on the lower slopes (altitude 1270 m) of Mount Hopkins, about 70 km south of Tucson, Arizona. Due to space constraints, the array has an irregular four-sided shape, with side lengths of 35, 85, 85 and 109 m, which results in a variety of different baselines between the telescopes.

2.1. Optical components

Each telescope comprises a steerable 12 m diameter reflector which collects Cherenkov light and directs it onto a camera made up of 499, 29-mm-diameter, photomultiplier tubes (Photonis XP2970/02). The reflector is of the Davies–Cotton type [7] and consists of 345 identical hexagonal facets attached to an optical support structure (OSS) made from tubular steel. The mirror facets are spherical, with a radius of curvature of 24 m and an area of 0.32 m^2; the surface area of each reflector is 110 m^2 and its focal length is 12 m. The camera is suspended by a steel quadrupod and is balanced by a counterweight behind the reflector, as shown in Fig. 1. To decrease the dead area between the PMTs and to shield against scattered background light, a matrix of light concentrators is mounted in front of the PMTs. The concentrators follow a modified Winston cone [8] design. The telescope plate scale is such that each PMT has an angular diameter of 0.15° and the entire camera has a field-of-view of 3.5°, with off-axis acceptance above 65% out to a radius of 1° from the centre.

Each reflector/camera combination is mounted on a commercially available altitude-azimuth positioner capable of slewing at approximately 1° per second.

2.2. Electronics and trigger

The signal from each PMT is pre-amplified locally and sent through a coaxial cable to an electronics trailer

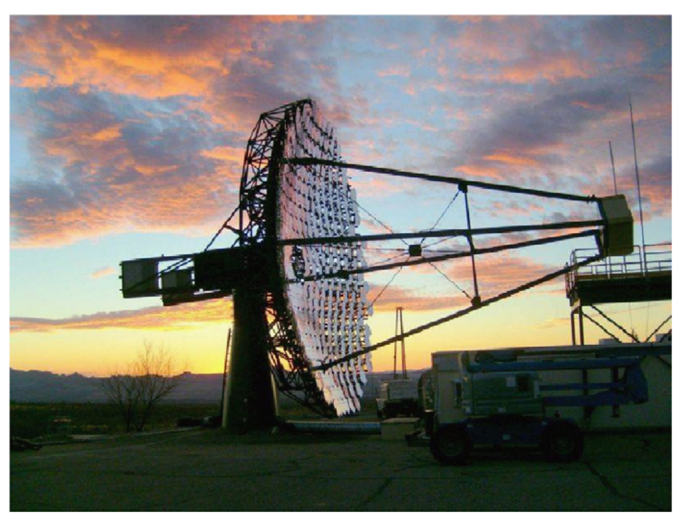

Fig. 1. Side view of one of the VERITAS telescopes showing the camera box at the focal point of a 12-m-diameter tesselated reflector of the Davies–Cotton design and balanced by a counterweight behind the reflector.

(one per telescope) where it is split, with one copy encountering a constant fraction discriminator (CFD) and the other copy a digitizer. The CFDs constitute the first-level trigger for VERITAS. Hits from the CFDs are used in the second-level trigger which looks for patterns where three or more adjacent PMTs have fired. The third-level, or array, trigger requires such clusters of hit pixels from a minimum number of telescopes to initiate readout of the digitizers.

Each pulse digitizer is a custom-made 500 MS/s Flash Analog to Digital Converter (FADC) which writes continuously into a 64 μs-deep memory. The FADC is an 8-bit device but saturating pulses trip an analog switch causing a copy of the pulse which has experienced less amplification (approximately a factor 6) to be digitized instead, thus increasing the dynamic range.

The data stream consists of 24-sample (48 ns) traces from all PMTs in the four cameras, together with a small amount of ancillary information such as PMT currents and telescope pointing information. Pulse timing and charge information is reconstructed off-line from the FADC information.

2.3. Construction history

VERITAS construction began in the summer of 2003 when a prototype was built at the Whipple basecamp. This prototype, comprising full-sized mechanical components with a reduced number of mirror facets and PMTs, was upgraded to become the first array telescope in 2005 [9]. The second telescope was completed and commissioned in the fall/winter of 2005/2006 and the third and fourth telescopes followed sequentially in 2006 with commissioning of telescope four taking place in early 2007. The results presented here come mainly from data obtained with two or three telescopes.

2.4. Performance of the array

Performance figures for the full four-telescope array have been predicted by Monte-Carlo calculations which have been validated using observations of the Crab Nebula made with two- and three-telescope configurations [10]. Some figures of interest are:

- effective area rising from $3\times10^4\,m^2$ to more than $10^5\,m^2$ over the energy range from 100 GeV to 30 TeV,
- energy resolution: 10–20% depending on energy,
- single event angular resolution: $<0.14^\circ$, and,
- sensitivity: a source with 10% of the Crab flux will give a 5σ detection in under 1 h.

3. Results from 2006 and 2007

In this section we present results of observations made during late spring and early summer of 2006 and from fall 2006 and winter 2007. During this period different telescopes and subsystems in the array were being brought on-line and we ran with a variety of configurations and sensitivities. In general, the data for a given source were taken with a particular configuration which will be specified as necessary.

3.1. Markarian 421 and Markarian 501

The two blazars Mrk 421 and Mrk 501 have been popular targets for VHE observations since they were first discovered in the 1990s [11,12]. Like all blazars, they are variable sources and these two are quite easy to detect when, in an active or flaring state, their fluxes exceed that of the Crab Nebula.

These two sources were observed in the spring of 2006 using the first two VERITAS telescopes [13]. Initially, data were taken using 'on–off' mode wherein a half-hour run with the telescopes tracking the source is followed by a half-hour run with the telescopes tracking a background region at the same declination but offset by 30 min in right ascension. This strategy is wasteful of observing time but was necessary in the early days to help understand the new instrument. Of the total of 17 h of the data for Mrk 421, 4.5 h, taken in April 2006, were obtained in this way. The data for Mrk 501 were obtained during the period from April to June 2006 using 'wobble' mode. This technique makes use of the relatively large field-of-view of the VERITAS cameras. With good acceptance out to a radius of 1° off axis, it is possible to track the source with it displaced by 0.3° from the centre of the camera. Background can be estimated by examining data from the same run. For example if the source is tracked offset to the east, background can be calculated by averaging the events which reconstruct to the same off-axis angle but in the west, south and north directions.

The VERITAS data-analysis package calculates the arrival directions of candidate gamma rays using the images in the camera planes resulting from the showers they generate. The squares of the differences between these angles and the direction of the source being tracked (θ^2) can be histogrammed, as in Figs. 2 and 3. Any signal is manifest as an excess of on-source entries over background entries at small values of θ^2.

The excess in Fig. 2 is a 35σ effect and the estimated average flux for this data set is calculated to be 5.7 gamma rays per minute. This strong signal is a consequence of the fact that Mrk 421 was particularly active during this period. In contrast, Mrk 501 was relatively quiet during the 2006 observations, as is evidenced by the weaker signal (16σ) in Fig. 3, which corresponds to a gamma-ray rate of 0.8 gamma rays per minute. Note that this flux level, although it is not necessarily the baseline flux from Mrk 501, is lower than the sensitivity levels of previous-generation detectors such as the Whipple 10-m telescope [2] and the HEGRA array [14].

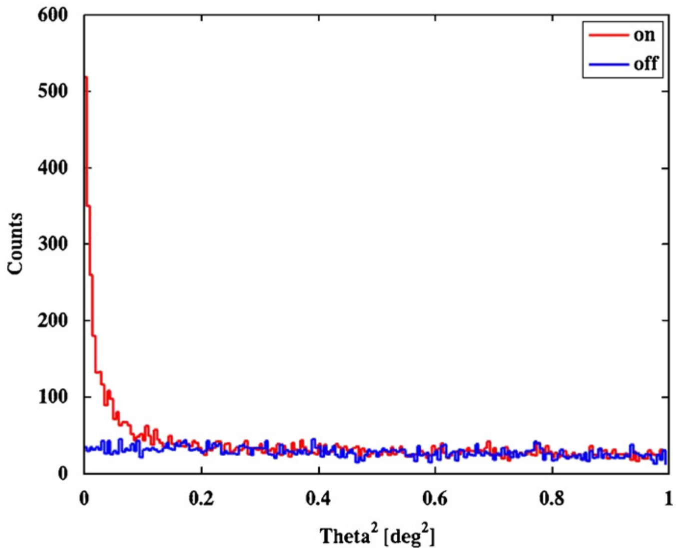

Fig. 2. Number of gamma-ray candidates as a function of the square of the angular distance between the target and the reconstructed direction of the candidate. The curve labelled as ‘on’ results from data taken with the telescopes tracking the source (Mrk 421) and the ‘off’ curve data were obtained with the telescopes tracking a similar region of sky not containing the target source.

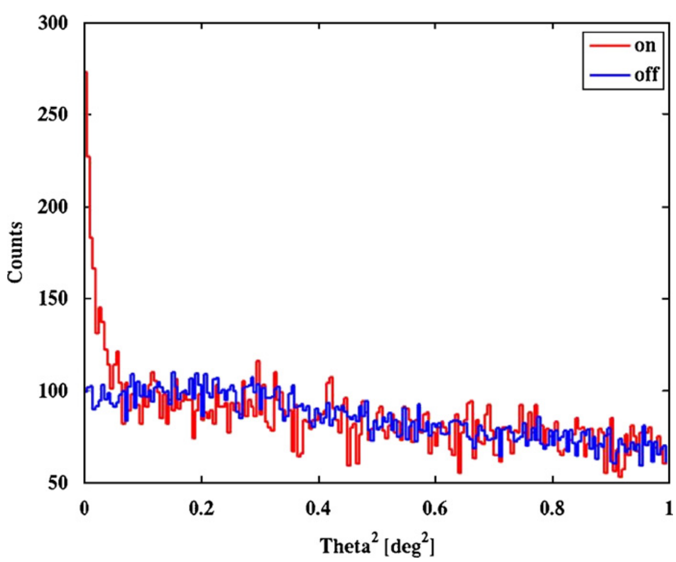

Fig. 3. As for Fig. 2 but for Mrk 501 and using ‘wobble’ mode rather than ‘on–off’ mode for background estimation.

3.2. 1ES1218+304

1ES1218 + 304 is a TeV blazar. Like Mrk 421 and Mrk 501, it belongs to the class of sources called high-frequency-peaked BL-Lac objects (HBLs) but it is much further away, at $z = 0.182$. (Mrk 421 is at $z = 0.031$ and Mrk 501 is at $z = 0.034$.) It was predicted to be a TeV emitter by Costamante and Ghisellini [15] based on its large X-ray flux and their modelling of the spectral energy distributions of BL-Lac objects; it was recently detected for the first time by the MAGIC collaboration [16].

VERITAS observed 1ES1218 + 304 during the period from December 2006 through March 2007 [17] with two or three telescopes and using ‘on–off’ and ‘wobble’ observing modes. Most of the data were obtained using three telescopes and the ‘wobble’ mode with offset angle 0.5°; we report on these data here. After preliminary selection based on weather and hardware requirements we are left with 17.4 h of data taken at zenith angles ranging from 2° to 35°. Preliminary results are shown in Figs. 4 and 5. The θ^2 plot shows a clear excess (8.9σ) of signal over background at small values ($\theta < 0.158$) so we can confirm the original MAGIC discovery. Since flux from blazars can vary with time, we have plotted flux levels (uncorrected for zenith-angle acceptance effects) as a function of time in Fig. 5. The upper panel shows the flux for all of the data runs, each 20 min in length. The lower panel displays the daily averages. The data are consistent with constant flux but statistics are limited. More observations on this source are planned since, due to its great distance, it is an important source of information on the attenuation of gamma rays by the extragalactic background light (EBL) [18].

3.3. M87

M87 is a giant elliptical radio galaxy located in the Virgo cluster of galaxies at a distance of about 16 Mpc. It has an active nucleus powered by a super-massive (3.2×10^9 solar mass) black hole and a kiloparsec-scale jet is seen to emerge from the galaxy. The angle of the jet is not precisely known although there is evidence from superluminal motion [19] that it is as small as 20° with respect to our line-of-sight to M87. Except for the jet orientation, M87 is very similar to

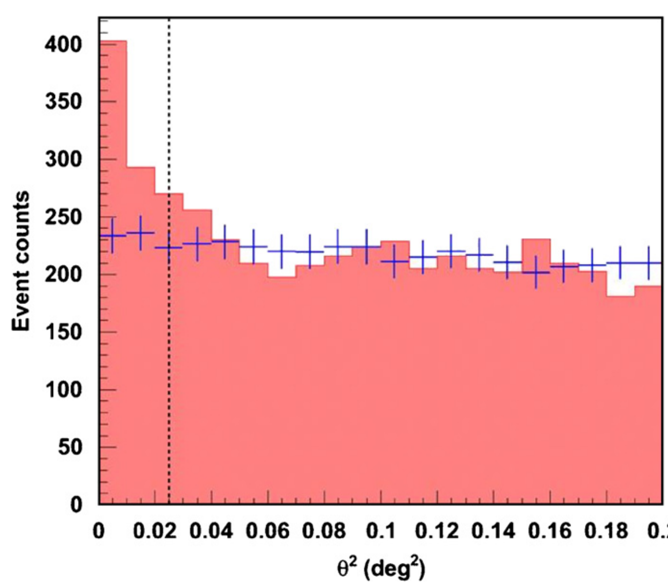

Fig. 4. θ^2 plot for 1ES1218 + 304 data taken in ‘wobble’ mode. The solid histogram entries correspond to the direction of the source while the crosses are background levels calculated from the corresponding off-source directions. The vertical line denotes the cut at $\theta = 0.158°$ used for calculating flux levels.

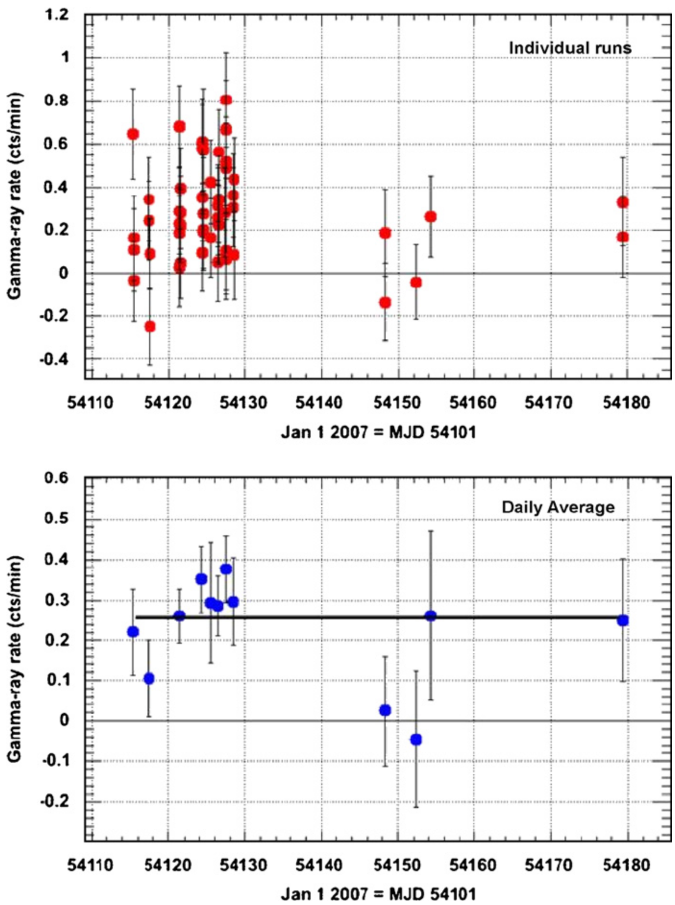

Fig. 5. Raw flux levels (uncorrected for zenith-angle effects) versus observation time for 1ES1218 + 304. The upper panel shows a data point for each 20-min data run and daily averages are plotted in the lower panel.

BL-Lac objects and could therefore be a TeV gamma-ray source. Indeed, a flux of VHE photons has been detected from this source by the HEGRA [20] and HESS [22] collaborations. Day-scale flux variations were observed by the HESS group, indicating a compact production region for the gamma rays but it is not yet clear whether production occurs close to the core of M87 or in the compact radio structures that can be seen in the jet. As the only non-blazar extragalactic VHE source detected to date, M87 is an object of great interest.

M87 was observed by the VERITAS array [21] from February through April of 2007 at elevations from 55° to 71°. Data were taken in ‘wobble’ mode with a 0.5° offset and although the last 6% of the data were taken using four telescopes, the preliminary analysis reported on here was carried out using only the first three telescopes. Fifty-one hours of data were accumulated and 90% of them passed weather and detector-related quality cuts.

The θ^2 plot for M87 is shown in Fig. 6. An excess of 261 events is evident at small θ^2 values and its distribution is consistent with that which would be obtained from a point-like source (dotted line). The estimated energy threshold for this measurement is 250 GeV and at these energies the excess, which has a statistical significance of 5.1 standard deviations, corresponds to a flux level of about 1.7% of the Crab flux. The data are consistent with a constant flux from M87, although with the modest statistics available, any temporal structure would be hard to detect. The HESS observations [22] which showed evidence for significant day-to-day variations were obtained in 2006 when the source was in a high-flux state.

3.4. LS I +61 303

High mass X-ray binaries can be sources of VHE gamma rays. At the time of writing, three have been detected at TeV energies: PSR B1259-63 [23] and LS 5039 [24] in the southern skies and LS I +61 303 [25] in the north. The latter system is believed to consist of a massive Be-type star with a dense circumstellar disk, orbited by a neutron star or black hole once every 26.5 days. The orbit is close, with the two objects within several stellar radii of each other. Details of the orbit, as determined from optical [26] and radio [27] observations are summarized in Fig. 7 [28].

There are several classes of models which aim to explain the VHE gamma-ray emission from LS I +61 303. One popular class comprises the micro-quaser models wherein the compact object accretes material from the Be star and uses some of the gravitational binding energy to power relativistic jets, which are the sites of gamma-ray production, like in AGNs. Models in the other leading class conjecture that gamma rays are produced in shocks formed from the collision of a relativistic pulsar wind with the wind from the Be star. Observations at a variety of wavelengths and over an extended period will eventually allow the correct description to be determined.

VERITAS observations of LS I +61 303 were made from September through November 2006 and again in January and February 2007 [29]. The first data set was

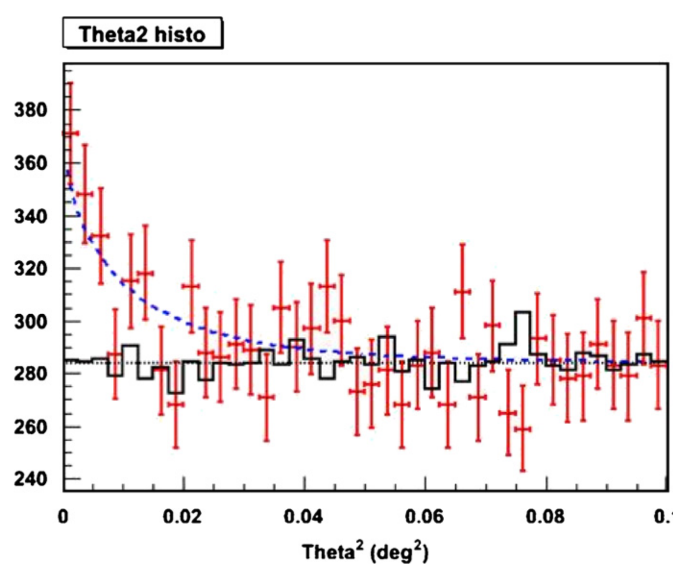

Fig. 6. θ^2 plot for M87 data. The excess is a 5.1 standard deviation effect and its distribution in θ^2 (dotted line) is consistent with that coming from a point source.

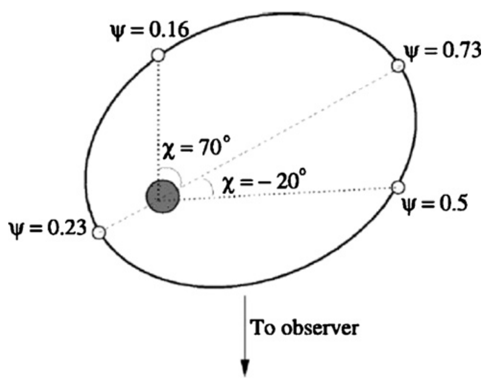

Fig. 7. Orbital details of the LS I +61 303 system as determined from optical and radio data. The period is 26.5 days. (From Ref. [28].)

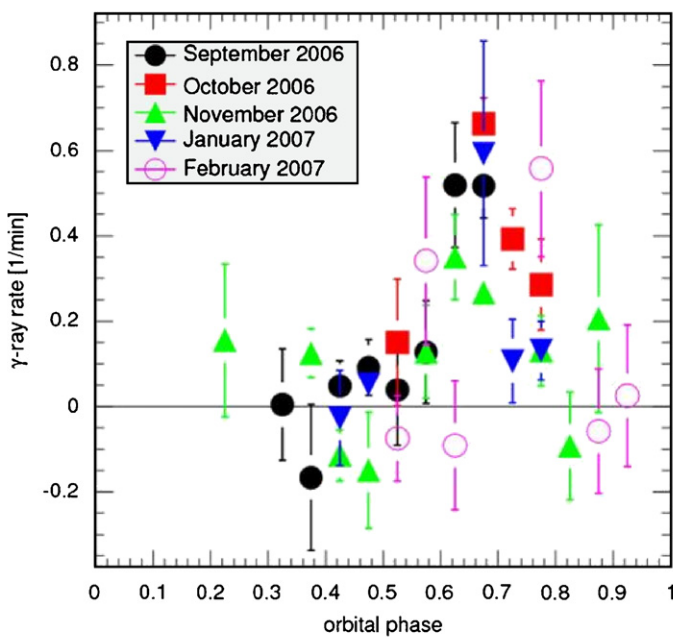

Fig. 8. Raw excess event rates versus orbital phase for five orbits of the LS I +61 303 system, each of which is approximately one month long.

obtained using the first two telescopes in 'wobble' mode with a 0.3° offset and the later data set was obtained with three telescopes and a 0.5° wobble offset. After quality selection cuts, there remained 32 hours of two-telescope data and 12 hours of three-telescope data. The mean elevation of the source for these observations was 60°.

Fig. 8 shows the rate of excess events, uncorrected for elevation angles, array configuration or dead-time (3–7%) as a function of orbital phase. Due to the 26.5 day orbital period of the binary system, which is almost the same length as the lunar cycle, there are no data from the orbital phases between 0.95 and 0.20 which coincided with nights where the moon was above the horizon and no observations were made. At other phases there are varying degrees of rate with a fair amount of statistical scatter. It is evident that significant flux occurs in the phase region 0.6–0.8, corresponding to the part of the orbit where the two objects have their greatest separation. Indeed, for every observation month, except February which had less observation time, detections at or above the 4σ level were obtained.

The detection significance for the entire data set is 8.8 standard deviations. If one combines the data from the five orbits one gets flux values which range from less than 3% of the Crab Nebula flux (99% CL assuming a Crab-like spectrum) in the low state to above 10% of the Crab flux in the high state.

4. Future plans

The construction and commissioning of the VERITAS array are now complete. Detailed understanding of the instrument and its capabilities is improving as more observing and analysis is carried out. At the time of writing, the VERITAS collaboration is beginning its first full observing season with all four telescopes. It is also part of the way through a series of four key science projects which were begun during the previous season and will continue this year. The key science projects, which are to use approximately 50% of the available observing time during the first two years of full operation are:

- a survey in the region of the Cygnus Arm of our galaxy (130 h/year),
- a study of active galactic nuclei (110 h/year),
- a study of supernova remnants (100 h/year), and,
- a search for dark matter annihilation (60 h/year).

The rest of the time will be devoted to proposals submitted to the collaboration's time allocation committee. Follow-up of gamma-ray burst notifications will be given priority when they occur.

5. Conclusions

VERITAS has joined the international group of third-generation VHE gamma-ray detectors and has already been able to make significant contributions to the science that these instruments were built to explore. With a completed telescope array and maturing analysis techniques, we anticipate an exciting future.

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