Analyzing VERITAS Observations of High Energy Gamma Ray Sources: A Comparison of the Ring Background Model with the Maximum Likelihood Method

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The Big Picture: Abstract

VERITAS is a ground-based gamma ray observatory set in Arizona, comprising of a four-telescope array that gathers both gamma ray and cosmic ray events, with electronic detectors that reconstruct the collected data for analytic perusal. We have used data from sources both strong and weak as well as those in different stages of flaring and quiescence to compare two methods for data analysis. In every case, we have found the Maximum Likelihood Method to yield a higher significance of gamma ray detection as opposed to the Ring Background Model, deeming the former the more sensitive and sophisticated of the two alternatives.

Probing the Powerful: Gamma Ray Astronomy

Twenty kilometers above the earth's surface, a very energetic gamma ray (emitted by a blazar, an active galactic nuclei, a supernovae remnant or any other energetic cosmic phenomena) collides with a proton or neutron present inside an air molecule in our atmosphere. This interaction produces a cascade of electrons and positrons that collectively head towards the earth. These secondary particles are also inordinately energetic in character, and travel faster than the speed of light in the atmosphere. This process results in an electromagnetic shock wave that appears as bluish light called the Cerenkov radiation. Large optical telescopes with electronic detectors are capable of recording this brief pulse of light and reconstructing information about the original gamma ray, and this undertaking forms the very basis of gamma ray astronomy.

On a Quest for the Truth: VERITAS

The Very Energetic Radiation Imaging Telescope Array System (VERITAS) is an array of four 12 m diameter ground-based telescopes located south of Tucson, Arizona at the Fred Lawrence Whipple Observatory. It detects the Cerenkov light from gamma ray air showers using a 400-pixel photomultiplier camera positioned in the focal plane of each telescope. Combining the information from all the four telescopes, the array is able to recreate the three-dimensional images of the air showers traveling through our atmosphere. VERITAS is sensitive to gamma rays present in the energy band of 200 GeV to 20 TeV. Figure (i) is a depiction of the VERITAS array.

Figure (i) The VERITAS Array

Down with the Impostors: Cosmic Rays and Background/Noise

Unfortunately, gamma rays are not the only particles that are capable of creating such air showers. Cosmic rays (such as energetic protons and heavier atomic nuclei like Helium) undergo a similar interaction upon striking the atmosphere. The showers they produce bear characteristics both similar and different from those of the gamma ray showers. However, the problem is that cosmic rays produce a far larger number of showers as opposed to gamma rays, and so they form a massive background in comparison to the gamma ray signal we expect to obtain. Various efforts have been assumed to devise a variety of methods to distinguish and discriminate between the two types of showers, but even the best of these methods is incapable of eliminating all the background.

Can we do it? Yes, we can!

In this perplexing situation, we use a method loosely termed the 'On – Off' technique. Upon pointing the telescope at a target source, it collects events both from the target—gamma ray events—along with events from the background. The actual number of events collected, then, is given by N_{on}, such that $N_{on} = N_S + N_{off}$, where N_S stands for the number of events from the source and N_{off} those from the background [1]. If the number of background events were altogether known then the significance of the detection would be given by the statistic:

$$\sigma = (N_{on} - N_{off}) / (N_{on} + N_{off})^{1/2} \qquad \text{(i)}$$

Currently, the standard method used by VERITAS to estimate the background events and the significance of any detection is called the Ring Background Model (RBM). The value of N_{on} is determined by drawing an imaginary circle around the source position in the camera and counting all the events occurring within the circle. Following this, N_{off} is determined by drawing an annulus or a ring about some small distance around the circle, and counting the events in this region after appropriate normalization. These values are used in equation (i) to determine the significance of the source.

Enter MLM: A Force like No Other

The purpose of this project was to test an alternative method, the Maximum Likelihood Method (MLM), for determining the significance of the detection. MLM employs a different approach—rather than applying equation (i) and specifying regions as 'on' and 'off', it utilizes background events from the entire field of view and a computer model of what a gamma ray signal should look like. We then test the two hypotheses:

(i) data best fit by background alone, and
(ii) data best fit by background along with the gamma ray signal.

Following this, we set up a grid for each point in the field of view and draw a map of the respective significances. The detailed procedure for determining the significance of a signal detection using MLM is described in [2].

The Battle Begins

To compare the efficiency of the two alternatives, we used data obtained by VERITAS in the 2008-2009 observing seasons. We analyzed a variety of sets of data, encompassing strong through weak sources. We elected:

(i) the Crab nebula: the standard candle for gamma ray astronomy (a steady source for comparison)
(ii) stronger sources: two different AGNs in flaring states—Mrk 421 and 1ES1218+304
(iii) a weaker source: 3C66A
(iv) a source with both flaring and quiescent data: WComae.

For this procedure, we searched through nightly log files and chose candidates depending on weather and other quality characteristics as depicted in the observer logs. Upon selecting the appropriate runs, we transferred the data files from the UCLA depository and ran them through the four stages of our standard data analysis program: VEGAS (VERITAS Gamma Ray Analysis Suite).

Stage 1 entails the nightly calibration of the data. Stage 2 is responsible for converting the electronic signal (in the photomultiplier tubes) into a measure of the brightness of light detected by the tubes. Stage 3 reconstructs the parameters that describe the image of our event in each individual camera. Stage 4 sifts images from the individual cameras and combines them into a singular array event, and finally stage 5 determines whether the array event is more likely to be a gamma ray event or a cosmic ray event. It is also responsible for eliminating the cosmic ray events. After stage 5, we have computer files comprised of array events that pass the gamma ray selection criteria.

The reconstructed location of each event on the sky is projected onto what we term a sky map. This map is finally fed into either RBM or MLM, which determine if a gamma ray signal is present at any position on the map. Figure (ii) shows this significance map for Mrk421.

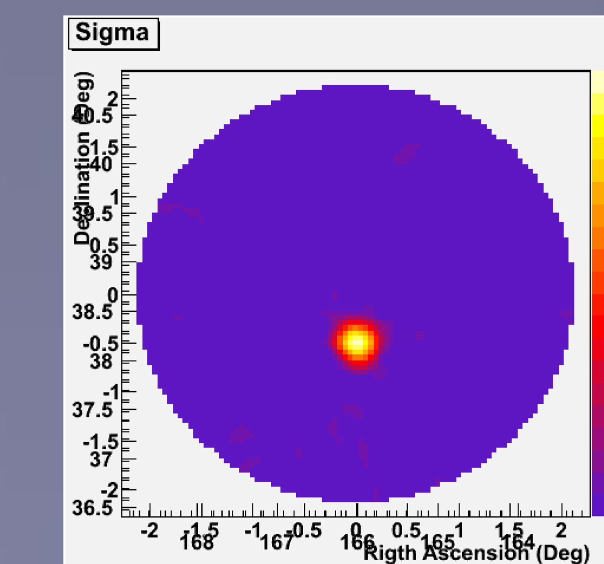

Figure (ii) Mrk421 Sigma Plot

MLM Saves the Day

Our results are presented in Table (i), which lists the chosen sources, dates of data collected, and the duration of source exposure to the array. RBM and MLM both provide the values of sigmas obtained along with an estimate for the number of gamma rays obtained per minute. The final column, sigma per square root hour, takes into account the sigmas over the actual exposure time—for instance, for WComae, we obtained 10.39 sigmas in MLM over 165.24 minutes, translating to a value of 6.26 sigmas per square root hour. In contrast, the Mrk421 data was so strong that in only 8.92 minutes, we had 30.54 sigmas, resulting in a value of 79.17 sigmas per square root hour. In almost every case, MLM yields us a higher value of significance of detection, and we therefore deduce it to be the more sensitive alternative for VERITAS data analysis.

Sr. No.	Source	Date	Duration of Exposure (min)	Sigmas in RBM	Sigmas in MLM	Rate of sigmas/min	SigmaSqrt(hr)
1	Mrk421	27-Mar-08	8.92	23.52	30.54	33.97	79.17
		28-Mar-08	8.97	17.01	21.63	21.24	55.94
2	Crab Nebula	26-Sep-08	55.19	31.079	36.42	9.48	37.98
3	WComae	June, 2008	165.24	8.18	10.39	1.17	6.26
		12-Mar-08	90.02	1.38	4.82	0.38	3.53
					Source Only: 0.99	0.13	0.81
		13-Mar-08	162.34	5.27	7.22	0.78	4.39
		14-Mar-08	125.83	2.26	3.67	0.21	2.63
		15-Mar-08	125.39	3.78	3.83	0.12	2.65
				Source Only: -1.9	Source Only: 0		
		March, 2008	503.57	3.98	6.01	0.35	2.08
		2009	308.74	2.4	4.28	0.12	1.89
					Source Only: 2.74	0.19	1.21
4	1ES1218+304	2009	908.12	17.97	22.67	1.11	5.83
5	3C66A	1-Oct-08	147.46	4.43	5.39	0.61	3.44

Table (i) Results Obtained from RBM and MLM

References

[1] Li and Ma, Astrophysical Journal 272 : 317 – 324, 1983 September 1.
[2] G.H. Sembroski, M.P. Kertzman, S.J. Fegan, Proceedings of the 30th International Cosmic Ray Conference, 2007. Vol. 3 (OG part 2), pages 1409 – 1412.

Acknowledgements

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