Investigating TeV Emission from the Crab Nebula and the Flaring Active Galaxy BL Lacertae

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Abstract. Over the past seven years, the VERITAS gamma ray observatory has seen a substantial flux decrease across its observations. The current hypothesis is that this decrease stems from lower gains and throughput in all of the four telescopes in the array. To combat the problem, correction factors have been developed to account for the flux decrease. We test out these correction factors on the Crab Nebula, a common calibration source used by VERITAS, and explore the implications of the factors on subarray analyses. We also apply these factors to BL Lacertae, an active galactic nucleus and blazar that has exhibited several TeV flares. Our analysis shows that the correction factors do increase the flux from the Crab but do so inadequately, and lead to some unphysical results. Furthermore, they fail to bring about significant changes in BL Lacertae's flux or light curves during an energetic flare in the spring of 2019.

1. Introduction

Gamma ray astronomy provides a window into some of the most energetic objects in the universe. At GeV and TeV energies, high-energy binary systems, supernova remnants, active galactic nuclei and other exotic objects become visible. Studying gamma ray emission from these sources reveals the energetic mechanisms behind them, giving more insight into the fundamental properties of the objects. Although gamma ray astronomy as a science is less than one century old, it has been proved to be extremely useful in uncovering the details behind how these systems work.

1.1 VERITAS

One of the major gamma ray observatories currently in operation is the Very Energetic Radiation Imaging Telescope Array System, or VERITAS, located on Mount Hopkins, in Arizona. VERITAS consists of four identical 12-meter imaging atmospheric Cherenkov telescopes (IACTs), which typically operate simultaneously to observe high energy sources. Since achieving first light in 2007, the telescopes have observed both galactic and extragalactic sources across a wide range of energies, focusing particularly on gamma rays from 100 GeV to several tens of TeV, including very high energy (VHE) gamma rays. [1]

IACTs observe gamma rays indirectly, by detecting the air showers the photons trigger upon entering Earth's atmosphere. When a gamma ray collides with a nucleus, typically about 20-30 km above Earth's surface, electron-positron pair production occurs. The resulting leptons interact with other ambient nuclei, emitting bremsstrahlung radiation and forming additional electron-positron pairs. This eventually results in a relativistic cascade of particles called an air shower. The charged leptons, which are typically traveling faster than the speed of light in air, produce Cherenkov radiation, which is what an IACT detects.

If the Cherenkov radiation from a single shower is observed by multiple telescopes in an array of IACTs, information about the shower, and thus the original gamma ray, can be reconstructed. Image analysis makes it possible to determine the gamma ray's direction, energy, and time of arrival. The air shower can also be distinguished from the much more abundant air showers produced by cosmic rays, which exhibit different morphologies and tend to contain many hadrons, including neutral and charged pions, as well as muons and neutrinos.

1.2 The Crab Nebula

For VERITAS, the brightest object in the gamma ray sky is the Crab Nebula, a pulsar wind nebula located approximately 2 kpc away. Though it has been studied across the electromagnetic spectrum for centuries, it was first detected in gamma rays only in 1998 [2]. Due to its brightness and lack of variability, the Crab is a convenient target and calibration source for VERITAS and other IACTs.

The Crab Nebula is a pulsar wind nebula, powered by the fast-spinning neutron star known as the Crab pulsar. The pulsar loses rotational kinetic energy constantly, emitting some of this in the form of radio waves. Much of the energy is transported to the nebula itself, resulting in continuum synchrotron radiation from a population of relativistic electrons, along with a contribution from inverse Compton scattering.

The simplest description of the Crab's spectrum is a naive power law:

$$\phi(E) = \phi_0 \left(\frac{E}{E_0}\right)^{\Gamma}$$

where Γ is the spectral index. Early power law results indicated a hard gamma ray spectrum for the Crab, with $\Gamma = -2.49 \pm 0.06 \pm 0.04$ [2]. An alternative spectral fit is a logarithmic parabola of the form

$$\phi(E) = \phi_0 \left(\frac{E}{E_0}\right)^{\alpha + \beta \log(E/E_0)}$$

where α is the photon index and β is the curvature parameter. Values of $\alpha = -2.467 \pm 0.006$ and $\beta = -0.16 \pm 0.01$ fit the observed data well [3]. This spectrum extends into the TeV range, making the Crab one of a few known galactic TeV sources.

1.3 BL Lacertae

VERITAS is also sensitive to extragalactic gamma ray sources, many of which are active galactic nuclei (AGNs). The spectrum of an AGN depends on the angle between its jets and an observer's line of sight, as well as whether the AGN is radio-loud or radio-quiet. Blazars are a class of radio-loud AGN with jets pointing nearly directly at Earth; one gamma ray-emitting subset of blazars are BL Lac objects, named after their prototype, BL Lacertae.

A blazar's spectrum is characterized by two peaks, one at low energies and one at high energies. The precise emission mechanism is currently unknown, although two classes of models - leptonic and hadronic - are favored. In both models, the low-energy peak is believed to be due to synchrotron radiation of relativistic electrons in the blazar's jet. The high-energy peak is then due to either inverse Compton scattering of the same population of electrons, or else some process involving protons and heavier nuclei, such as proton synchrotron radiation or collisions between nuclei [4].

Some blazars exhibit flares from time to time. Studying these flares can provide us with information about the structure of the AGN and the mechanism behind its high-energy gamma ray emission. These flares tend to be short-lived, lasting tens of minutes. Some TeV flares have been recorded coming from certain blazars, including BL Lacertae. It is not currently known what processes are responsible for the TeV flares from BL Lac; prior observations have suggested that either shocks near the radio core or fast-moving high-density regions could be responsible for the observed multiwavelength emission [5][6].

2. Motivation

Throughout the past decade, VERITAS observations have indicated that the array is experiencing a decrease in flux. This has manifested itself as both a decrease in flux across each individual observing season, as well as a drop between season. This poses a significant problem, both for VERITAS and for ground-based gamma ray astronomy as a whole, given that only a few IACT arrays like it exist. Clearly, some long-term solution is required to ensure that VERITAS can continue operating normally.

2.1 Gain and throughput factors

The loss of sensitivity appears to be instrumental in nature, coming from the telescopes' mirrors, photomultiplier tubes (PMTs), and other electronics. In addition to mirror reflectivity decrases, the gain from the PMTs appears to be decreasing, as is the throughput, the transmission of the signal through the electronics. Periodic cleaning of mirrors mitigates the problem to some extent, but is inefficient and simply doesn't scale for larger arrays of IACTs, like the future Cherenkov Telescope Array (CTA). Other solutions are clearly needed.

To combat the ongoing sensitivity losses, numerical correction factors have been developed for the VERITAS observing runs. In particular, for each telescope during each night of observing, g and t factors have been computed. g is the ratio of the gain and the simulated gain; t is the ratio of the throughput and the simulated throughput. g and t are inserted at different stages of the analysis, as is

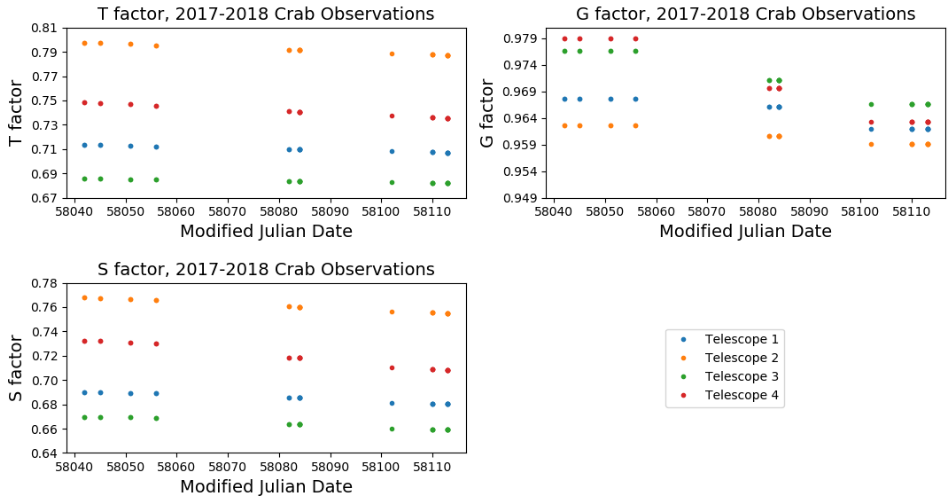

Figure 1: Plots of g, t and s factors for VERITAS for the nights from which Crab observations were used.

their product, $s = gt$. By using the proper gain and throughput factors for a run at the required points in the data analysis, the effects of the sensitivity losses should be mitigated. Plots of the some of the computed factors are shown in Figure 1.

2.2 Project goals

The aim of this project is twofold. The first goal is to test the numerical gain and throughput correction factors on observations of the Crab Nebula. Given the expected consistency of the source's brightness, it is an excellent testbed. Furthermore, to identify potential problems with individual telescopes, the same analysis can be performed on three-telescope subarrays by simply cutting one of the telescopes out of the analysis. Previous work had suggested that there might be disagreements between different subarrays, which should be visible in uncorrected data but disappear after the correction factors are applied [7].

The second goal is to then apply the correction factors to BL Lacertae, a decidedly non-constant source, which exhibited a gamma ray flare in the spring of 2019. This analysis should provide a more accurate picture of the flare, and better place it in context with BL Lac's previous variability, in particular the past TeV flares.

If the g and t correction factors produce significant improvements in the spectra of both the Crab Nebula and BL Lacertae, it would signal that they are a feasible path forward for dealing with the sensitivity problem. If not, some other solution would have to be investigated.

3. Methods

3.1 Data

Data on the Crab Nebula is taken regularly each observing season. For the Crab portion of this project, we focus on data from the 2017-2018 season, using runs spread out between September and March. The runlist was limited to nights with optimal weather conditions, with all four telescopes in the array operating normally.

BL Lacertae's flare occurred in early May 2019, with the strongest detections by VERITAS occurring on May 3 and May 5. As the AGN is much harder to detect in its quiescent state, only observations from May 3 were used in the final analysis, although runs from other nights throughout the 2018-2019 observing season were also studied.

3.2 Analysis

The VEGAS gamma ray data analysis package [8] was used to process the runlists. VEGAS was specifically designed to be used in conjunction with VERITAS data. It consists of six stages, with the third stage currently deprecated.

3.2.1 Primary analysis with VEGAS

The first stage involves hardware-related computations, including calculating particular calibration parameters. The second stage applies these calibrations, as well as some additional corrections. The

Telescopes	Correction Factors	Integral Flux (erg s^{-1} cm^{-2})	Spectral Index
1, 2, 3, 4	No	$(1.010 \pm 0.02013) \times 10^{-6}$	-2.469 ± 0.02248
2, 3, 4	No	$(7.542 \pm 0.1748) \times 10^{-7}$	-2.426 ± 0.02524
1, 3, 4	No	$(6.769 \pm 0.1646) \times 10^{-7}$	-2.390 ± 0.02597
1, 2, 4	No	$(7.365 \pm 0.1724) \times 10^{-7}$	-2.390 ± 0.02481
1, 2, 3	No	$(7.180 \pm 0.1691) \times 10^{-7}$	-2.427 ± 0.02609
1, 2, 3, 4	Yes	$(1.058 \pm 0.02085) \times 10^{-6}$	-2.316 ± 0.02040
2, 3, 4	Yes	$(8.127 \pm 0.1834) \times 10^{-7}$	-2.289 ± 0.02300
1, 3, 4	Yes	$(7.432 \pm 0.1757) \times 10^{-7}$	-2.236 ± 0.02301
1, 2, 4	Yes	$(8.082 \pm 0.1817) \times 10^{-7}$	-2.266 ± 0.02230
1, 2, 3	Yes	$(7.901 \pm 0.1796) \times 10^{-7}$	-2.287 ± 0.02263

Table 1: Best-fit parameters for corrected and uncorrected Crab data.

fourth stage reconstructs the properties of the observer shower, applying certain specific cuts to the data. The fifth stage implements background rejection, while the sixth stage performs background estimation and carries out the final portion of the analysis, producing spectral fits, where possible.

The primary changes we made to the normal process of analysis were twofold: the gain and throughput factors were applied in stage 2, when chosen, and the cuts specifying a particular subarray were applied in stage 4. For each subarray, the first stage did not need to be re-run after the first computations of the stage 1 parameters, since those remained the same for all subarrays.

For the Crab, medium cuts were applied, but for BL Lacertae, soft cuts were required, as the blazar has a softer spectrum. All other parameters were kept the same.

3.2.2 Light curves

After the initial analysis of BL Lacertae with VEGAS was completed, the vaMoonShine command was used to generate light curves. vaMoonShine allows the user to pick various parameters for the bins and energy limits, and thereby choose the parameters to produce a proper light curve. When studying the May 3 flare, small time bins were used, of 1 minute each.

4. Results

4.1 The Crab Nebula

The Crab proved to be an excellent test of the g and t correction factors. We found consistent results among all four telescopes and across the 2017-2018 observing season. Overall, we found spectral hardening among all four subarrays when the correction factors were added. We also produced increases in the integral flux above 0.3 TeV, though not enough to fully compensate for the flux decreases. Key Crab spectral parameters are listed in Table 1.

4.1.1 Spectra

The best-fit power law spectra derived from the four-telescope observations both with and without the correction factors are shown in Figures 2 and 3. The power-law model fits the data well for 200 GeV $< E <$ 10 TeV, with a slight statistical preference for the uncorrected model. We also note a hardening of the spectral index, from $\alpha = 2.469 \pm 0.02248$ to $\alpha = 2.316 \pm 0.0204$, the latter of which strongly conflicts with previous measurements.

The individual three-telescope subarrays change similarly, with harder spectral indices in all four cases, as shown in Figures 4 and 5. There is little scatter among the indices, and nothing statistically significant. The correction factors merely shift the spectral indices to harder values, rather than producing a significant change in their positions relative to one another.

4.1.2 Integral fluxes

Of particular interest is the integral flux of VHE gamma rays measured by each of the subarrays, in this case taken above 0.3 TeV. We would expect anomalous behavior in one of the telescopes to manifest itself here. Prior analysis [7] showed a statistically significant decrease in mean integral flux coming from the subarrays with Telescopes 1, 2 and 3 (T123), and Telescopes 1, 2 and 4 (T124) of approximately 5%, which would presumably show up in our uncorrected data and disappear once the correction factors are applied.

While the runlist does not reproduce the subarray discrepancy, it does demonstrate a slight increase in integral flux for all four subarrays, as well as the

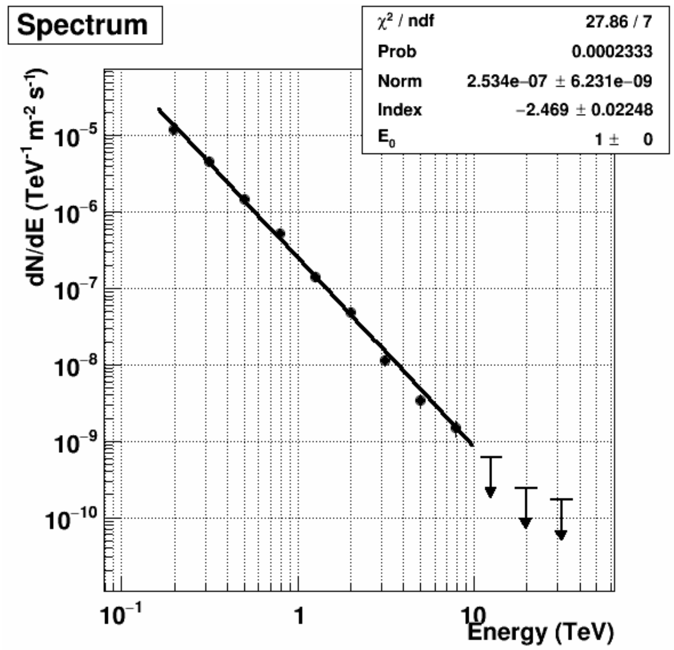

Figure 2: The uncorrected VHE spectrum of the Crab, fitted from measurements from the 2017-2018 observing season. Compare to figure 3.

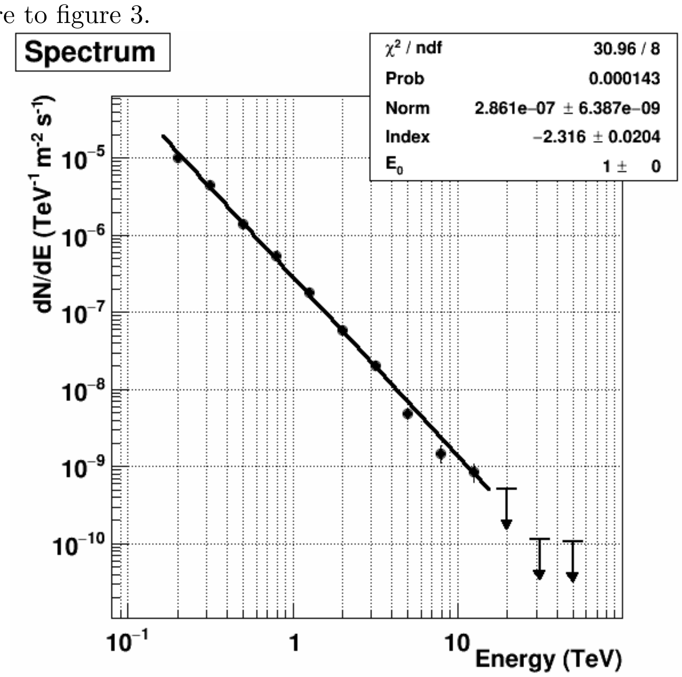

Figure 3: The corrected VHE spectrum of the Crab, fitted from measurements from the 2017-2018 observing season. Compare to Figure 2.

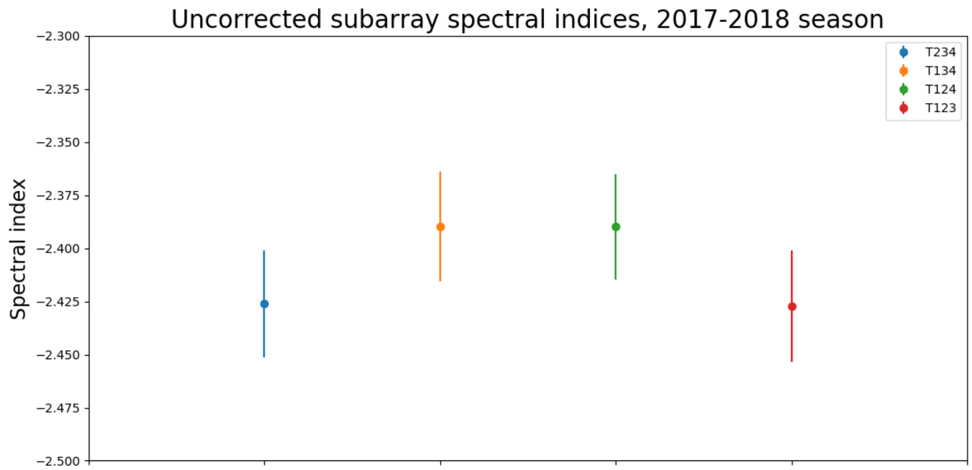

Figure 4: Uncorrected Crab spectral indices for individual VERITAS subarrays.

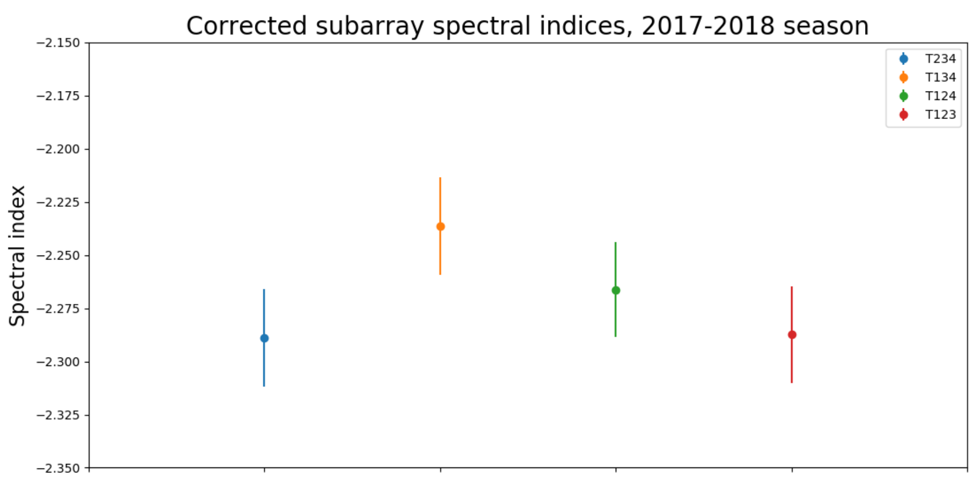

Figure 5: Corrected Crab spectral indices for individual VERITAS subarrays.

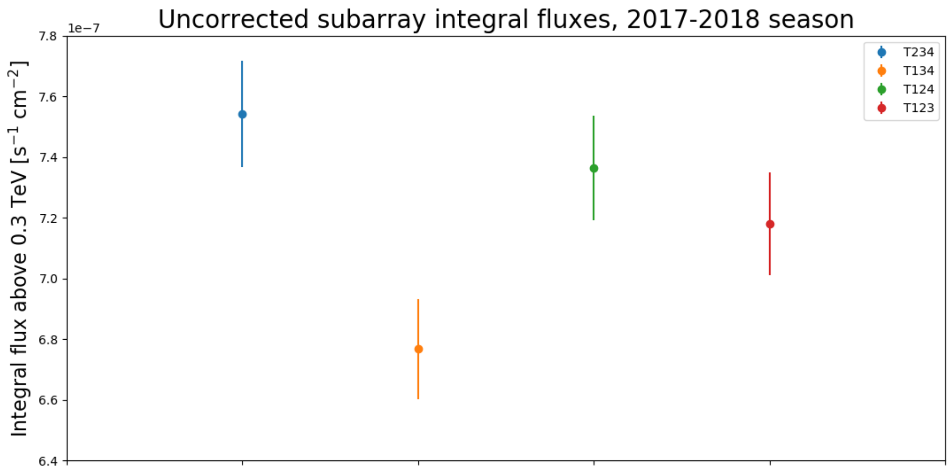

Figure 6: Uncorrected integral Crab fluxes for individual VERITAS subarrays.

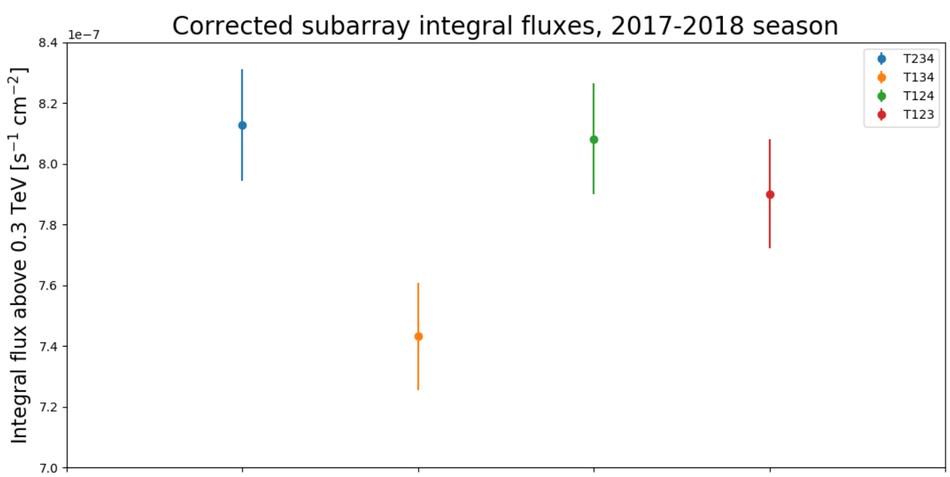

Figure 7: Corrected integral Crab fluxes for individual VERITAS subarrays.

array as a whole, indicating that the g and t factors do correct the data for the better. However, this increase is small and does not fully compensate for the flux decrease.

4.2 BL Lacertae

BL Lacertae proved a more challenging target than the Crab because in its quiescent state, it is dim and not easily detectable. Therefore, any flare analysis must take this into account and apply time and energy cuts carefully. The AGN proved difficult to detect on many runs throughout the 2018-2019 observing season, even when applying soft cuts and using the full array of telescopes.

4.2.1 Detection and spectra

On nights not involving the flare, BL Lacertae was not detected with any significance; the mean high-energy flux was too low. When the data from May 3 was analyzed on its own, however, VEGAS was able to detect the AGN, once soft cuts were applied and the runlist was limited to the run from that night.

The uncorrected spectra produced few VHE data points, and it was difficult to fit a power-law spectrum to the data. The g and t correction factors, however, made it possible to fit such a spectrum, though with large error bars. The spectral index for the VHE data was $\Gamma = -4.072 \pm 0.9433$ - extremely soft. This is not unexpected, however, as BL Lacertae is known to be a soft gamma ray source, and soft cuts were applied in Stage 4.

4.2.2 Light curves

vaMoonShine was used to produce light curves for the May 3 flare. Bins on the order of a day were unable to produce light curves on other nights, but enough significant events were detected on May 3 for 1 minute bins to be used.

Unfortunately, these bins did not yield a trend throughout the night, as would be expected from a TeV flare like the ones previously detected from the AGN. Varying the time bin size also did not improve the results. The g and t factors did not seem to have an effect on the light curve fits, nor did they even consistently decrease the size of the error bars on individual data points.

5. Discussion

5.1 Correction factors

The aim of this project was to experiment with the gain and throughput correction factors, testing the hypothesis that those losses are behind the VERITAS flux decrease. Unfortunately, the key integral fluxes did not change as expected. While there was consistent improvement across all four telescopes, the change was not dramatic.

Although analyzing the uncorrected Crab data produced spectral fits consistent with existing studies of the Crab, adding in the g and t factors produced substantial spectral hardening, visible across all four subarrays. This hardening is likely unphysical and simply an artifact of the correction factors. It seems

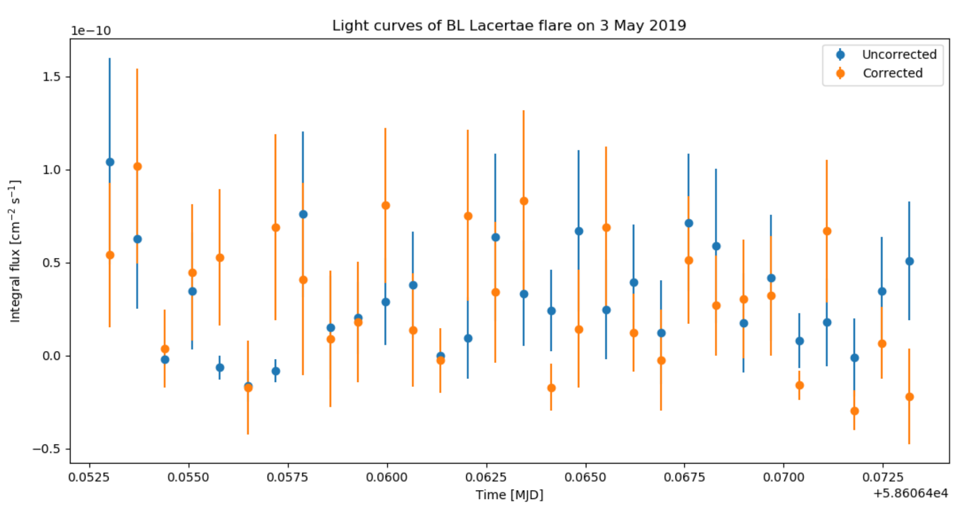

Figure 8: Uncorrected and corrected light curves for BL Lacertae during the flare on May 3, 2019.

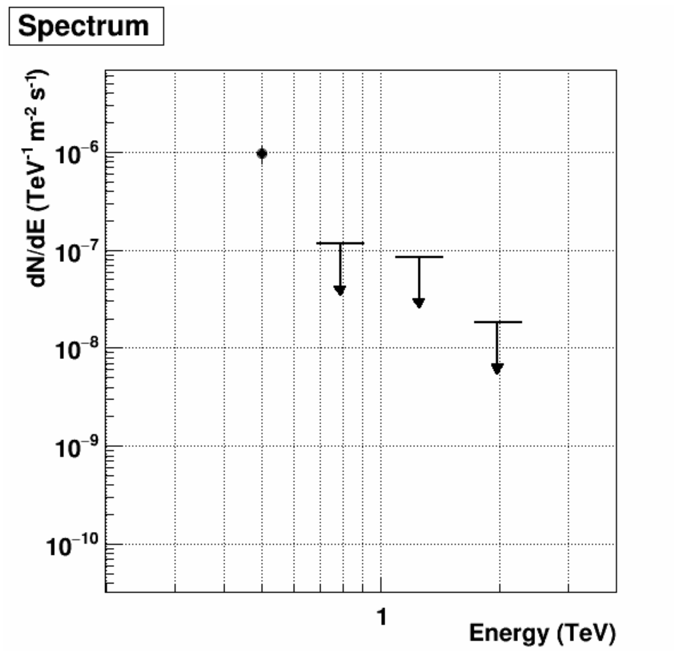

Figure 9: The uncorrected VHE spectrum of BL Lacertae during the May 3 flare.

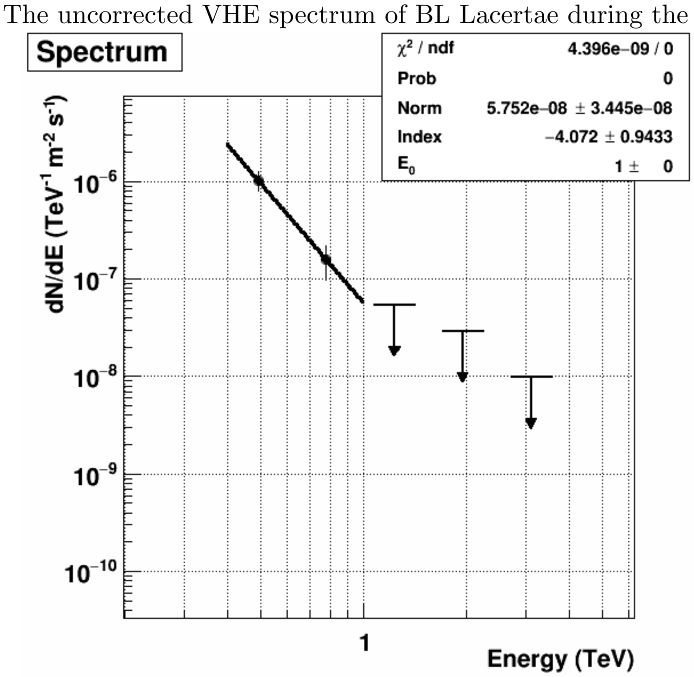

Figure 10: The corrected VHE spectrum of BL Lacertae during the May 3 flare.

to be another indicator that the current method of applying the correction factors is not the right way to adjust for the decrease in flux.

The failure to characterize of the May 3 flare in 1 minute bins both with and without the correction factors is also troubling. However, it is not entirely surprising. BL Lacertae is a dim target, and we expected to have difficulty deriving any information about the flare. We did find non-zero flux during the flare, indicative that there was indeed activity going on, but the correction factors did not improve this much.

5.2 Subarray behavior

Our subarray analyses failed to reproduce the flux discrepancy, which we expected to find. There are several possible reasons for this; for instance, we used different data analysis software, and it is possible that using the same software as [7] would have led to the same results.

That said, if our subarray results are indeed correct, then there is not a single telescope that has developed problems, which we are pleased to find. If we had seen a significant difference in flux coming from one or more telescopes, it would have been extremely troubling.

5.3 Future work

There are several directions in which followup work could extend this research. First, simply testing the gain and throughput factors on the Crab over other observing seasons would either support or cast doubt on the findings of integral flux and spectral hardening.

Second, if the current method of applying the factors is indeed unhelpful, it's possible that they could be used in a different way. The current method generates Monte Carlo simulations of the telescopes as they would behave in peak condition, and applies the correction factors to fix the data. An alternative would be to use the correction factors to degrade the simulations and compare these degraded simulations to the data.

Yet another possibility would be to apply the image template maximum likelihood method (ITM) in place of the standard VEGAS analysis [9]. Although ITM may be computationally more expensive, it would be an excellent check of the current results.

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