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Abstract

We perform an analysis of the long- and short-term variability of the very high energy (VHE; above 100 GeV) gamma-ray emission from the newly-detected distant blazar 1ES 0647+250. Both new and archival data from the VERITAS telescope were examined, and no strong evidence for integral flux variability on any timescale was found. This lack of variability is consistent with the application of current ultra-high energy cosmic ray (UHECR) models, which can produce secondary gamma-ray emission along the line of sight from the blazar; it also allows averaging over multiyear timescales without bias, aiding in the construction of spectral energy distribution plots (SEDs) for 1ES 0647+250. Because of its distance, 1ES 0647+250 is an object of interest for further study, particularly in efforts to constrain models of the extragalactic background light (EBL) and intergalactic magnetic field strength (IGMFs).

Keywords

blazars, high energy, distant, VERITAS, 1ES 0647+250

Cover Page Footnote

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I. Introduction

The extremely high energy released by the infall of matter onto a supermassive black hole (SMBH) provides excellent observational evidence to better understand black holes, cosmic rays, and high-energy astrophysics. Such an accreting black hole is called an active galactic nucleus (AGN), which is defined as a bright galaxy core dominated by non-thermal emission and associated with a presumed SMBH, which is surrounded by a hot accretion disk. Perpendicular to the disk, relativistically-beamed jets of high-energy particles and photons expel massive amounts of energy from the center of the SMBH (please see Krawczynski & Treister, 2013, or Urry & Padovani, 1995, for a detailed overview of AGN). AGN are generally classified firstly as either radio-quiet or radio-loud, depending on whether or not jet emission dominates the observed spectrum. Blazars are a type of radio-loud AGN oriented with their jets pointing very close to Earth's line of sight, and thus exhibit strong relativistic beaming and often high variability. The jets are thought to be powered by extremely strong magnetic fields resulting from the ionized accretion disc surrounding the spinning black hole (Blanford & Znajek 1977). However, our specific knowledge of intrinsic blazar behavior is quite limited, and much of the work in this field attempts to constrain models of jet mechanisms and emission spectra (Dwek & Krennrich 2013). Blazars produce gamma rays in the range 100 GeV to 30 TeV. Upon incidence to Earth's atmosphere, these rays produce Cherenkov radiation that can be detected by VERITAS and other ground-based telescopes and reconstructed to find the original gamma ray trajectory. The VERITAS collaboration is part of the emerging Very High Energy (VHE) subfield of astrophysics, which has the potential to investigate fundamental cosmological parameters as well as high-energy particle interactions.

Ultra-High-Energy Cosmic Ray (UHECR) Models

Primary γ-rays directly from the source may not be the only origins of γ-ray events. Blazars are likely to produce ultra-high-energy cosmic rays (UHECRs) as well, which can interact with background photons to produce secondary γ-rays during propagation. The secondary γ-ray signal from a nearby blazar is insignificant compared to its primary signal. However, for distant blazars, the primary γ-ray flux is exponentially attenuated by Extragalactic Background Light (EBL) photons before reaching Earth (Domínguez et al, 2013). In this case, the signal from UHECR interactions becomes important; this now-dominant source of secondary γ-rays depends on the unobservable proton high-energy spectrum (Essey et al. 2011). Although protons (cosmic rays) still interact only rarely with background photons, it is possible that the VHE signal from these distant sources ($z > 0.15$) is dominated by secondary γ-rays rather than primary γ-rays (Prosekin et al. 2012). Additionally, the secondary γ-rays have less distance to travel, once produced, and thus are less likely to themselves be attenuated by background. A detailed analytical description of these line-of-sight cosmic ray interactions is presented in Essey et al. (2011) and Prosekin et al. (2012).

The current standard models of blazars, e.g. synchotron-self-Compton (SSC) or External Compton models, do not include a contribution from UHECR secondary γ-rays. However, these models are insufficient to explain unexpectedly hard gamma ray spectra (i.e. their maxima are higher in energy than predicted) for some blazars (Katarzynski et al. 2006; Stecker & Scully 2007; Lefa et al. 2011). Other attempts have been made to solve this problem, such as introducing hypothetical new particles (de Angelis et al. 2007; Horns & Meyer 2012) or Lorentz invariance violation (Protheroe & Meyer 2000). Including a contribution from UHECR interactions offers an alternative solution. By adding a UHECR correction to existing blazar models, we hope to explain the intrinsic high-energy spectra of blazars more accurately. This correction is based on the assumption that, as mentioned earlier, primary VHE gamma rays will be attenuated much more strongly than secondary ones (for details, please see Prosekin et al. 2012).

Using Blazar Variability to Investigate UHECR Models and IGMF Strength

If a UHECR flaring event occurred locally at the blazar, the arrival of their corresponding secondary γ-rays would be smeared out in time. Each cosmic ray interacts with a background photon at a random point along the propagation length, resulting in temporal smearing due to both the v<c travel of the initial cosmic ray and the slightly off-axis travel paths of the secondary γ-ray (Prosekin et al. 2012). This temporal smearing of secondary γ-rays should make it nearly impossible to observe a UHECR flaring event for a distant blazar; only in the case of distant blazars does secondary γ-ray flux outshine the attenuated primary flux. Thus far, variability has been observed in nearby blazars on quite short time scales (Sadrinelli et al., 2014; Macomb & Shrader, 2014); however, these flaring events have not yet been observed for distant blazars. This evidence is consistent with the UHECR model. In the future, if variability for a distant blazar is observed, the UHECR model must be modified or discarded.

Since UHECRs are highly energetic charged particles, each one will be slightly deflected by turbulent Intergalactic Magnetic fields (IGMFs). For a cosmic ray to travel relatively straight towards Earth requires IGMFs less than $\sim 10^{-14}$ Gauss (Essey, et al. 2011). This value is in agreement with current constraints on IGMF strength. If the UHECR model were confirmed, quantifying the spatial smearing of secondary γ-ray arrival would place more accurate limits on IGMF strength. However, with current technology the deflections of cosmic rays are smaller than the angular resolution of Imaging Atmospheric Cherenkov telescopes like VERITAS, so this type of analysis is not quite feasible (Essey, et al. 2011).

In summary, if a distant blazar shows substantial variability, the secondary γ-ray signal is negligible. This could be due to stronger-than-expected IGMFs, but because IGMF strength is constrained by other unrelated experiments, the more likely cause would be that very few protons were actually produced at the blazar: a strike against the UHECR model. If a distant blazar does not show short-term variability, there are a few possible explanations. Firstly, the telescope may simply not have observed that particular object for a long enough interval to "catch" a flaring episode. Secondly, this UHECR model could be correct, and the observed signal, because it is dominated by temporally-smeared secondary γ-rays, does not show flaring.

Confirming Constant Flux for SED-Building

Performing variability analysis, particularly on multiyear timescales, can be an important precursor to building Spectral Energy Distribution plots (SEDs), which show source output flux as a function of photon wavelength. Confirming constant flux for a given source allows averaging over a long time period without introducing unwanted bias. Because SEDs are essential to our understanding of intrinsic blazar spectra, as much archival data as possible is usually utilized. It is therefore advantageous to ensure protection from any potential bias resulting from the use of older data. A proper assessment of upper limits and careful characterization of the variability properties of the source is required to remove the possibility of bias.

II. Experimental Procedure

Detecting γ-rays with VERITAS

When a VHE γ-ray enters the Earth's atmosphere, it produces an electromagnetic cascade of relativistic electrons, positrons, and more γ-rays. The produced particles are so energetic that they actually move faster than the phase velocity of light in the atmosphere. As they travel, they polarize neighboring molecules, which then decay back quickly to the ground state, emitting radiation. This radiation is called Cherenkov radiation, and peaks around 300-350nm. Imaging Atmospheric Cherenkov Telescopes (IACTs) like VERITAS indirectly detect γ-rays by measuring the brief flashes of Cherenkov radiation produced by each event. VERITAS' four telescopes each measure an elliptical projection of the electromagnetic shower, allowing the original γ-ray trajectory to be reconstructed using detailed moment analysis. A full description of VERITAS observations is provided in Acciari, et al. 2010.

Cosmic rays interacting with the atmosphere also produce Cherenkov radiation, creating potential false-positive detections. These false positives can be distinguished from real gamma-ray signals by analyzing the shape of the signal on the camera display. Figures 1 and 2 below show the camera display (signal to each pixel) for both a simulated gamma-ray and a real hadron (cosmic ray). Gamma-ray events tend to produce narrow and compact ellipses, while cosmic ray events produce wider and less compact ones. Current software successfully removes 99.9% of cosmic ray events, a rate of false-positive rejection that is appropriate in comparison to the relative frequency of cosmic rays and γ-rays entering the atmosphere.

Figure 1 – VERITAS Camera Image of Cosmic Ray Event

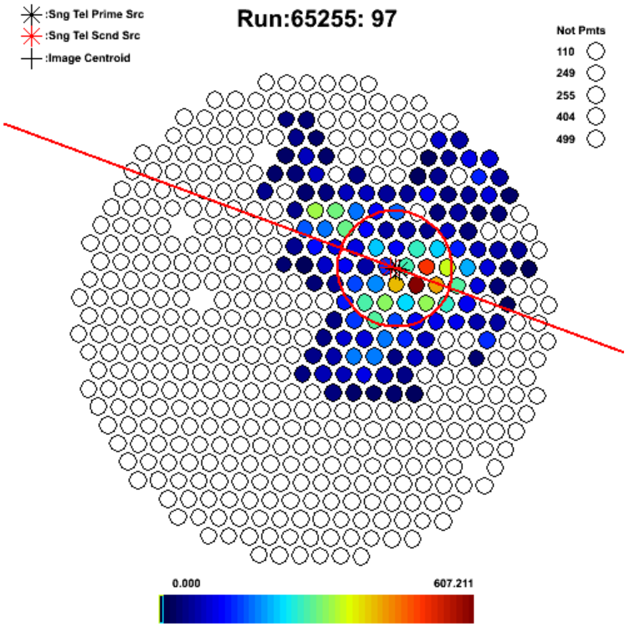
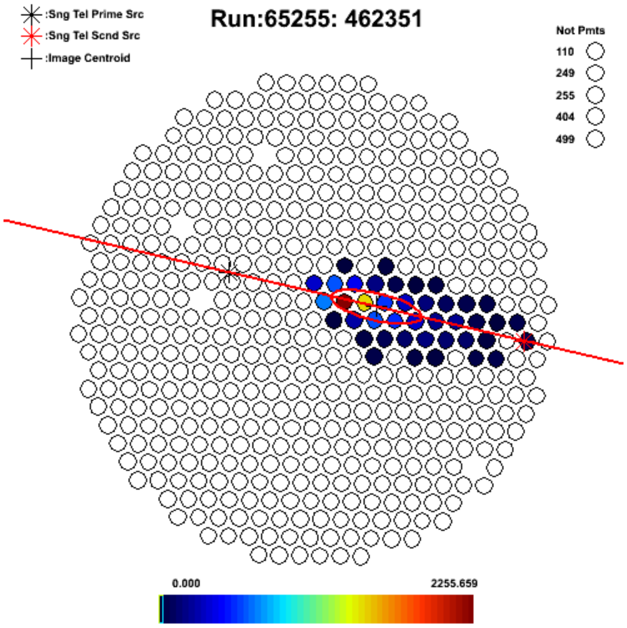


Figure 2 – VERITAS Camera Image of Gamma Ray Event



III. Data and Results: Blazar 1ES 0647+250

Blazar 1ES 0647+250 was first detected by VERITAS in 2013. Prior to the 2013 season, a significant upgrade to the VERITAS cameras was completed, resulting in ~35% higher quantum efficiency of the Photomultiplier Tubes. As a result of this equipment upgrade as well as upgrades to the software analysis pipelines, 1ES 0647+250 was VHE-detected in only ~10 hours, despite having been observed previously for 27 hours without detection. Recent literature (Kotilainen et al.) estimates a redshift of ~0.45, making 1ES 0647+250 the 3rd or 4th most distant VHE-detected blazar and so a good candidate for testing UHECR propagation models. The 2013 data contain enough nights of observing time to examine short-term variability, and by looking at the 27 hours of archival data we are able to compare the older upper limit with the detected flux from this year's data, which gives an estimate of long-term variability. Finally, we combine our VHE gamma-ray data with observations at other wavelengths and begin to build an SED for this object.

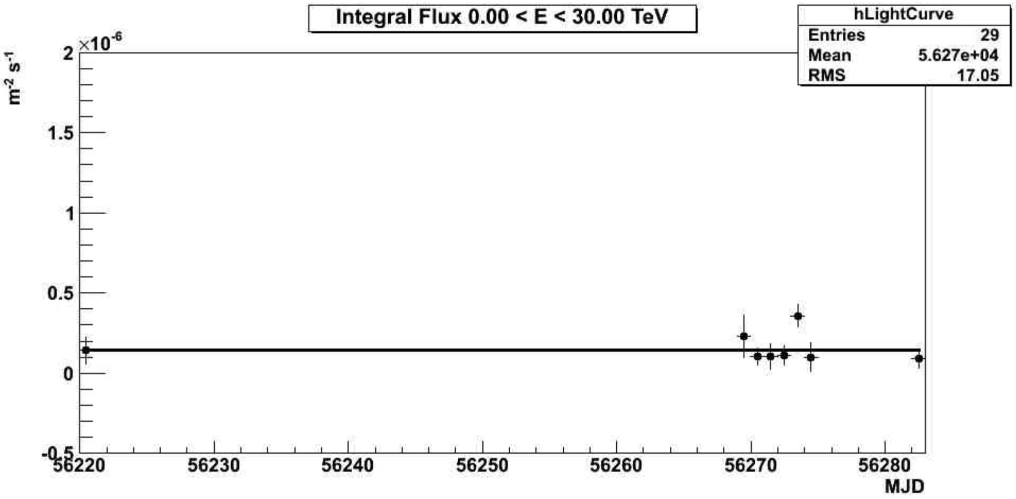
2013 VERITAS data:

In 7.7 hours of 2013 observing time, VERITAS measured a signal of 1328 “on” events and a background of 5889 “off” events, where “on” is detection of a gamma ray coming from 1ES0647+250 and “off” is detection of a background gamma ray. After normalizing the background to the source extraction area, this corresponds to a rate of 0.52 +/- 0.09 γ/min. The strength of this signal compared to the background was enough to confirm detection of 1ES 0647+250 with a significance of 6.4σ; this value is the confidence level that there is an object in the sky at this location producing γ-rays.

Table 1 – Flux Calculations

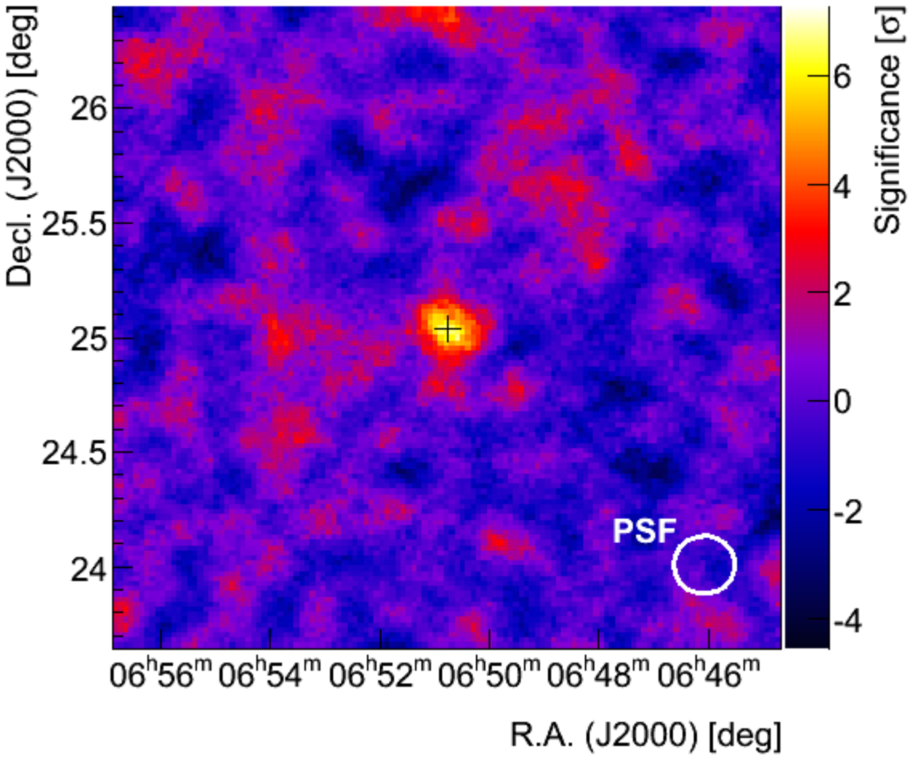
	Integral flux above 200 GeV (γ/m^2s)
Pre-2013 (upper limit)	$< 3 \times 10^{-8}$ (5-sigma confidence)
2013 data (detection flux)	$3 \times 10^{-8} \pm 30\%$

Figure 3 – Light Curve



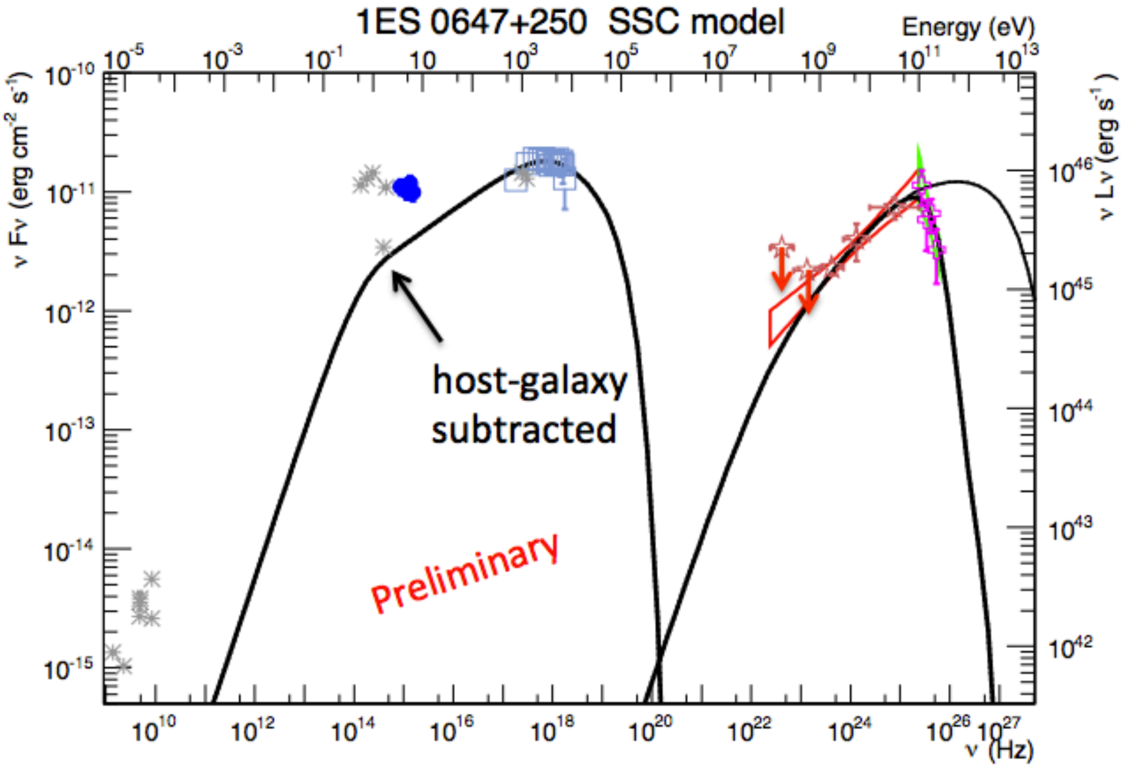
Light curve produced from 2013 observation. The plot shows integral flux vs. time, in Modified Julian Date. The data were placed in nightly bins, so each point represents one night of observation.

Figure 4 – Significance Map



The significance map shows a skymap (declination vs. right ascension) that contains the blazar 1ES 0647+250. The color shading represents how many "excess" (signal – background) gamma ray events were measured coming from a certain point in the sky, in terms of significance. The bright region in the center of the plot is the blazar; the corresponding 6.4 sigma is a peak value. The white circle shows the size of the point-spread function.

Figure 5 – Spectral Energy Distribution (SED):



Preliminary SED for 1ES 0647+250. It shows integral flux (scale on left) and power (scale on right) as a function of photon frequency (scale on bottom) and photon energy (scale on top). The plot is built by combining observations at many different wavelengths. Different colored and shaped points show data and their error bars collected from different instruments. The pink data are VHE gamma rays detected by VERITAS; the red data are HE gamma rays detected by NASA's Fermi satellite; the light blue data are X-rays from NASA's Swift satellite; the dark blue are optical data. In addition, two black solid lines show two different SSC models, as the title suggests; their deviation is most apparent at the far right of the graph. The upper one is the unabsorbed expectation; the lower one that agrees very well with the pink VERITAS data is what we expect after EBL attenuation assuming z = 0.45. Further discussion is found below.

IV. Discussion

Short-term Variability: After applying a UHECR correction to standard models of distant blazars, we expect a strong secondary γ-ray flux and therefore for all flaring events to be temporally smeared. Strong evidence for VHE variability in distant blazar 1ES 0647+250 would rule out models where observed γ-rays are secondaries from UHECRs interacting during propagation. Considering the 2013 light curve (flux vs. time), we see no evidence of short-term flaring on a nightly timescale, shown in Figure 4. Thus the application of current UHECR models to this source remains valid, and our data is in agreement with models presented in Prosekin et al. (2012) and Domínguez et al. (2013).

Long-term Variability: Variability could also potentially occur over multiyear time scales, allowing us to place different limits on UHECR, EBL, and IGMF models. Based on archival analysis, an upper limit for the integral flux was calculated (see Table 1). If our 2013 measurement was significantly higher than this upper limit, long-term variability could be claimed. However, our newest measurement's error bars contain the old upper limit, so no evidence for variability is present. Again, the application of current UHECR models to this source remains valid.

Building a Preliminary SED: Because long-term variability was not found, we are able to assume constant flux and average over all archival data. With the addition of VHE gamma-ray data from VERITAS, we can see that the spectrum agrees with what we expect after EBL attenuation assuming a redshift of $z = 0.45$, a reasonable estimate for 1ES0647+250. So although we have the lack of variability that is consistent with the UHECR secondaries, our SED shown in Figure 5 is actually well-modeled under the standard blazar paradigms. The particular 'standard' model applied here is one of the top 2 or 3 in terms of extreme jet parameters, with high Doppler factor and intense magnetic fields, called an extreme HBL. Because the standard model remains appropriate, we are yet awaiting clear evidence for the UHECR scenario.

V. Conclusions and Future Work

Based on recent variability analysis of blazar 1ES 0647+250, we are able to conclude that this source shows no evidence for variability over time. Our conclusion has two primary consequences. First, the data are consistent with application of UHECR models to this source and other distant blazars. Second, when we build Spectral Energy Distributions for the source, we can average over long periods without worrying about bias. A preliminary SED shows agreement with current standard blazar models, and thus we are yet awaiting clear evidence for the UHECR scenario. Going forward, similar variability analyses will be performed for other blazars, such as 1ES 1011+496 and 1ES 1741+196. Though these blazars are not totally analogous to 1ES 0647+250, because they have different high-energy spectra and are not quite as distant, they should still provide a helpful consistency check. We hope that a detailed investigation of these cosmic ray models can eventually help to constrain not only IGMFs and the EBL, but other poorly-understood parameters, such as the cosmic gamma ray horizon, which gives an estimate of the opacity of the Universe to VHE gamma rays. As technological advances allow more sophisticated observation at this energy range, exciting new areas of astrophysics are sure to be uncovered.

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