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Investigating the unusually hard gamma-ray spectrum of the extreme blazar 1ES 0229+200 with HAWC

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The very-high-energy (VHE) gamma-ray spectrum of the extreme blazar 1ES 0229+200 as observed by imaging atmospheric Cherenkov telescopes (IACTs) is surprisingly hard and only weakly variable. Several theories advanced to explain the VHE observations of this source invoke the interactions of cosmic rays along the line of sight, leading to predictions of observable gamma-ray emission that is steady on year-long time scales, with energies well in excess of the cutoff expected from attenuation by the extragalactic background light. The High Altitude Water Cherenkov (HAWC) observatory is ideally suited to investigate this scenario due to its excellent sensitivity at multi-TeV energies, its continuous monitoring of the source over several years, and the declination of the source which maximizes the HAWC sensitivity. Over the past three years, HAWC has collected the world's most sensitive data set on 1ES 0229+200 at multi-TeV energies, allowing us to place strong constraints on the VHE emission from line-of-sight interactions from this source. In this presentation, we discuss the implications of the non-observation of 1ES 0229+200 in the HAWC data set in terms of the long-term gamma-ray emission from this source, focusing especially on models involving line-of-sight interactions of cosmic rays.

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1. The hardness and stability of extreme blazar spectra

Blazars—active galactic nuclei (AGNs) with a relativistic jet oriented at a small angle with respect to the line of sight to Earth—produce electromagnetic radiation across the entire observed spectrum, from radio to gamma rays (see e.g. [1, 2] and references therein). In the very-high-energy (VHE) band (energies $\gtrsim$100 GeV), blazars are typically highly variable, with variability ranging from high states that last for months or years [3, 4] to extreme flares characterized by time scales of minutes and flux variations of more than two orders of magnitude [5]. When modeled as a simple power law $F(E) \propto E^{-\Gamma}$, the VHE flux $F(E)$ as a function of energy E is typically soft, with spectral index Γ of order 3 or 4. This is widely understood to be due to pair production interactions between the primary VHE gamma rays and the photons of the extragalactic background light (EBL), which attenuate the gamma-ray signal at high energies [6].

Recent years have witnessed the emergence of a new class of blazars known as extreme high-synchrotron peaked BL Lac objects, or EHBLs [7], with unusually hard and relatively stable VHE spectra [8]. Perhaps the most well known member of the EHBL class is 1ES 0229+200, a blazar with an observed VHE spectral index of $\Gamma \approx 2.5$. VHE emission from this source was discovered by the High Energy Stereoscopic System (HESS) in 2007 with no evidence for variability [9]. Subsequent observations by the Very Energetic Radiation Imaging Telescope Array System (VERITAS) revealed evidence for weak variability in the total flux [10], which was later confirmed by HESS [11]. No evidence for variability in the spectral index has been reported.

The apparent stability of 1ES 0229+200 as initially reported by HESS prompted models to explain its VHE emission as arising due to cosmic-ray interactions with the cosmic microwave background radiation and EBL along the line of sight [12, 13]. These models are also well motivated by the expectation that AGNs are probable sites for the acceleration of extragalactic cosmic rays, including ultra-high-energy cosmic rays (UHECRs) with energies above $\sim 10^{19}$ eV. They predict steady VHE emission resulting primarily from the deflection of the cosmic rays in the structured intracluster and filament magnetic fields in the vicinity of the source [14]. Consequently, the subsequent variability detected in 1ES 0229+200 can be used to limit the contribution of cosmic-ray line-of-sight interactions to the VHE spectra of EHBLs.

In this work, we report on more than three years of observations of 1ES 0229+200 with the High Altitude Water Cherenkov (HAWC) observatory. In addition to comparing the HAWC observations with those reported by HESS and VERITAS, we place constraints on one particular model proposed to explain the observed VHE spectrum of the source as arising due to UHECRs undergoing photomeson production and Bethe-Heitler processes along the line of sight [14].

2. The HAWC observatory

The HAWC observatory detects gamma rays and cosmic rays in the energy range from $\sim$300 GeV to $>$100 TeV. Located at 4100 m above sea level in the state of Puebla, Mexico, the observatory consists of 300 densely packed water Cherenkov detectors (WCDs) surrounded by a sparse array of 345 smaller outrigger tanks. Primary gamma rays and cosmic rays interacting with the atmosphere produce secondary particles in extensive air showers that pass through the WCDs and outriggers, emitting Cherenkov radiation that is observed by upward-facing photomultiplier tubes (PMTs).

The WCDs each have four PMTs, while the smaller outriggers each have a single PMT. In contrast to HESS and VERITAS, which are imaging atmospheric Cherenkov telescopes (IACTs), HAWC observes the air shower particles directly. This allows it to operate both day and night with a duty cycle in excess of 95% and a field of view of 2 sr, providing unbiased sensitivity to all VHE sources between -26° and $+64^{\circ}$ in declination. The sensitivity of the detector is maximized for declinations near $+19^{\circ}$. This makes 1ES 0229+200 an ideal target for HAWC observations. Further details on the operation and performance of HAWC are presented elsewhere [15].

3. HAWC constraints on the VHE emission from 1ES 0229+200

The present analysis uses HAWC data collected between 11 June 2015 and 25 July 2018. After data quality selection, the total livetime for the dataset is 1034 days. The HAWC observations reveal no significant emission from the location of 1ES 0229+200. We therefore set upper limits on the average VHE emission from the source during this time period. Adopting a simple power-law model for the observed spectrum, we compute upper limits at a confidence level corresponding to 2σ using the Feldman Cousins method [16] for spectral indexes ranging from 2.0 to 3.2. This range is motivated by consistency with the observations reported by HESS and VERITAS. For consistency with the HESS observations and the expectation that highest energies are strongly suppressed by pair production interactions with the EBL, we also assume a step function cutoff at 10 TeV.

Our results appear in Figure 1, which shows the upper limit on the differential flux at 1 TeV as a function of spectral index. For comparison, we also show the allowed regions (at confidence levels of 1σ and 2σ) for the HESS and VERITAS observations, using the data points reported by the respective instruments [9, 10]. In the case of VERITAS, which reported evidence for two distinct states, we use the average spectrum. Spectral information from the later HESS observations [11] has not been reported. Figure 1 clearly shows that, while the IACT spectra are broadly consistent with each other, there is very little overlap between the HAWC and VERITAS regions allowed at 2σ, and no overlap between HAWC and HESS. We therefore clearly confirm the variability of the source, and note that its average flux during the period from June 2015 to July 2018 is likely substantially lower than the IACT observations.

The variability of 1ES 0229+200 as reported by HESS limits the fraction of the average emission which could be due to UHECR line-of-sight interactions [11]. Constraints on the average flux can be used to place a conservative limit on the contribution of a steady component due to such interactions. Figure 2 shows the HAWC limit on the "E19 best-fit" model from Murase et al. (2012) [14], which assumes that protons accelerated to a maximum energy of 10^{19} eV in the source subsequently interact with the best-fit EBL model of Kneiske et al. (2004) [17] as they propagate to Earth. At the 2σ confidence level, we allow a maximum contribution from UHECR line-of-sight interactions at a level of 11% of the E19 best-fit model prediction.

4. Conclusion

The HAWC observations strongly constrain models that have been proposed to explain the VHE emission from 1ES 0229+200 as arising from cosmic-ray interactions along the line of sight.

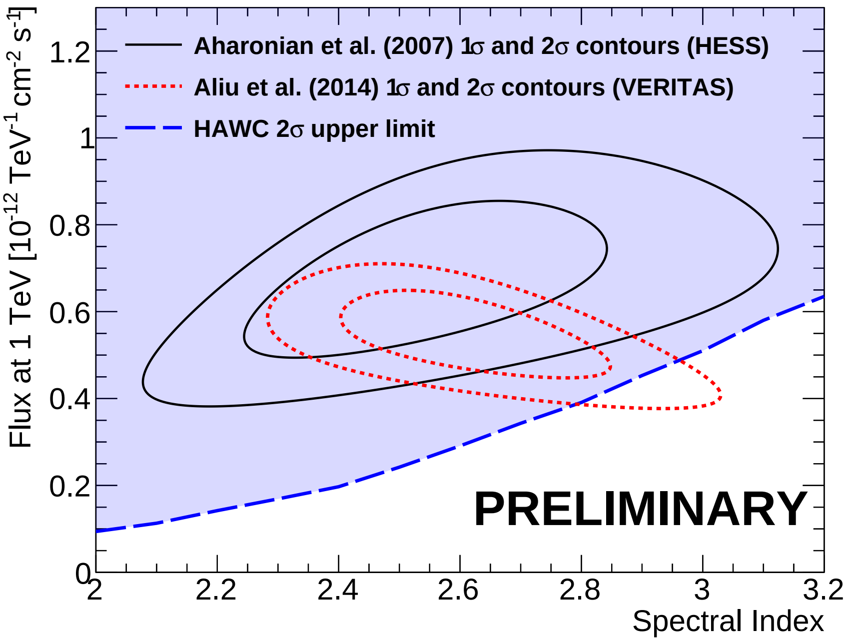

Figure 1: HAWC constraints on a simple power-law model for the observed spectrum of 1ES 0229+200 between 0.3 and 10 TeV. The shaded blue region bounded by the long dashed blue line is ruled out by the HAWC observations at a confidence level of 2σ. For reference, the solid black lines show the range of models consistent with the HESS observations [9] at confidence levels of 1σ and 2σ, and the short dashed red lines show the range of models consistent with the VERITAS average spectrum [10] at the same levels of confidence.

As is evident in Figure 2, the predictions for the E19 best-fit model [14] extend to at least 100 TeV, far in excess of the energies for which primary gamma rays are expected to survive EBL attenuation. Since the line-of-sight interactions are expected to be steady over many years, the HAWC observations apply generally to this model and are not sensitive to the particular dates of observation.

We have also shown that the average VHE spectra from 1ES 0229+200 as reported by the IACTs are inconsistent with the more recent HAWC observations. There could be several reasons for this. Since the source has been shown to be variable, 1ES 0229+200 may have been in a low average state during the period from 2015 June to 2018 July compared to its past activity. Alternatively, a simple power-law model for the VHE emission up to 10 TeV, while consistent with the IACT observations, may poorly represent the true spectrum. A more thorough analysis of the HAWC data allowing for spectral curvature could address this. It could also be the case that the previous observations do not represent an accurate long-term average for the source, as the pointed nature of IACT observations necessarily requires a prioritization of the amount of time spent on each source, which has the potential for biasing the results. The observational duty cycles for the HESS and VERITAS results referenced in this study are less than 0.5%, while for the HAWC observations the duty cycle is close to 25%, the fraction of time that the source spends within the

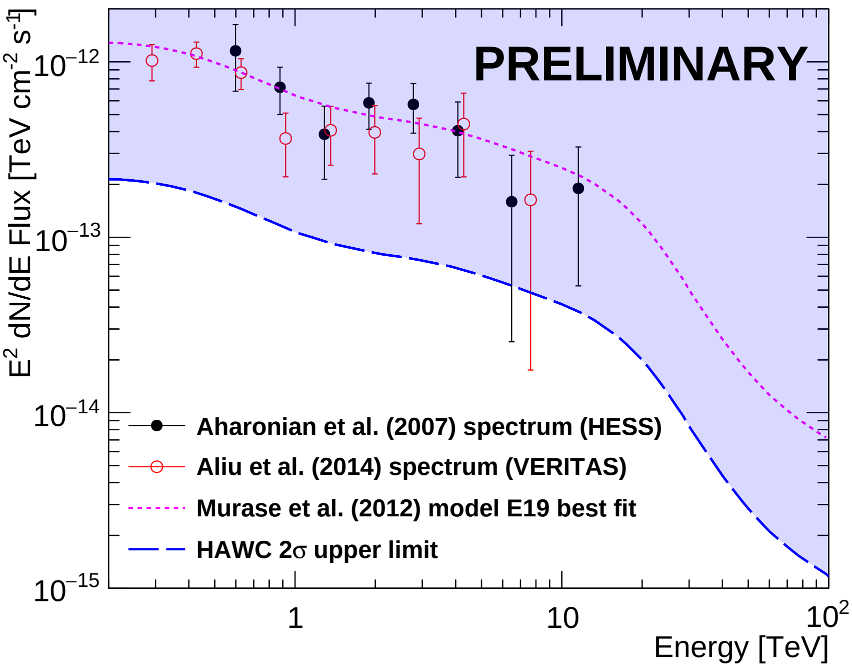

Figure 2: HAWC limit (long-dashed blue line) on the E19 best-fit model [14] (short-dashed magenta line) based on the non-observation of 1ES 0229+200. The shaded blue region is ruled out at a confidence level of 2σ. The HESS (solid black circles [9]) and VERITAS average (open red circles [10]) spectra are shown for reference.

HAWC field of view. In any event, the HAWC observations suggest that results relying on the assumption that the IACT observations represent the average flux from the source over long time periods, such as those used to place limits on the intergalactic magnetic field (e.g. [18]), should be viewed with caution.

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