Simulations of Line-of-sight UHECR-induced γ-rays from Blazars using CR-Propa

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Abstract: Recent analyses of very high energy (VHE; >100 GeV) blazar spectra have shown evidence for an excess of γ-rays when attenuation by extragalactic background light (EBL) is expected to be high. A possible explanation for this anomaly is secondary γ-rays from ultra-high-energy cosmic rays (UHECRs) interacting with background photons. If the intergalactic magnetic field strength is sufficiently small, these UHECRs could travel straight enough for long enough that the secondary VHE γ-rays would appear point-like for existing imaging atmospheric Cherenkov telescopes. We will show results from a study using the publicly available UHECR propagation code CRPropa to investigate the cosmic-ray power and spectrum required to account for the anomaly as well as the impact of a range of EBL models.

Keywords: icrc2013, UHECRs, gamma rays, blazars.

1 Introduction

The current generation of imaging atmospheric Cherenkov telescopes (IACTs) have so far detected about 50 very high energy (VHE; >100 GeV) blazars. Blazars are a subclass of active galactic nuclei (AGNs) with the relativistic jet directed along our line-of-sight [1]. These detections span a range of redshift out to at least $z = 0.6035$ in the case of PKS 1424+240 [2]. The emission from blazars is broadband, spanning radio through VHE wavelengths. The radio to X-ray emission is generally accepted to be synchrotron emission from relativistic electrons accelerated in the jet. The origin of the γ-ray emission is less well-known, but is usually explained by synchrotron self-Compton (SSC) models in which the electrons inverse-Compton scatter the lower-energy photons to make γ-rays [3, 4]. For some blazar classes a contribution from an external photon field is preferred. An alternative scenario is for the γ-ray emission to be from hadronic cosmic-ray interactions [5].

The horizon of the universe observable with γ-rays shrinks with increasing energy. This is because of the well-known attenuation of γ-rays by e^+e^- pair production on the bath of photons making up the extragalactic background light (EBL) ($\gamma_{\rm VHE} + \gamma_{\rm EBL} \to e^+ + e^-$). The EBL is the diffuse radiation field spanning UV to IR wavelengths with two distinct peaks in the spectral energy distribution (SED). The peak in the UV to near-IR range is largely from direct starlight while the peak in the mid to far IR is light that has been reprocessed by dust (see [6] for a review). While direct detection of the EBL has proven to be difficult, the absorption imprints features on blazar spectra, otherwise thought to be smooth. VHE γ-rays have been used to indirectly constrain (see [7] for a review) and, recently, to measure the EBL SED [8]. The results of these measurements are close to the minimum guaranteed amount of EBL [9].

A population study using VHE spectra has shown anomalous hardening in the spectra of blazars at energies where high attenuation is expected. This hardening has been called an indication for a pair production anomaly (PPA) [10, 11], and the analysis is described as follows. All VHE spectra that extend to an optical depth (τ) of at least 2 are absorption corrected according to a minimal EBL model [9] and fitted with smooth functions in the optically thin regime ($\tau < 1$). Blazar modeling indicates that the differential flux as a function of energy should fall off as a power law or faster. Residuals between the data and the fit are expected to center around zero (or less). However, in the optically thick regime ($\tau > 2$), the residuals tend toward positive values with $\sim$2–4 σ significance, depending primarily on the EBL model used.

A number of mechanisms have been proposed to explain this anomaly, including photons oscillating to axion-like particles (ALPs) [12], Lorentz-invariance violation [13, 14], and line-of-sight interactions between ultra-high-energy cosmic rays (UHECRs) and photon backgrounds [15, 16, 17, 18].

UHECRs have already been associated with AGN [19], although the significance of this result has not improved with recent data. UHECRs are deflected by magnetic fields and only point back to their source at the highest energies. It is possible that UHECRs travel undeflected for the majority of their journey with much of the deflection happening within our own galaxy, which has larger magnetic fields than the intergalactic medium. Magnetic fields inside of galaxies have been measured using Faraday rotation and Zeeman splitting to be 1 – 10 μG. These strengths can persist throughout the cores of galaxy clusters before falling to 10 – 100 nG on the outskirts of galaxy clusters. The intergalactic magnetic field (IGMF) strength and structure outside of clusters are not well constrained. With some reasonable assumptions about magnetic field correlation length, upper limits of $\sim$1 nG have been derived [20]. Taking the IGMF magnitude to be 10 fG, deflections are small enough that secondaries produced from interactions of UHECRs (discussed in the next section) will appear as an approximately point-like source ($< 0.1°$) [17].

Several studies have been performed to investigate how UHECR secondaries might be detected by IACTs [15, 16, 17, 18, 21, 22, 23]. We focus on the hypothesis that UHECRs modifying blazar spectra are a solution to the PPA. We repeat the analysis of refs. [10, 11] to confirm their result. Then we find the γ-ray flux residuals required to completely eliminate the high optical depth excess, source by source. Using the publicly available CRPropa 2.0 [24] simulation package to propagate UHECRs and their secondaries, we then generate predictions for the total UHECR power required to explain the PPA and compare these results with similar predictions.

2 Simulations using CRPropa

CRPropa 2.0 is a tool for propagating UHECRs through the intergalactic medium and accounting for all relevant sources of energy loss. It models interactions with background radiation fields (primarily EBL and CMB), tracking and propagating stable byproducts of these interactions, e.g., secondary γ-rays, e^+e^- pairs, and neutrinos [24].

Three models for the EBL are implemented in CRPropa. The primary model is from ref. [25], hereafter KN04. There are two additional, "low" and "high" implemented models, differing by a factor of 5 in flux, and derived by scaling a model presented in [26], hereafter FR01-L and FR01-H.

A Monte Carlo approach is used for propagating UHECRs in a one-dimensional (1D) or a three-dimensional (3D) environment in CRPropa. UHECRs can be injected with a monochromatic or a power-law (with spectral index α) distribution in energy, where emission is isotropic around the source. The maximum energy of injected nuclei is given by, $E_{max} = A \times 10^{22}$ eV, where A is the mass number. Propagation is handled step-by-step, where at each step Lorentz equations are solved and possible interactions are carried out, tracking any resulting secondaries. The 3D environment allows for modeling of source distribution and of IGMF effects, including deflections of cosmic rays (secondaries are assumed to travel in straight lines); however, it cannot accommodate for redshift evolution. The 1D mode can successfully model redshift evolution, but the IGMF is simplified and limited to affecting synchrotron losses from e^+e^- pairs [27].

To model effects of cosmic-ray composition, injection of nuclei up to iron is allowed. In the case of an injected proton, the main interactions with background radiation considered by CRPropa are pion production and pair production by protons [24]. Pion production is modeled using the SOPHIA package [28], modified to encompass interactions with the EBL in addition to the CMB. Neutrinos from pion decay are assumed to propagate with energy loss only due to redshift, while the electromagnetic cascades are handled with code from ref. [29]. This takes care of single, double, and triplet pair-production and inverse-Compton scattering between electromagnetic products and background radiation [27]. In addition to the above interactions, heavier nuclei can undergo photodisintegration from background photons with energies, in the nucleus rest frame, greater than the nuclear binding energy. For photodisintegration cross sections, CRPropa relies on the TALYS framework, version 1.0 [30] and for effects of propagating nuclei, it follows ref. [31]. Nuclear decay is also accounted for in cases where photodisintegration or pion production leave behind an unstable nucleus.

We use CRPropa in the 1D mode, with the injected UHECRs following a pure proton composition and a power-law distribution in energy. The choice of the 1D mode is motivated by the need to account for redshift evolution, given the considerable redshift range of our sources ($0.031 < z < 0.536$), as well as by the expected lack of strong IGMF that would necessitate a 3D treatment.

3 Results

The results of running CRPropa with a nominal set of parameters (pure proton composition, $\alpha = 2.2$, $E_{\rm max} =$ 300 EeV, $B_{\rm IGMF} = 10$ fG) and fitting for the best UHECR power emitted by the source are shown with three EBL models in figure 1. In each case, the residuals (excess flux above expectation) can be readily described with secondaries from UHECR line-of-sight interactions. For all sources, the fits result in a $\chi^2 \ll 1$.

The fraction of total observed VHE γ-ray emission contributed by secondary γ-rays from UHECR interactions varies from a few percent (for nearby Mrk 421 and Mrk 501) to the entire amount (for distant sources 1ES0414+009 and 3C279, depending on the EBL model used). This changing contribution of UHECR secondaries with redshift and energy is expected because the primary γ-rays suffer higher attenuation for the more distant blazars. The flux not accounted for by UHECRs is presumably due to primary γ-rays created at the source in, e.g., an SSC scenario. Multi-component fitting between SSC models and CRPropa predictions will be the subject of future work.

This work looks at spectra of seven blazars obtained from refs. [10, 11]. The UHECR power required to explain the excess flux in each case is given in table 1. The power required can change by about an order of magnitude within the allowed range of the UHECR spectral index ($2.0 < \alpha < 2.7$), as was shown in ref. [17]. The power can be greatly lowered by assuming beamed instead of isotropic emission. For a typical jet opening angle of 6°, the power is reduced by a factor of 2.74×10^{-3}. Using the KN04 EBL model produces the highest contribution from UHECR interactions for every source, while using the FR01-L model produces the lowest. The results for individual sources are highlighted below.

Mrk 421 ($z = 0.031$) and **Mrk 501** ($z = 0.034$) each have a single spectral point with $\tau > 2$. The contribution to the total VHE γ-ray flux from UHECR interactions is up to 2% for Mrk 421 and 9% for Mrk 501, as expected for such bright, nearby sources.

H1426+428 ($z = 0.129$) and **1ES1101–232** ($z = 0.186$) allow a significant but moderate fraction of the total VHE γ-ray flux to be explained as secondaries from UHECR interactions (13–19% and 34–59% respectively).

1ES0347-121 (z=0.188) is not shown. It is the one example where $\tau > 2$ flux residuals are negative, which could be due to stronger intrinsic cutoff in the flux or a lack of UHECR acceleration in this particular source.

1ES0414+009 ($z = 0.287$) and **3C279** ($z = 0.536$) exhibit secondary γ-ray fluxes comparable to the total VHE flux with the KN04 model (107% and 87% respectively). In the case of 3C279, the KN04 model over-predicts the observed flux at lower energies by about a factor of two, though the large uncertainties in the residuals can easily allow for a normalization that avoids this issue. Moreover, the cosmic-ray power required for generating these secondaries is unphysically large, at 1.1×10^{49} erg s^{-1}. The required cosmic-ray powers and the secondary γ-ray fluxes with FR01-L and FR01-H EBL models are more reasonable, predicting γ-ray fluxes from UHECR interactions at 28% and 42% of the observed γ-ray flux for 3C279, and at 33% and 39% for 1ES0414+009.

Source	KN04 (erg s^{-1})	FR01-L (erg s^{-1})	FR01-H (erg s^{-1})
Mrk421	6.6×10^{45}	2.1×10^{45}	3.5×10^{45}
Mrk501	5.6×10^{46}	1.5×10^{46}	3.1×10^{46}
H1426+428	9.2×10^{45}	1.1×10^{45}	2.1×10^{45}
1ES1101-232	3.7×10^{45}	5.2×10^{44}	7.0×10^{44}
1ES0414+009	4.3×10^{45}	1.7×10^{44}	3.3×10^{44}
3C279	1.1×10^{49}	5.6×10^{45}	1.5×10^{46}

Table 1: Cosmic-ray power at the source required for reproducing the observed excess in γ-rays at $\tau > 2$ energies, using secondary γ-rays from line-of-sight cosmic-ray interactions with background radiation. Cosmic-ray power is calculated for the three available EBL models: KN04, FR01-L, and FR01-H.

4 Conclusions

We investigated the hypothesis of UHECR line-of-sight interactions as a solution to an anomaly observed in blazar spectra. In this scenario, VHE γ-rays are created in between the source and the observer and suffer less attenuation due to pair production on the EBL than a pure SSC scenario, where all γ-rays are created near the source. The result of such a process is a hardening in the γ-ray spectrum that depends on energy and redshift.

For six blazars showing higher-than-expected flux at high optical depth, we simulated the propagation of UHECRs and their secondaries from interactions on universal photon backgrounds using the publicly available CRPropa package. In all cases, the flux predictions from UHECRs interacting en route are able to adequately describe the anomalous flux.

Because of the wide range of redshifts, the fraction of the total γ-ray flux due to UHECRs varies from 2% to 100%. For distant blazars 1ES 0229+200, 1ES 0347+121, and 1ES 1101+232, it has been shown independently that all of the VHE γ-ray flux can be explained by UHECR line-of-sight interactions with the UHECR power as the dominant uncertainty [17].

The UHECR powers given in table 1 are in reasonable agreement with previous studies (e.g. [17, 21, 32]), with values ranging from 10^{44}–10^{46} erg s^{-1} and with one outlier at 10^{49} erg s^{-1}. Besides the outlier, these powers are comparable with powers from hadronic models of primary γ-rays. Although beaming could potentially lower the total power by $\sim$3 orders of magnitude, the total power requirement may be increased by one or two orders of magnitude when intervening large scale structures isotropize the UHECR flux, as described in ref. [21]. This higher power requirement would challenge the UHECR scenario, as the luminosities would approach the Eddington luminosity for 10^9 solar mass black holes.

Future work will focus on updated EBL models, multi-component fitting between primary and secondary γ-ray emission models, further exploration of UHECR composition, and testing a range of IGMF strengths.

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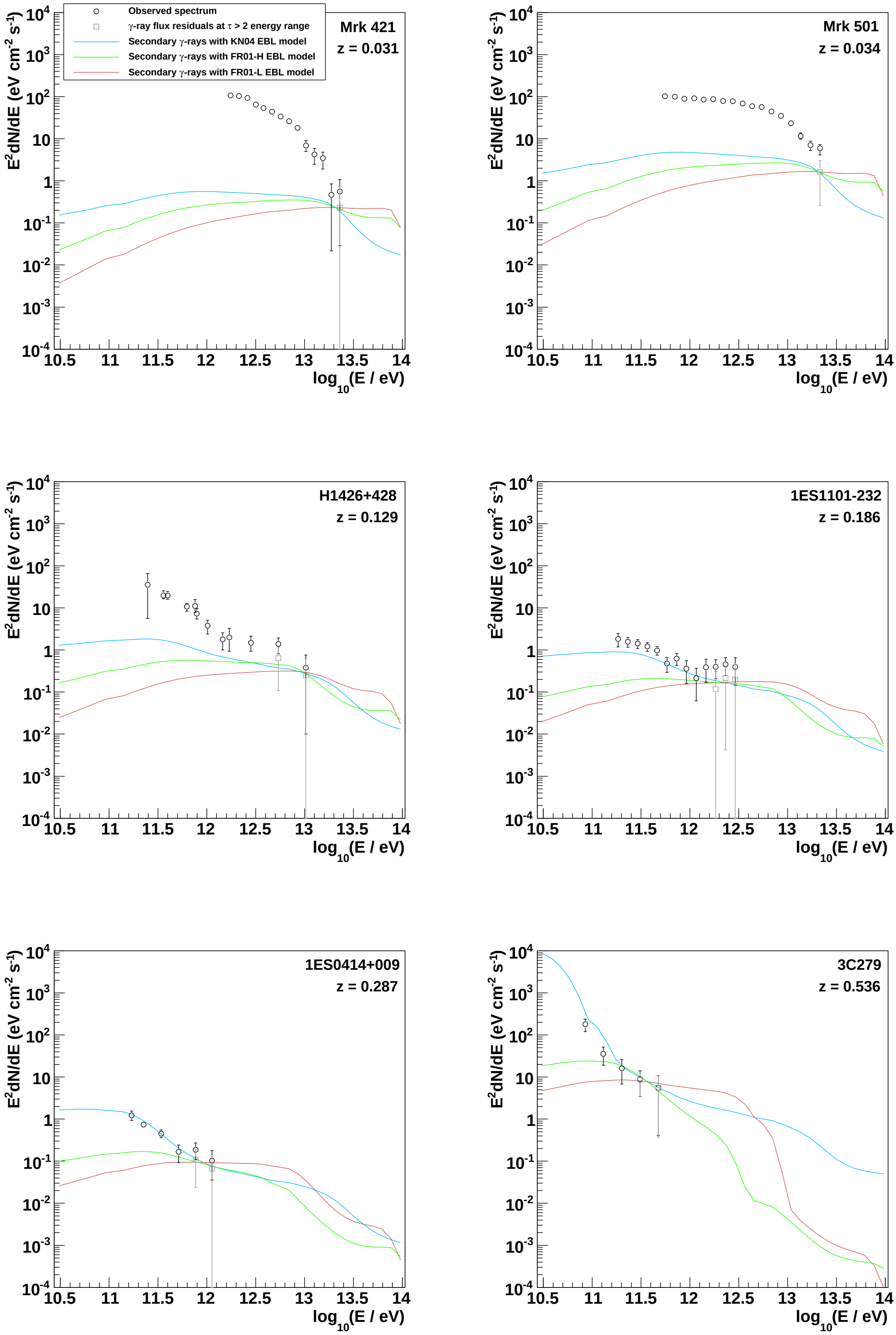

Fig. 1: Observed γ-ray spectra of six blazars, taken from refs. [10, 11] showing excess flux at $\tau > 2$ energies (positive residuals). The flux normalization of secondary γ-rays from line-of-sight UHECR interactions with background radiation is fitted to the residuals.