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Constraining the Extragalactic Background Light in the near-mid IR with the Cherenkov Telescope Array (CTA)

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Abstract: The next generation imaging atmospheric Cherenkov telescope (IACT), the Cherenkov Telescope Array (CTA), will have improved sensitivity, cover a broader energy range, and posses a wider field of view than the current generation of IACTs. CTA is therefore an ideal instrument for acquiring precise spectral measurements, at very high gamma-ray energies, on a large population of blazars. This is highly advantageous for studies of the extragalactic background light (EBL) since very-high-energy gamma rays from blazars interact with EBL photons as they propagate through the Universe. The signatures of EBL absorption are therefore imprinted on the observed spectra of blazars. One of the possible absorption features is that of a spectral hardening/softening in the observed emission between approximately 1 and 5 TeV. This spectral break is dependent on both the source redshift and EBL spectral energy distribution. One can therefore constrain the EBL by measuring the spectral break versus redshift distribution from a large sample of blazars. This analysis was originally developed using blazar measurements from the current generation of IACTs. Here we discuss how CTA can improve upon this technique by taking advantage of the instruments wide field of view and high sensitivity in the requisite energy range. In particular, we consider the exposures and source statistics CTA can reasonably obtain to improve current constraints on the EBL.

Keywords: blazars, CTA, extragalactic background light, gamma rays

1 Introduction

The extragalactic background light (EBL) is a diffuse photon field spanning wavelengths from $\sim 0.1\,\mu$m to $1000\,\mu$m and is second in intensity only to the cosmic microwave background. It has a bimodal distribution with peaks at $\sim 1\,\mu$m (near-infrared) and $\sim 100\,\mu$m (far-infrared). The near-infrared peak derives from the collective emission of nuclear (stars/galaxies) and gravitational (accretion onto active galactic nuclei) energy releases while the peak in the far-infrared is due to the absorption and re-radiation of this near-infrared emission. See [1] and [2] for reviews on the origins and cosmological implications of the EBL.

The EBL is difficult to measure directly due to overwhelming foreground emission from both zodiacal light within the solar system and radiation from the Galaxy. Limits on the EBL can be obtained using the integrated light from galaxy counts as well as gamma-ray observations of extragalactic objects at very-high energies (VHEs). The latter approach exploits the fact that as VHE gamma rays propagate over cosmological distances they can interact with the diffuse infrared photons of the EBL via pair production (i.e., $\gamma_{\rm VHE}\,\gamma_{\rm EBL} \rightarrow {\rm e}^{+}\,{\rm e}^{-}$) [3]. The signature of this absorption is left imprinted on the VHE spectral energy distribution (SED). The characteristics of this feature are dependent on the intensity and shape of the EBL SED.

The amount of absorption present in VHE spectra is dependent on, among other things, the distance of the emitting source. Blazars are therefore suitable sources for constraining the intensity of the EBL given their large redshifts and high VHE fluxes. The work discussed here investigates the potential for the Cherenkov Telescope Array (CTA), a next generation imaging atmospheric Cherenkov telescope (IACT), to place strong constraints on the EBL and potentially *detect* an EBL absorption signature.

2 Cherenkov Telescope Array

Two separate Cherenkov telescope arrays will constitute CTA, with the aim to: increase sensitivity by and order of magnitude for deep observations around 1 TeV, increase the overall detection area and therefore detection rates, increase angular resolution to improve capabilities for resolving the morphological properties of extended sources, provide uniform energy coverage for photons from tens of GeV to more than 100 TeV, and enhance sky survey and monitoring capabilities [6]. These two arrays will be located in the nothern and southern hemispheres. In addition, CTA will have the ability to operate sub-arrays in differen-

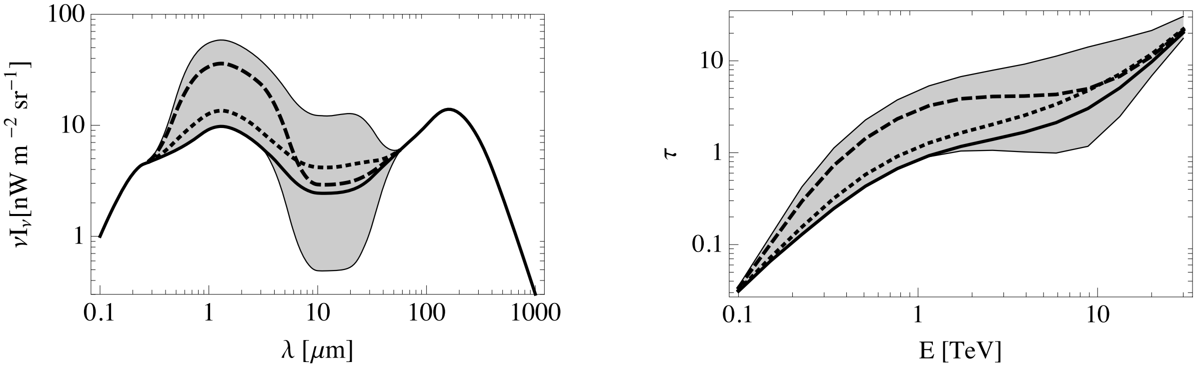

Figure 1: *Left*: EBL intensity versus photon wavelength. The shaded region indicates the range of scenarios tested. The thick solid line designates the baseline shape used, from which all other scaled shapes are generated. For clarity, two additional models are shown (dotted and dashed) illustrating the independent scaling of the near- and mid-IR regions. *Right*: Optical depth τ (at $z = 0.1$) versus gamma-ray energy in TeV for each EBL scenario tested. The optical depths for the baseline and two additional EBL models shown in the left panel are shown as well.

t observing modes to maximize both source coverage and science return.

A significant change for CTA with respect to the current generation of IACTs is its open data access policy. A Science Data Center will provide public access to all CTA data as well as tools for their analysis and associated tutorials to facilitate the data processing. These changes will open the field of TeV gamma-ray astronomy to the astronomical community at large.

3 Detecting an EBL Absorption Signature with CTA

Limits on the intensity and shape of the EBL SED can be obtained by calculating the gamma-ray absorption resulting from different EBL scenarios and comparing this with VHE observations. Figure 1 shows a range of EBL scenarios and their calculated $\gamma_{\text{VHE}}\,\gamma_{\text{EBL}}$ optical depths. The increase in absorption with gamma-ray energy (right panel of Figure 1) produces a softening in the observed VHE spectra of extragalactic sources such as blazars. The flattening of the optical depth at 1 TeV, for some EBL SEDs, produces a break in observed spectra at approximately this energy. Figure 2 illustrates both of these effects. The magnitude of the spectral softening and break increases with source redshift.

Evidence for this EBL-induced, redshift- dependent, spectral break can be searched for using a large sample of VHE blazars. This was done using using observations of 12 blazars from the current generation of IACTs [4]. Each source in the sample was fit with a broken power-law with a break energy of $1.3\,\text{TeV}$. This choice of break energy is a direct result of the location of the near-infrared peak of the EBL, which governs where the $\gamma_{\text{VHE}}\,\gamma_{\text{EBL}}$ optical depth significantly changes slope.

The peak of the photon-photon cross-section can be approximated using the relation,

$$\lambda_\epsilon\ [\mu\text{m}] \approx 1.24 E_\gamma\ [\text{TeV}]\,, \qquad (1)$$

where λ_ϵ is the EBL photon wavelength in μm and E_γ is the gamma-ray energy in TeV [5]. A near-infrared EBL SED peak at $\sim 1.6\,\mu$m therefore corresponds to an interaction cross-section peak of $\sim 1.3\,\text{TeV}$.

Figure 3 shows the spectral break versus redshift distribution for the 12 blazars used in the study by [4] (open symbols). It can clearly be seen that the size of the error bars on the spectral break measurements vary substantially from source to source. This is due to the different instrument sensitivities and exposure times associated with each source. Nonetheless, a fit to this data with a flat line located at $\Delta\Gamma(z) = 0$ can be excluded with a significance of 3.2 standard deviations.

To determine the expected spectral break versus redshift distribution for CTA, the set of analysis tools `ctatools`, provided by the CTA consortium, were used. The currently measured flux and spectral index for each source was used, along with the expected spectral break given the current IACT data shown in Figure 3, to simulate the expected result from 50 hours of CTA observations. A broken power-law was simulated between $100\,\text{GeV}$ and $4\,\text{TeV}$ following the form

$$\frac{\mathrm{d}N}{\mathrm{d}E} = \begin{cases} N_0 \left(\dfrac{E}{E_{\text{break}}}\right)^{-(\Gamma+\Delta\Gamma/2)} & ,\ E \leq E_{\text{break}} \\[2em] N_0 \left(\dfrac{E}{E_{\text{break}}}\right)^{-(\Gamma-\Delta\Gamma/2)} & ,\ E > E_{\text{break}} \end{cases}\,, \qquad (2)$$

where N_0 is the normalization at the break energy E_{break}, Γ is the spectral index measured by current IACTs, $\Delta\Gamma$ is the expected spectral break given the current best linear fit to the data in Figure 3, and E is the energy. The

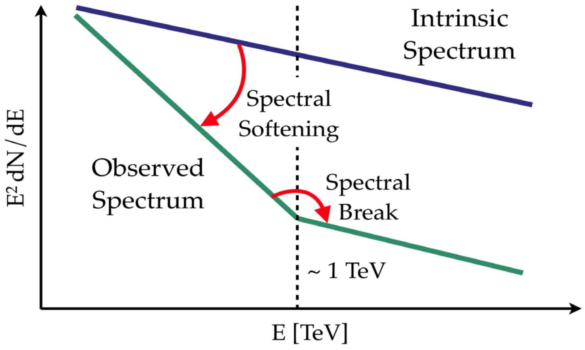

Figure 2: Illustation of two EBL absorption effects - a spectral softening due to increased absorption with increasing gamma-ray energy and a spectral break due to the slope of the EBL SED between near- and mid-infrared wavelengths.

flux normalization at $E_{\rm break}$ for the simulated spectrum was chosen based on existing measurements. These simulations were then processed through the CTA data selection and unbinned likelihood analysis tools. The resulting spectral break versus redshift distribution is shown in Figure 3 (filled symbols).

There are a few important things to note about the CTA spectral break versus redshift distribution. First, while no spectral break measurement currently exists for the distant blazar 1ES 0414+009 ($z = 0.287$), CTA will be able to achieve this within 50 hours. The detection of EBL absorption signatures at such large redshifts will be critical to understanding how the EBL has evolved over cosmic time. Second, there are no CTA simulation results shown for the blazars PKS 0548-322 and PKS 2005-489. This is due to the fact that 50 hours of CTA observations will not yield a spectral break measurement for either of these sources that will contribute to the overall significance of the spectral break versus redshift distribution result.

It is partly due to their low redshifts that CTA will not be able to measure the small expected spectral breaks in PKS 0548-322 and PKS 2005-489 within 50 hours. Their redshifts alone are not the limiting factor, however, given that breaks can be measured in 1ES 1959+650 and 1ES 2344+514, both of which have smaller redshifts. The more significant limiting factor for PKS 0548-322 is its low flux ($\sim 1\%$ of the Crab Nebula flux $> 200\,$GeV) which will yield measurements above 1 TeV with large uncertainties thereby resulting in large errors on the small expected spectral break [7]. In the case of PKS 2005-489, its very soft power-law spectral index ($\Gamma = 4.0 \pm 0.4$) in conjunction with a relatively small flux ($\sim 2.5\%$ of the Crab Nebula flux $> 200\,$GeV) will yield large errors bars on its small expected spectral break [8].

There is still a large uncertainty, given current data, in the spectral break versus redshift distribution. What the CTA simulated observations show, however, is that the excellent sensitivity of CTA in the regime around 1 TeV will yield high precision measurements of blazar spectra. This in turn provides high precision measurements of blazar spectral breaks which yields valuable results for the spectral break versus redshift distribution, even for small breaks.

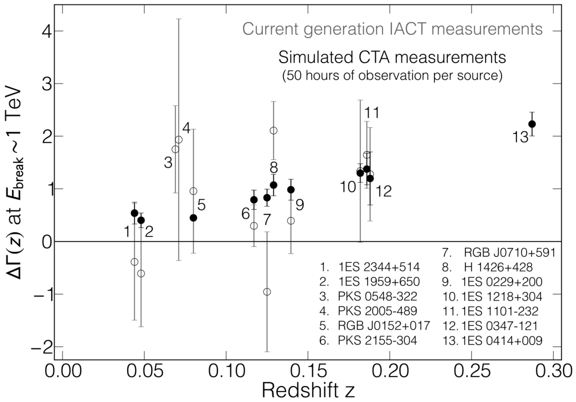

Figure 3: Spectral break versus redshift distribution for 12 blazars measured by the current generation of IACTs (open symbols). Also shown are the projected spectral break measurements for 50 hours on each source with CTA. While no spectral break measurement currently exists for the distant blazar 1ES 0414+009 ($z = 0.287$), CTA will be able to achieve this with high significance in 50 hours. However, no anticipated CTA results are shown for PKS 0548-322 or PKS 2005-489 as CTA will not obtain a significant spectral break measurement for either these sources with 50 hours of observing time.

4 Constraining the EBL with CTA

The spectral break versus redshift distribution shown in Figure 3, in addition to providing evidence for an EBL absorption signature, can be used to constrain the ratio of near- to mid-infrared intensities of the EBL. Each EBL SED possessing a different near- to mid-infrared ratio predicts a unique spectral break versus redshift distribution.[1] The predicted redshift dependence can be calculated using a test spectrum for the intrinsic blazar emission, placed over a range of redshifts sufficient to sample the distribution, which then gets absorbed according to the calculated optical depth for the EBL scenario in question. The binning of the test spectrum can be chosen in a variety of ways, but the method best suited for CTA is to use the energy binning and redshift sampling representative of the actual blazar observations.

The predicted spectral break versus redshift distribution can be calculated for a wide range of EBL SEDs and then compared with the observations (i.e., Figure 3). EBL scenarios can then be ruled out based on their level of dis-

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[1] To a lesser degree, this distribution also depends on the overall intensity of the EBL, which alternative techniques are better suited to constrain (see [4]).

agreement with CTA observations. This method, combined with techniques along the lines of [9], can provide strong constraints on the EBL.

5 Advancing Studies of the EBL with CTA

Given the results shown in Figure 3, it is likely that CTA will have the capability to detect the signature of EBL absorption in blazar spectra and trace its trend with redshift. There is another aspect CTA's capabilities, not yet considered, that will further advance studies of the EBL well beyond anything achievable with the current generation of IACTs. This key component is the ability of CTA to monitor and survey the sky. Not only will the CTA telescopes have a wider field of view (~ 6–$8°$), but the Northern and Southern arrays will provide full sky coverage and the many tens of telescopes will allow the observation of multiple sources simultaneously using subsections of the overall array (if so desired).

It is anticipated that CTA will detect on the order of 1000 sources, roughly a factor of 10 more than are currently detected at TeV energies. The CTA blazar catalog will therefore likely contain hundreds of sources. Of these blazars, not all will be suitable for these spectral break studies, but it is reasonable to assume that CTA will populate the spectral break versus redshift distribution with several tens of objects.

Not only can the evolution of the EBL over redshift be studied using this potentially large sample of blazars, but also the instrinsic (dis)similarities between sources. If conflicting constraints on the EBL are obtained from different source types (e.g., low-, intermediate-, and high-frequency-peaked BL Lac objects), they can be used to asses the validity of certain assumptions regarding the intrinsic properties of these same sources.

6 Discussion & Conclusions

CTA will have a greatly improved performance as compared with the current generation of IACTs. It therefore stands to significantly progress studies of the EBL using VHE observations. If a redshift-dependent spectral break exists, it is likely that CTA will definitively detect this EBL absorption signature in the spectra of blazars. The detection of this absorption signature can also be used to place constraints on the shape of the EBL SED. In addition, CTA will significantly expand the known population of VHE blazars which will advance studies of the EBL performed with IACTs beyond what is currently possible. Namely, the evolution of the EBL with redshift can be studied and the intrinsic properties of sources can begin to be disentangled from the effects of EBL absorption. The prospects for investigating both blazars and the EBL with CTA are very promising.

Acknowledgements

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