Gamma-Ray Analysis of the Most Energetic Blazars to Probe the Cosmos

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***Abstract*— Direct measurement of the Extragalactic Background Light (EBL) is difficult due to foreground emissions. An alternative method is to indirectly probe the EBL from its interaction with blazar gamma (γ) rays. The Fermi Large Area Telescope (Fermi-LAT) and H.E.S.S. collaborations proposed using a scaling factor α to normalize EBL density based on previously existing models. However, initial normalizations analyzing 10 years of data from the Fermi-LAT Fourth Source Catalog Data Release 2 (4FGL-DR2) resulted in numerous outliers, whose values differed more than 3σ from an existing EBL model. We performed a new spectral analysis on 12 years of Fermi-LAT observations, focusing on outlier and bright sources. The changes of α derived from our analysis resolve the issue for most of the outlier sources, while creating a new outlier from our "bright sources" sample. By estimating the factor α for a large number of blazars, this study will contribute to the creation of a density map of the EBL.**

I. INTRODUCTION

Proper measurements of the Extragalactic Background Light (EBL), the sum of all infrared to optical light emitted since reionization, are key to understanding the universe's makeup and evolution. Our study uses 12 years of data from the NASA space Fermi Large Area Telescope (LAT) which observes γ-rays from ~100 MeV to TeV energies. Using blazar sources from the Fermi-LAT Fourth Source Catalog Release 2 (4FGL-DR2) [1], and Fermipy, a Fermi analysis python package (Wood et al. 2017), we created optimal observed spectral energy distributions (SEDs), or plots of flux over energy. The relationship between observed and intrinsic spectra is shown in equation 1:

$$\Phi_{obs} = e^{-\alpha\tau(E,z)}\Phi_{intr}$$

Equation 1. Φ_{obs} and Φ_{intr} are the observed and intrinsic spectra, α is the normalization value, and τ(E,z) [3] is EBL optical depth.

An optimal α value is considered after performing a likelihood test with a given intrinsic spectrum [2].

II. METHODS

Fermipy analysis produces counts maps (Fig. 1), residual maps (Fig. 2), likelihood fits (Fig. 3), and SEDs (Fig. 4).

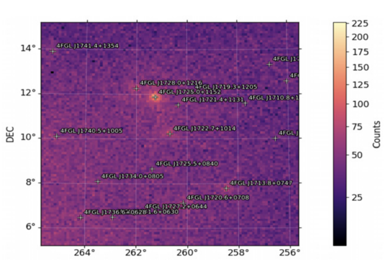

Figure 1. Photon data counts map of TXS 1720+102. The source in the center is surrounded by the region of interest, or the total area from which photon and background data is considered.

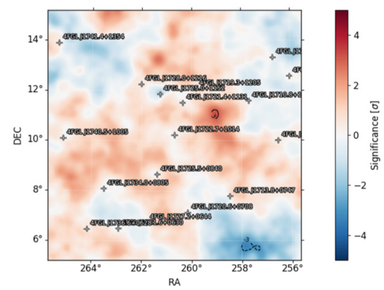

Figure 2. Residual plot of TXS 1720+102, illustrating the difference between values of the counts map and spectral models of all sources and background in the region of interest. Near zero σ represents a good fit.

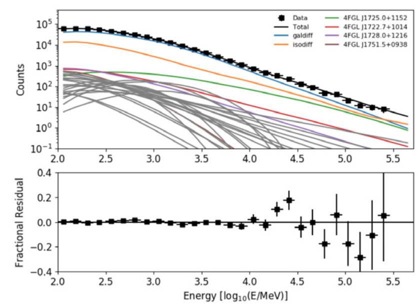

Figure 3. Likelihood fit of all sources in the region of interest. The red line shows the best spectral fit of TXS 1720+102.The top portion is a map of counts vs. energy. The bottom is a graphical residual plot.

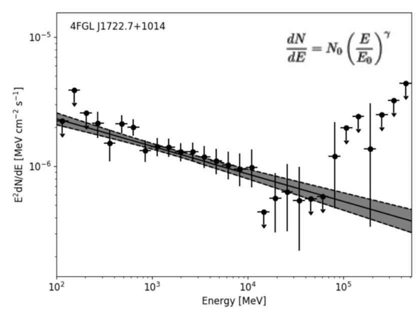

Figure 4. SED of TXS 1720+102.

One way to optimize SEDs for analysis is through bin reduction. Upper limits lack error bars, indicating a 95% chance the flux value is below the horizontal line. Having upper limits in the middle energies of an SED signifies an oversampling of flux emission, indicative of a non-optimized spectrum for EBL normalization (Fig. 4). Thus, we perform iterative bin reductions by merging coincident energy bins to remove these upper limits. Another way to optimize SEDs is through spectral model change. With 12 years of data, the default 4FGL-DR2 spectral models used for 10 years of data may not accurately describe the SEDs produced in our study and can be changed. The models mostly used were Power Law, Log Parabola, and Power Law with exponential cutoff (Eq. 2, 3, 4). Here, $\frac{dN}{dE}$ is flux density, and E is energy.

$$\frac{dN}{dE} = N_0 \left(\frac{E_0}{E}\right)^{\gamma}$$

Equation 2. Power Law. Set factors: E_0(scaling factor). Free factors: N_0 (prefactor), γ(index)

$$\frac{dN}{dE} = N_0 \left(\frac{E}{E_0}\right)^{-(\gamma+\beta \log\left(\frac{E}{E_b}\right))}$$

Equation 3. Log Parabola. Set factors: E_b(scaling factor). Free factors: N_0 (norm), γ(index 1), β(index 2).

$$\frac{dN}{dE} = N_0 \left(\frac{E_0}{E}\right)^{\gamma} \exp\left(\frac{E}{E_{cut}}\right)^{b}$$

Equation 4. Power Law with Exponential Cutoff. Set factors: E_0(scaling factor). Free factors: N_0 (prefactor), γ(index 1), b (index 2), E_{cut}(cutoff)

With two more years of data than 4FGL-DR2, we were able to significantly improve the underlying spectral model of certain sources (Fig. 5).

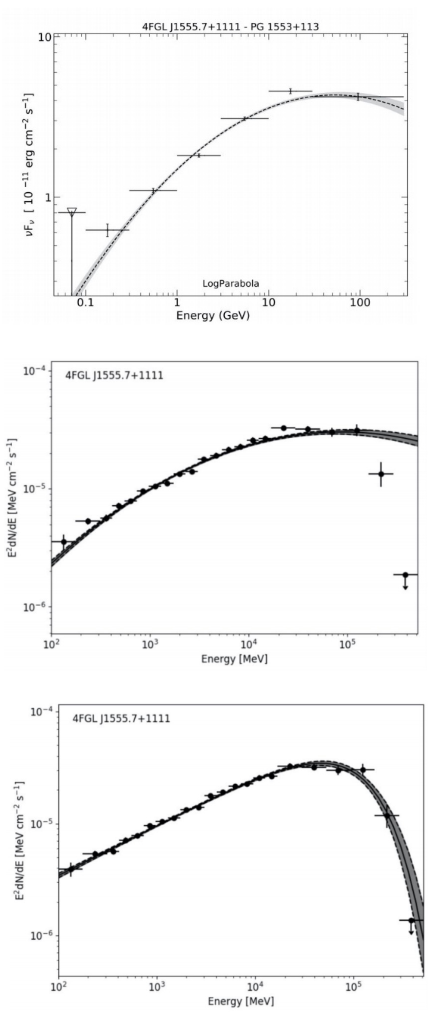

Figure 5. Changes between the 4FGL-DR2 catalog (top) and analysis using 12 years of data (bottom) for source 4FGL J1555.7+1111: bins are smaller, and a model change from Log Parabola to Power Law with Exponential Cutoff shows a much better fit of the Fermi-LAT data.

III. RESULTS AND DISCUSSION

Our analysis using 12 years of data created 54 new SEDs for 18 outlier and 36 additional bright sources.

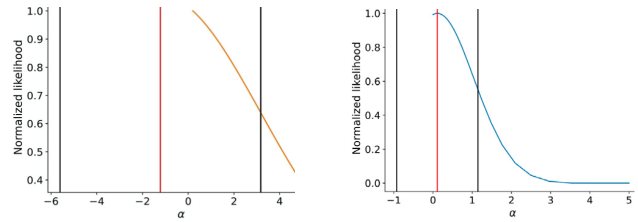

Figure 6. Likelihood profiles of α using 10 years of data (left) and 12 years of data (right) for source 4FGL J1555.7+1111. These plots are produced from our analyzed spectra by the UCSC Particle Physics team hosting our research. α deviations from normalization using 10 years of data are resolved with our analysis using 12 years of data [2].

While we were able to resolve 17 outlier sources, analysis of bright sources significantly changed the normalization value of the EBL, creating a new outlier source: one of the bright sources studied differed more than 3σ from the newly calculated normalization value. As analysis of the corrected outlier 4FGL sources reduced discrepancies between the source value and a nominal EBL model [3], it can be surmised that issues in the initial catalog caused σ-disagreement rather than the intrinsic spectra of our sources. However, causes of discrepancy for the new outlier source are unknown; problems could be in the nature of the source, or in the analysis itself. For instance, sources with specifically high variability can have a reconstructed 12-years spectra unable to show any given real state of activity, inducing bias in α values. Additionally, for certain sources, we had to change the spectral model from the original catalog description. For 4FGL J1555.7+1111, the large energy bin at 100 GeV in the 4FGL-DR2 spectrum (See fig. 5 top) minimized the real spectral curvature at high energies. This can lead to an underestimation of EBL absorption, creating an outlier source. Future work will include checking which of the mentioned possibilities may be creating the new outlier source. The results of this study will contribute to the first EBL skymap ever created from normalization and to the probing of possible anisotropies.

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