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The Spectral Index Distribution and the Spectral Shape of Unresolved Emission of GeV Blazars: Prospects for GLAST

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Abstract: We present a maximum-likelihood method of determining the intrinsic spectral index distribution (ISID) of a population of gamma-ray emitters which accounts for error in measurement of individual spectral indices, and we apply it to the case of Energetic Gamma-Ray Experiment Telescope (EGRET) blazars and simulated Gamma-ray Large Area Space Telescope (GLAST) blazars. We find that the most likely Gaussian ISID for EGRET blazars has a mean of 2.27 and a standard deviation of 0.20. We also test for spectral index hardening associated with blazar variability for which we find no evidence. Finally, we calculate the unabsorbed spectral shape of the blazar contribution to the EGRB using the derived ISIDs finding an only mildly convex, although not very well constrained, spectrum.

Introduction

Blazar spectra in the γ-ray regime encode important information concerning particle acceleration and emission processes in blazar jets [see e.g. 12 and references therein]. In addition, the distribution of blazar γ-ray spectral indices is a critical input in the estimation of the unresolved blazar contribution to the extragalactic gamma-ray background (EGRB) [7; 9]. Whether the collective emission of unresolved blazars may be the dominant component of the diffuse extragalactic gamma-ray background depends not only on intensity, but also on spectral shape. However, blazars must be accounted for in any attempt to understand or model the high-energy diffuse photon inventory (e.g. in constraining exotic high-energy physics). Thus, the spectral index distribution (SID) of blazars needs to be understood.

Obtaining the spectral index distribution of blazars presents three major difficulties. First, large measurement uncertainties in individual blazar spectral indices, due to low photon statistics, contaminate the sampling of the underlying *intrinsic* spectral index distribution (ISID)[1], by exaggerating its spread, possibly to a large degree. Second, the possible systematic change of the spectral index with flaring could result in an SID more representative of more easily seen flaring blazars. Third, the possible existence of two spectrally distinct populations (BL Lacs and flat spectrum radio quasars - FSRQs) in the resolved blazar sample [e.g. 4; 7] should be accounted for.

Here, we seek to: (a) estimate the extent to which individual measurement errors affect the sampling of the SID of EGRET blazars and perform a maximum likelihood analysis which accounts for these errors and determines the "most likely" parameters of the ISIDs; (b) assess how much measurement errors affect the spectral shape of the unresolved blazar spectrum; (c) predict to what extent the upcoming GLAST observations will help us in resolving the aforementioned issues. The dataset used for our analysis is the set of 66 blazars characterized as "confident AGN identifications" in the 3EG catalog [2]. We divide the population into 14 BL Lacs and 51 FSRQs as in [5]. To test the sensitivity of our results to the utilized blazar sample we compare with the confident blazar set of [3].

1. "Spectral index distribution" refers to the distribution of measured spectral indices "intrinsic spectral index distribution" refers to the distribution free of contamination by measurement errors.

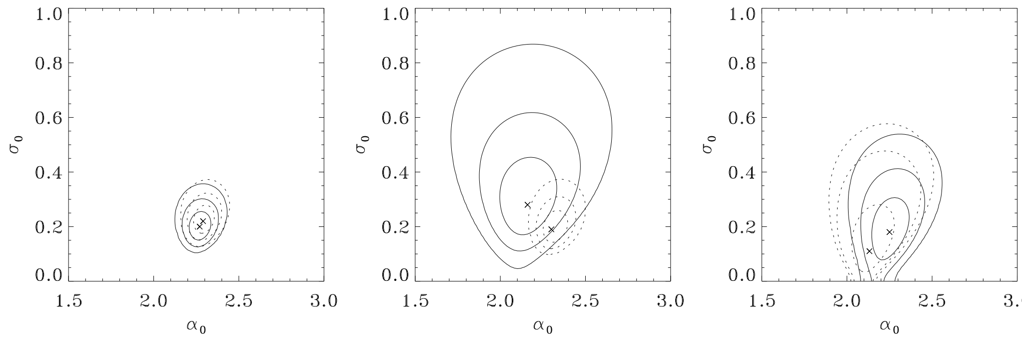

Figure 1: *Left:* Likelihood function 1σ, 2σ, and 3σ contours for the Mattox [3] (solid lines) and the 3EG [2] (dashed lines) confident blazar samples. *Center:* Same for BL Lacs (solid) and FSRQs (dashed). *Right:* Same for "mostly flaring" (solid) and "mostly quiescent" (dashed) blazars. The axes represent the mean (α_0) and spread (σ_0) of the ISID. The maximum-likelihood parameters of each ISID are denoted by $\times$.

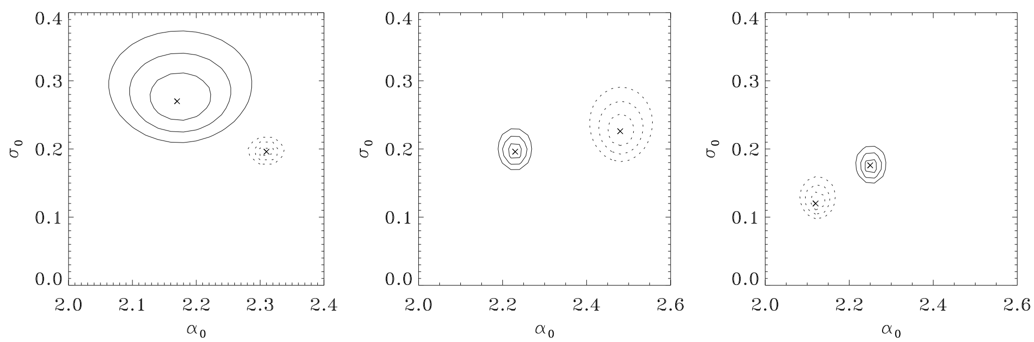

Figure 2: ISID contours for simulated GLASt blazar datasets. *Left:* BL Lacs (solid) and FSRQs (dashed). *Center, Right:* "mostly flaring" (solid) and "mostly quiescent" (dashed) blazars for spectral index hardening (center) or softening (right) with flaring.

Analysis and Results

To assess the significance of error contamination in the SID, we perform a simple Monte Carlo test. We consider separately the samples of confident EGRET BL Lacs and FSRQs assuming that the ISID of each subset is a Gaussian. We take the mean of each sample, α_0, to be the "trimmed mean" of the sample and the variance σ_0^2 to be variable. We also calculate, the "trimmed variance," σ_t^2, of each population. The trimmed means and variances are calculated by trimming the top and bottom five percent of the combined populations. In this way, we obtain for the BL Lacs: $\alpha_0 = 2.20$ and $\sigma_t = 0.33$; and for the FSRQs: $\alpha_0 = 2.39$ and $\sigma_t = 0.22$. We then draw spectral indices[2] for BL Lacs and FSRQs from ISIDs with mean α_0 and varying σ_0 and calculate the fraction of sets for which the trimmed variance is greater than σ_t^2. The median ISID spread is equal to 0.27 for the BL Lacs and 0.20 for FSRQs–nearly half of the values that would have been obtained from fits to histograms of spectral indices.

We now employ a likelihood analysis which allows us to explicitly account for these errors and con-

2. Errors are accounted for by adding to the drawn spectral index an error drawn from a Gaussian with mean of 0 and σ equal to one of the EGRET blazar uncertainties.

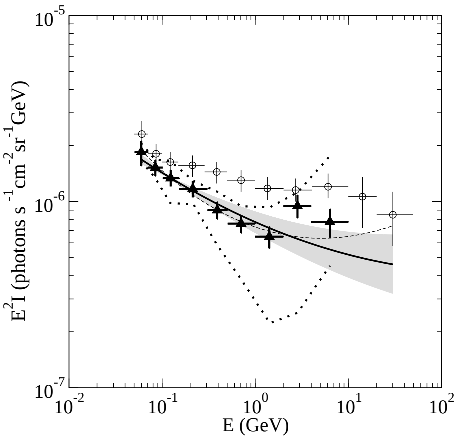

Figure 3: Spectral shape of the unresolved blazar emission. Solid line: spectral shape based on maximum-likelihood ISID for the confident blazar sample of [3]. Grey region: spectral shapes for ISID parameters within the 1σ likelihood contour. Filled triangles: EGRB determination of [10]. Open circles: EGRB determination of [8]. Error bars are statistical errors only. Thick dotted lines: EGRB systematics of [10]. Thin dotted line: spectral shape determined from the measured SID.

strain the parameters (α_0 and σ_0 for a Gaussian) of the ISID. Without accounting for measurement uncertainties, the likelihood of measuring a spectral index α_j given a Gaussian ISID would simply be the ISID calculated at α_j; however, in including measurement uncertainty, the likelihood l_j of measuring α_j becomes the product of two Gaussians [11]. If we have N independent spectral index measurements, then the overall likelihood becomes $\mathcal{L} = \prod_{j=1}^{N} l_j$. The parameters of the ISID can be found by maximizing this likelihood.

In the left panel of Fig. 1, we plot likelihood contours for the confident blazar set of [3] (solid lines; maximum-likelihood ISID parameters: $\alpha_0 = 2.27$, $\sigma_0 = 0.20$) and of the 3EG [2] (dashed lines; maximum-likelihood ISID parameters: $\alpha_0 = 2.29$, $\sigma_0 = 0.22$). In the center panel, we show contours for the BL Lac ISID (solid lines; maximum-likelihood parameters: $\alpha_0 = 2.15$, $\sigma_0 = 0.28$) and the FSRQ ISID (dashed lines; maximum-likelihood parameters: $\alpha_0 = 2.3$, $\sigma_0 = 0.19$) which are marginally separated at the 1σ level. In the right panel, we show ISID contours for the populations of EGRET blazars which were most frequently seen in their flaring state (solid lines) and blazars which were mostly seen in their quiescent state (dashed lines)[3] which are consistent with each other and indicate the lack of evidence for or against spectral hardening with variability.

We apply a similar analysis to simulated datasets of spectral indices and spectral index uncertainties for GLAST-detectable blazars[4]. The spectral indices are drawn from their respective EGRET population ISIDs and, in assigning measurement uncertainties, we make use of the anti-correlation of EGRET spectral index uncertainties with the number of P1234 photons. Results are shown in the left panel of Fig. 2. Excellent approximations of the assumed underlying ISID parameters are found from the analysis, and the separation between the BL Lac and FSRQ ISIDs is well established with a significance greater than 3σ. Also shown in Fig. 2 are the results of likelihood analyses performed on two different simulated datasets of mostly flaring and mostly quiescent GLAST blazars (one assuming that flaring blazars are harder on average, as in [9], and the other assuming that quiescent blazars are harder on average, as indicated tentatively by the maximum-likelihood parameters of the "mostly flaring" and "mostly quiescent" ISIDs of the EGRET sample; see [11]). If there is a separation between these two populations, GLAST will also be able to distinguish between them with a significance greater than 3σ in both scenarios.

Finally, we apply the above ISIDs to a calculation of the spectral shape of the unabsorbed, unresolved blazar emission spectrum [6]. As shown in [6], this spectral shape, if spectral indices are independent of blazar luminosity and do not evolve with redshift (as demonstrated in [11]), depends solely on the ISID. The overall magnitude of the blazar contribution is not constrained in this analysis which concentrates solely on the spectral shape[5]. For

3. These populations are determined based on how the fluxes of individual viewing periods compare with that of the P1234 Flux [11].

4. The numbers of BL Lacs and FSRQs are determined from the gamma-ray luminosity functions found in [1].

5. The overall magnitude of the blazar contribution can be as little as a few percent to as much as 100 per-

easy visual comparison with the spectral shape of the observed EGRB, we normalize the spectral shape curves so that they pass through the 83 MeV point of [10]. In Fig. 3, we show our results as compared with two determinations of the EGRET EGRB and the spectral shape determined from the *measured* SID (not correcting for error in measurement of the spectral indices).

As the figure shows, the spectral shape of the blazar contribution to the EGRB is not very well constrained if only information from EGRET is to be used in its calculation. The uncertainty of the theoretical calculation is comparable with the statistical uncertainty of EGRET observations. The spectrum is only mildly convex, so if we were to take at face-value the upward trend seen in the EGRET EGRB of [10], we would have to conclude that even if the blazar contribution dominates the EGRB at lower energies, it would not be sufficient to explain the EGRB at high energies. However, the systematic uncertainties in the observational determination of the EGRET EGRB are high, and no strong conclusions can be drawn at this point. Nevertheless, GLAST data will greatly improve the situation as they will appreciably shrink the uncertainties in the theoretical model (through large number statistics; see [6]). Moreover, the determination of the GLAST EGRB is expected to be significantly more confident, both in statistical and systematic uncertainties, than the EGRET EGRB.

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cent of the EGRB depending on the luminosity function [for discussion, see 11 and references therein].