Joint anisotropy and source count constraints on the contribution of blazars to the diffuse gamma-ray background

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We place new constraints on the contribution of blazars to the large-scale isotropic gamma-ray background (IGRB) by jointly analyzing the measured source count distribution (log N-log S) of blazars and the measured intensity and anisotropy of the IGRB. We find that these measurements point to a consistent scenario in which unresolved blazars make \(\lesssim 30\%\) of the IGRB intensity at 1–10 GeV while accounting for the majority of the measured anisotropy in that energy band. These results indicate that the remaining fraction of the IGRB intensity is made by a component with a low level of intrinsic anisotropy.

Introduction.—The origin of the isotropic gamma-ray background (IGRB), the observed all-sky diffuse emission at MeV to GeV energies, remains uncertain. Some or all of this emission is expected to arise from astrophysical sources (e.g., active galactic nuclei, blazars, star-forming galaxies, millisecond pulsars, galaxy clusters, cluster shocks, and cascades from ultra-high-energy cosmic rays; see [1]) as well as possible exotic sources (e.g., dark matter annihilation or decay [2]). The Fermi Large Area Telescope (LAT) Collaboration has provided a new measurement of the IGRB energy spectrum [3] with improved accuracy, covering the broad energy range from 200 MeV to \(\sim\) 100 GeV. However, the energy spectrum of the IGRB is reported to be consistent with a power law, and thus provides little clue to the origin of this emission in the form of spectral features. As a result, the contributions of individual source classes to the IGRB are poorly constrained, severely limiting our ability to search for signals of new physics or to place constraints on emission from exotic sources.

One way to tackle the problem is through population studies of resolved sources. Gamma-ray source classes with resolved members, such as blazars and millisecond pulsars, are obvious candidate contributors to the IGRB via emission from their yet unresolved members. The source count distribution in flux (log N-log S, the number of sources, N, per unit flux, S) of LAT-detected gamma-ray blazars has recently been studied [4] down to fluxes of \(S_{100} \sim 10^{-10}\) cm\(^{-2}\) s\(^{-1}\), where \(S_{100}\) denotes the individual source flux above 100 MeV. For the first time, the log N-log S is found to be well-described by a broken power law, and the position of the break and the slope of the log N-log S below and above the break have been measured.

It is possible to estimate the contribution to the IGRB of blazars below the LAT point source sensitivity of \(\sim 10^{-10}\) cm\(^{-2}\) s\(^{-1}\) by extrapolating the measured log N-log S to zero flux. For the energy range 0.1–100 GeV, Ref. [4] reports that unresolved point sources contribute 22.5 \(\pm\) 1.8\% of the IGRB intensity measured by [3]. As blazars constitute the vast majority of LAT-detected sources, this is a good indicator of the expected unresolved blazar contribution, as well as a firm upper limit for sources that follow the measured source count distribution. In the following we use the terms blazars and unresolved sources interchangeably.

Another constraint, which has not yet been explored, is provided by the level of anisotropy of the IGRB. Recently the first measurement of the small-scale anisotropy of the IGRB has been made [5], while in the last few years predictions have been derived for the anisotropy of many gamma-ray source classes, including blazars and galaxy clusters [6], millisecond pulsars [7], star-forming galaxies [8] and dark matter annihilation and decay [9]. These source classes often produce similar energy spectra but very different anisotropies, suggesting that anisotropy analysis could be a powerful tool for distinguishing possible IGRB contributors.

In this Letter, for the first time we use the observed anisotropy information to constrain the properties of the source classes contributing to the IGRB. We calculate the intensity and anisotropy produced by the unresolved members of a source population whose detected members follow a broken power-law log N-log S (such as the LAT-detected blazars). We then compare the predictions for this class of models with the measured IGRB intensity [3] and anisotropy [5] to identify the range of log N-log S parameters that are consistent with both measurements.

The source count distribution.—The log N-log S of sources detected by the LAT is compatible with a broken power law [3],

\[
\frac{dN}{dS} = \begin{cases} 
A S^{-\beta} & S \geq S_b \\
A S_b^{-\beta+\alpha} S^{-\alpha} & S < S_b 
\end{cases}
\]  

(1)
where \( A \) is the normalization, \( S_b \) is the flux where the power law breaks, and \( \alpha \) and \( \beta \) are the power-law slopes below and above the break, respectively. The fluxes \( S \) and \( S_b \) are implicitly normalized to 1 cm\(^{-2}\) s\(^{-1}\).

The log \( N \)-log \( S \) of the Fermi LAT sources has been measured in several energy bands \( [3, 4] \). We find that the contribution from the unresolved sources can be estimated by integrating the distribution from the source detection threshold down to zero flux:

\[
I = \int_0^{S_t} \frac{dN}{dS} S dS, \tag{2}
\]

where \( S_t \) is the flux sensitivity threshold for point source detection. Due to the energy-dependent angular resolution of the LAT, the value of \( S_t \) for a given source depends on its spectral index. However, this spectral index bias is small in the 1–10 GeV range \([4]\). We thus derive an effective \( S_t \) for the value \( I = 5.5 \times 10^{-8} \) cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\) reported in Table 6 of Ref. \([4]\), which, for the best-fit log \( N \)-log \( S \) parameters, corresponds to unresolved blazars contributing 14% of the measured IGRB flux in this energy range \([3, 4]\). We find \( S_t = 3.7 \times 10^{-10} \) cm\(^{-2}\) s\(^{-1}\) for the 1–10 GeV band.

The angular power spectrum. —The Poisson term of the angular power spectrum of the sources, \( C_P \), can be calculated from the log \( N \)-log \( S \). It takes the same value at all multipoles and is given by

\[
C_P = \int_0^{S_t} \frac{dN}{dS} S^2 dS. \tag{3}
\]

This formula gives \( C_P \) in the units appropriate for the angular power calculated from an intensity map, i.e., units of intensity\(^2\) \( \times \) solid angle, where intensity is in units of the number of photons per area per time per solid angle. Evaluating Eq. \( 3 \) using the best-fit log \( N \)-log \( S \) parameters yields \( C_{P,\text{pred}} = 8.0 \times 10^{-18} \) (cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\))\(^2\) sr. Under the assumption that the sources are point-like and unclustered on the angular scales of interest, the Poisson term is the only contribution to the angular power.

The predicted power, \( C_{P,\text{pred}} \), has an uncertainty due to the propagation of the uncertainties in the parameters of the log \( N \)-log \( S \) function. We estimate this uncertainty from the log \( N \)-log \( S \) in the range 0.1–100 GeV, where the parameters have smaller statistical uncertainties, and then rescale it to the 1–10 GeV range. The rescaling was done by computing the flux conversion factor: \( \kappa = S_{x-y}/S_{u-v} = (y^{-\gamma+1} - x^{-\gamma+1})/(v^{-\gamma+1} - u^{-\gamma+1}) \), where \( \gamma \) is the average photon index of the sources, and \( x-y \) and \( u-v \) are the edges of the two energy bands. Then the Poisson anisotropies in the two bands are simply related by \( C_P^u = \kappa^2 C_P^v \). From the full covariance matrix \([10]\) of log \( N \)-log \( S \) parameters in the 0.1–100 GeV range, we obtain \( \delta C_P^{\text{1–100}} = 0.54 \times 10^{-15} \) (cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\))\(^2\) sr, which, assuming \( \gamma = 2.4 \), can be rescaled to \( \delta C_P^{\text{pred}} \equiv \delta C_{P,\text{pred}} = 0.8 \times 10^{-18} \) (cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\))\(^2\) sr, so that \( \delta C_{P,\text{pred}} = (8.0 \pm 0.8) \times 10^{-18} \) (cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\))\(^2\) sr.

Ref. \([5]\) reports measurements of \( C_P \), obtained by averaging the angular power spectrum coefficients \( C_\ell \) over the multipole range 155 \( \leq \ell \leq 504 \), in the energy ranges 1–2 GeV, 2–5 GeV, 5–10 GeV, and 10–50 GeV. Using the same analysis pipeline as Ref. \([5]\), we have also calculated the anisotropy for the 1–10 GeV energy band for the foreground-cleaned data, which yields \( C_{P,\text{data}} = (11.0 \pm 1.2) \times 10^{-18} \) (cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\))\(^2\) sr. This value can be directly compared with the predicted value derived above. The two values are compatible at the 2\( \sigma \) level so that unresolved blazars can account for almost all of the observed anisotropy. We discuss this point further in the next section. The 2\( \sigma \) upper limit on the non-blazar anisotropy is \( \Delta C_{P,\text{U}} = (C_{P,\text{data}} - C_{P,\text{pred}}) + 2 \sqrt{\delta C_{P,\text{data}}^2 + \delta C_{P,\text{pred}}^2} = 5.9 \times 10^{-18} \) (cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\))\(^2\) sr.

Using the best-fit log \( N \)-log \( S \), we also compare the predicted \( C_P \) with the anisotropy measurements in the four energy bands used in Ref. \([5]\) (Table II). In this case we use the rescaling method described above to calculate both the predicted mean values and their uncertainties. The derived 2\( \sigma \) upper limits on the level of residual anisotropy in each energy bin are reported in Table II. These limits can be used to constrain models of astrophysical or exotic source populations, based on their predicted level of anisotropy. We note that the uncertainties, and, except for the 1–10 GeV case, the central values for \( C_{P,\text{pred}} \) used to derive these limits rely on the rescaling method described above, and thus on the assumption of an average index for the sources. However, we find that varying \( \gamma \) from 2.2 to 2.6 produces only a small change.

Finally, as a technical remark, we emphasize that the use of the dimensionful intensity angular power, rather than

| \( E_{\text{min}} \) (GeV) | \( E_{\text{max}} \) (GeV) | \( C_{P,\text{data}} \) \( \times 10^{-19} \) (cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\))\(^2\) sr | \( C_{P,\text{pred}} \) \( \times 10^{-19} \) (cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\))\(^2\) sr | \( C_{P,\text{U}}^\Delta \) \( \times 10^{-19} \) (cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\))\(^2\) sr |
|----------------|----------------|----------------|----------------|----------------|
| 1.0            | 10.0           | 110 \pm 12     | 80 \pm 8       | \(< 59\)        |
| 1.04           | 1.99           | 46.2 \pm 11.1  | 27.1 \pm 2.7   | \(< 41.9\)      |
| 1.99           | 5.00           | 11.30 \pm 2.20 | 6.6 \pm 0.7    | \(< 9.3\)       |
| 5.00           | 10.4           | 0.845 \pm 0.246| 0.40 \pm 0.04  | \(< 0.94\)      |
| 10.4           | 50.0           | 0.211 \pm 0.086| 0.096 \pm 0.010| \(< 0.288\)     |
than the *dimensionless* fluctuation angular power, conveniently avoids the need to treat contamination of the anisotropy measurement by possible residual Galactic diffuse emission or instrumental backgrounds. These backgrounds are, to good approximation, isotropic, or vary only on large angular scales, and thus their contribution to the intensity angular power spectrum appears only at multipoles far below the range used to measure the angular power reported in \[\text{Fig. 1}\]. In the following, when discussing the IGRB intensity, \(I_{\text{IGRB}}\), we use the measurement given in \[\text{Fig. 1}\].

**Constraints on unresolved blazars.**—We now explore more generally the parameter space of the \(\log N - \log S\) function to determine the region that is compatible with the measured anisotropy, intensity, and source count data. We define the parameter space of the source count distribution by the position of the break flux, \(S_b\), and the faint-end slope, \(\alpha\), of the \(\log N - \log S\) function at fluxes below the break flux. We fix the normalization and slope of the \(\log N - \log S\) at high fluxes, as the efficiency in detecting point sources at high fluxes is \(\sim 1\), and thus these parameters are well-determined (i.e., potential biases in these parameters are small). For each point in the \(S_b - \alpha\) parameter space we calculate the predicted \(I_{\text{IGRB}}\) and \(C_p\) from the corresponding \(\log N - \log S\) function.

In Fig. 1 we show the region of the \(\log N - \log S\) parameter space in which blazars contribute 100% of the IGRB intensity (light blue) and that in which they contribute 100% of the angular power (dark yellow) in the 1–10 GeV energy band. The widths of these regions show the 68% (1\(\sigma\)) confidence level regions, reflecting the respective 1\(\sigma\) uncertainties in the measured \(C_p\) and \(I_{\text{IGRB}}\).

Above the light blue region, blazars contribute less than 100% of the measured IGRB intensity; below this region, blazars overproduce the IGRB intensity. Similarly, above the dark yellow region blazars do not contribute the entirety of the measured angular power, whereas below this region they overproduce the anisotropy. We emphasize that the constraint from the anisotropy measurement is stronger than that from the intensity measurement except for at very high values of \(\alpha\).

As noted in the previous section, the predicted \(C_{p, \text{pred}}\) from the best-fit \(\log N - \log S\) agrees with the measured \(C_{p, \text{data}}\) to within 2\(\sigma\). We now ask “how well do the parameters of the \(\log N - \log S\) function inferred from \(C_{p, \text{data}}\) agree with those found from the source count analysis?” The best-fit 1\(\sigma\) region of \(S_b\) and \(\alpha\) for the blazar \(\log N - \log S\) given in [4, 11] overlaps well with the 1\(\sigma\) region inferred from \(C_{p, \text{data}}\). This is a non-trivial result, as the measured anisotropy and source count distribution are independent observables, determined from independent data analyses. Here the agreement is at the 1\(\sigma\) level since the errors on the 1–10 GeV \(\log N - \log S\) parameters shown in the plot are taken directly from [4, 11] and are larger than the rescaled ones used in the previous section.

There is a region of parameter space in which blazars contribute 100% of the IGRB intensity without exceeding the measured \(C_p\); however, this region has a high break flux \((S_b \approx 10^{-8}\text{cm}^{-2}\text{s}^{-1})\) which is incompatible with the break measured from the source count analysis. Such a high break flux can be robustly excluded, as it would lie in the flux range where the source detection efficiency is close to 1, and thus this kind of feature is unlikely to have been missed. Taking the measured value of the break flux as an upper limit, we find that the contribution from blazars in the region allowed by \(C_{p, \text{data}}\) cannot be more than \(\sim 30\%\) of the IGRB mean intensity (see labeled contours in Fig. 1), a value which is in agreement with the results of the source count analysis alone.

To further demonstrate how anisotropy data can be a powerful tool for distinguishing between multiple scenarios we test an alternative fit to the blazar \(\log N - \log S\) obtained by Stecker & Venters [11]. A notable feature of this alternative fit is that it can account for \(\sim 60\%\) of the IGRB mean intensity. We have calculated \(C_p\) from their \(\log N - \log S\) [11, 12] and, using a threshold of \(3.7 \times 10^{-10}\text{cm}^{-2}\text{s}^{-1}\) (the same used in the rest of our analysis), obtain \(C_p = (2.4 \pm 0.4) \times 10^{-17}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}\) (the error reported on this prediction being likely an overestimate since it neglects the covariance of the parameters).
This value is a factor $\sim 2.4$ larger than the measured value, in significant tension with the anisotropy data.

Comparing the measured anisotropy of the IGRB and the predicted anisotropy from blazars leads to another important conclusion. Since, for the best-fit source count distribution, blazars already account for $\sim 100\%$ of the observed anisotropy and, in intensity units, Poisson angular power is additive, the remaining component (or components) making $\sim 70\%$ of the IGRB intensity must contribute a low level of anisotropy in order to not over-produce the observed angular power. Interestingly, this can be achieved quite naturally since some proposed contributors to the IGRB, such as star-forming galaxies \cite{8}, are expected to contribute negligibly to the anisotropy. On the other hand, this result implies strong constraints on source populations with large intrinsic anisotropy.

We note that the anisotropy and intensity contributions from a source population have different dependences on the source count distribution, and consequently they represent complementary observables which are sensitive to different source flux ranges. This is demonstrated in Fig. \ref{fig:anisotropy} which shows the cumulative contribution to the intensity and anisotropy above 100 MeV as a function of source flux for the \textit{Fermi} LAT best-fit $\log N \cdot \log S$ parameters. From the relative flatness of the cumulative flux distribution below the threshold flux, it can be inferred that the IGRB intensity contribution from unresolved blazars has only a weak dependence on the effective flux sensitivity. The cumulative anisotropy distribution, however, falls off more quickly below the threshold flux, so the anisotropy from unresolved sources is more strongly dependent on the sensitivity limit, and improved point source sensitivity is thus likely to have a more notable impact on the measured IGRB anisotropy.

\section*{Additional energy bands}

We briefly consider this analysis in other energy bands. The range above 10 GeV is currently not suitable since the error on the measured $C_P$ is large and the $\log N \cdot \log S$ is not well-constrained. A natural extension is thus to include the low-energy range down to 100 MeV. However, spectral index bias is non-negligible in this energy band, and the predicted anisotropy is quite sensitive to the shape of the source detection efficiency function, which characterizes this bias. In addition, there is not yet a measurement of the anisotropy below 1 GeV. For these reasons, an analysis of lower and higher energy bands is left for future work.

\section*{Conclusions}

We performed a joint analysis of the source count distribution of blazars and the measured anisotropy of the IGRB in the energy range $1–10$ GeV, and find that a consistent picture emerges in which unresolved blazars account for only $\sim 30\%$ of the IGRB intensity but $\sim 100\%$ of the angular power. The sources contributing the remaining $\sim 70\%$ of the IGRB intensity are thus constrained to provide only a small contribution to the anisotropy. Viable models of sources contributing to the IGRB must satisfy the upper limits on their anisotropy that we reported in the last column of Table \ref{table:anisotropy}. These results demonstrate the power of anisotropy information for constraining the origin of the IGRB.

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\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{anisotropy.png}
\caption{Cumulative contribution of blazars in linear (top) and log (bottom) scale to the IGRB anisotropy (dashed) and intensity (solid) for the \textit{Fermi} best-fit $\log N \cdot \log S$ ($E > 100$ MeV) as a function of source flux.}
\end{figure}
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