The Astrophysical Journal, 933:221 (17pp), 2022 July 10 https://doi.org/10.3847/1538-4357/ac6c85

Flat-spectrum Radio Quasars and BL Lacs Dominate the Anisotropy of the Unresolved Gamma-Ray Background

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Received 2022 January 28; revised 2022 April 29; accepted 2022 May 2; published 2022 July 15

Abstract

We analyze the angular power spectrum (APS) of the unresolved gamma-ray background (UGRB) emission and combine it with the measured properties of the resolved gamma-ray sources of the Fermi-LAT 4FGL catalog. Our goals are to dissect the composition of the gamma-ray sky and to establish the relevance of different classes of source populations of active galactic nuclei in determining the observed size of the UGRB anisotropy, especially at low energies. We find that, under physical assumptions for the spectral energy distribution, i.e., by using the 4FGL catalog data as a prior, two populations are required to fit the APS data, namely flat-spectrum radio quasars at low energies and BL Lacs at higher energies. The inferred luminosity functions agree well with the extrapolation of the flat-spectrum radio quasar and BL Lac ones obtained from the 4FLG catalog. We use these luminosity functions to calculate the UGRB intensity from blazars, finding a contribution of 20% at 1 GeV and 30% above 10 GeV. Finally, bounds on an additional gamma-ray emission due to annihilating dark matter are also derived.

Unified Astronomy Thesaurus concepts: Gamma-ray sources (633); Blazars (164); Gamma-rays (637)

1. Introduction

The extragalactic gamma-ray sky has been surveyed by the Fermi Large Area Telescope (LAT) since the summer of 2008 (Atwood et al. 2009). The outstanding capability of this instrument has been groundbreaking for several aspects of high-energy astrophysics. One important result is the detection and cataloging of extragalactic gamma-ray sources. The 8 yr Fermi-LAT source catalog, called the 4FGL catalog (Abdollahi et al. 2020),[11] counts more than 3300 extragalactic sources, more than 60% of the entire catalog. Almost all the extragalactic sources are blazars, a subclass of active galactic nuclei (AGNs), with a jet pointing toward us: 35% are BL Lacs (BLLs), about 22% are flat-spectrum radio quasars (FSRQs), and about 41% are blazars of unknown type (BCUs).

On top of the numerous extragalactic sources detected, even more numerous subthreshold sources populate the unresolved gamma-ray background (UGRB).[12] The UGRB emission represents about 20% of the total gamma-ray emission, and offers a unique observable of the extragalactic gamma-ray sky below the Fermi-LAT source detection threshold.

The UGRB is by definition a mission-time-dependent component: the more Fermi-LAT surveys the sky, the more sensitive it becomes to less bright sources, leaving only the faintest objects unresolved. Guaranteed contributors to the UGRB emission are sub-detection-threshold blazars (Cuoco et al. 2012; Di Mauro et al. 2018), misaligned AGNs (mAGNs; Di Mauro et al. 2013), and star-forming galaxies (SFGs; Roth et al. 2021; Tamborra et al. 2014). Additionally, we cannot exclude contributions from more exotic components, such as dark matter (DM; Ando 2009; Bringmann et al. 2014; Ajello et al. 2015; Fornasa et al. 2016; Zechlin et al. 2018)

The UGRB emission has been studied through three main observables: its energy spectrum (Abdo et al. 2011; Ackermann et al. 2015), its 1-point probability distribution function (1pPDF), through photon count statistics (Lisanti et al. 2016; Zechlin et al. 2016b, 2016a; Di Mauro et al. 2018), and its angular power spectrum (APS; Ackermann et al. 2012; Fornasa et al. 2016; Ackermann et al. 2018). The latter two observables investigate fluctuations over the UGRB isotropic emission to infer the properties of the underlying sources at the subthreshold level. In this unresolved regime, mAGNs and SFGs, fainter than blazars but much more numerous, are expected to dominate the UGRB energy spectrum (Di Mauro et al. 2013; Roth et al. 2021). At the same time, at the current level of sensitivity, the blazars produce a higher level of spatial anisotropy than mAGNs and SFGs, and hence the former are expected to dominate the APS of the UGRB (Di Mauro et al. 2014; Cuoco et al. 2012). SFGs and mAGNs could eventually emerge once the majority of the blazars have been resolved. Moreover, an improvement in the sensitivity is necessary in

[11] This catalog is now also called 4FGL-DR1.
[12] The UGRB is also called the isotropic gamma-ray background in the literature. While for intensity studies it can be considered isotropic, at a deeper level it is definitely not. Since we study its anisotropies in this paper, it is more appropriate to call it *unresolved* instead.

order to reveal the large-scale structure (LSS) of the universe traced by gamma-ray sources (see, e.g., Ando 2009) that is encoded in a multipole-dependent APS. It is, therefore, crucial to update the UGRB anisotropy measurement in parallel with the detection of more sources in the LAT catalogs.

The latest UGRB anisotropy measurement was performed by the Fermi-LAT Collaboration in 2018 (Ackermann et al. 2018). In that work, 8 yr of Pass-8 (R3) data were analyzed, and it was consistently the case that the source catalog was based on the same amount of observation time (FL8Y, a preliminary version of the 4FGL). The APS of the UGRB was measured in 12 energy bins between 500 MeV and 1 TeV. Additionally, the cross-correlation signal between the different energy bins (generically denoted by i and j) was derived. In all cases, the APS (above $\ell = 50$) was compatible with a constant value, C_P^{ij}, with no hint of LSS signature in the multipole range considered. This result confirms that the UGRB intensity fluctuation field, at the current level of the sensitivity of the detector to point sources, is still dominated by a population of relatively bright and not very numerous sources, so that the isotropically distributed fluctuations from Poisson noise dominate over the correlation due to clustering. Additionally, the anisotropy energy spectrum revealed a preference for a double-power-law trend (with a high-energy exponential cutoff) over a single power law (with a high-energy exponential cutoff), placing a spectral break around 5 GeV.

Previous interpretative works, based on antecedent measurements of the UGRB anisotropy energy spectrum, were devoted to determining the components that contribute to the measured signal. In particular, Ando et al. (2017) studied the results of Fornasa et al. (2016) and inferred the presence of a second steeper component, in addition to the blazar-only model, emerging below 2 GeV. However, the very soft spectral index implied by this analysis challenges the interpretation in terms of a known source population. Recently, Manconi et al. (2020) combined the 1pPDF, using methods as in Zechlin et al. (2016a), with the latest measurement of the anisotropy energy spectrum of the UGRB by Ackermann et al. (2018) to test blazar models (yet not distinguishing between BLLs and FSRQs), as well as the source count distribution of the blazars extracted from the 4FGL catalog. They found that the assumption of the UGRB fluctuation field being entirely dominated by blazars was in agreement with both observables, which appear to show remarkable complementarity. Past works have also focused on the DM interpretation of the UGRB anisotropy, such as Fornasa et al. (2016), where numerical simulations were used to model the DM distribution and its uncertainty in order to constrain the contribution from weakly interacting massive particles (WIMPs) in Galactic and extragalactic structures. The derived bounds are in the same ballpark as for other UGRB probes, but still significantly above the so-called thermal WIMP scenario. For a comprehensive overview of the UGRB-related measurements and interpretative works prior to Fornasa et al. (2016), we address the reader to the review of Fornasa & Sánchez-Conde (2015).

In this work, we will focus on the latest measurement of the UGRB anisotropy energy spectrum (Ackermann et al. 2018). We investigate the contributions of the different blazar types, distinguishing between BLLs and FSRQs. We find that BLLs and FSRQs can account for the totality of the UGRB anisotropy and also well reproduce the spectral features observed by Ackermann et al. (2018). The analysis allows us to constrain many of the most relevant parameters of the blazar models in the unresolved regime. As a second step, we include the contribution to the UGRB arising from an annihilating DM particle, and perform a global analysis to derive the constraints on the particle DM parameters. We account for both Galactic and extragalactic DM contributions, under different assumptions of the DM subhalo contribution, and by including cross-terms in the anisotropy APS, due to the cross-correlation of the contribution from blazars and the DM halos hosting them.

The paper is structured as follows. Section 2 is devoted to blazars: we describe the blazar model adopted in our study, we introduce the fit procedure, and we show the results. In Section 3, we discuss the DM constraints for both Galactic and extragalactic DM components. Finally, we conclude in Section 4. Additionally, we present a phenomenological approach to the interpretation of the UGRB anisotropy energy spectrum in Appendix A, while in Appendix C we relate our results to the findings of previous measurements.

2. Modeling Blazar Populations

In Manconi et al. (2020), it was pointed out that a single blazar model is sufficient to describe both the anisotropy level $C_{\rm P}$ and the 4FGL catalog data, at the expense of allowing a relatively broad distribution of the spectral index. Such an approach can be seen as an effective description, where the different subpopulations (with narrower spectral index distributions) are combined in a single model (Ajello et al. 2015). We reproduce the finding of Manconi et al. (2020), although in a more general way, and by using a phenomenological model, in Appendix A. However, we note that the blazar model in Manconi et al. (2020) was only compared to the catalog data in bins of flux and redshift, and not in bins of spectral index, which constrains the spectral energy distribution (SED). Here, in contrast, we intend to use the full catalog information.

In this section, we will therefore consider a physical description of the two populations of blazars that are more numerous in the 4FGL catalog, namely BLLs and FSRQs. We aim to assess their ability to explain the APS measurement. In other words, we test the possibility that the FSRQs, with properties compatible with their cataloged sample, are the population that accounts for the low-energy anisotropy found in Ackermann et al. (2018), while the BLLs are the origin of the high-energy anisotropy. Below, we will show that the two populations are preferred when the information of the 4FGL catalog is included as a prior.

2.1. The Gamma-Ray Luminosity Function

We summarize here the parameterizations of the gamma-ray luminosity function (GLF) and the SED of the BLLs and FSRQs adopted in our analysis. For more details, see Ajello et al. (2012) and Ajello et al. (2014). The GLF $\Phi(L_\gamma, z, \Gamma) = {\rm d}^3N/{\rm d}L_\gamma {\rm d}V {\rm d}\Gamma$—defined as the number of sources per unit of luminosity L_γ, the comoving volume V at redshift z, and the photon spectral index Γ—is typically decomposed in terms of its expression at $z = 0$ and a redshift evolution function:

$$\Phi(L_\gamma, z, \Gamma) = \Phi(L_\gamma, 0, \Gamma) \times e(L_\gamma, z), \tag{1}$$

where L_γ is the rest-frame luminosity in the energy range (0.1–100) GeV, i.e., $L_\gamma = \int_{0.1\ \mathrm{GeV}}^{100\ \mathrm{GeV}} \mathrm{d}E_r\, \mathcal{L}(E_r)$, with

$$\mathcal{L}(E_r) = \frac{4\pi d_L^2(z)}{(1+z)} E\, \frac{\mathrm{d}N}{\mathrm{d}E}, \tag{2}$$

with E being the observed energy, related to the rest-frame energy E_r as $E_r = (1+z)E$. The comoving volume element in a flat homogeneous universe is given by $\mathrm{d}^2V/\mathrm{d}\Omega\mathrm{d}z = c\,\chi^2(z)/H(z)$, where χ is the comoving distance (related to the luminosity distance d_L by $\chi = d_L/(1+z)$) and H is the Hubble parameter. We use a ΛCDM cosmology, with parameters from the final full-mission Planck measurements of the cosmic microwave background anisotropies (Aghanim et al. 2020).

At redshift $z = 0$, the parameterization of the GLF is

$$\Phi(L_\gamma, 0, \Gamma) = \frac{A}{\ln(10) L_\gamma}\left[\left(\frac{L_\gamma}{L_0}\right)^{\gamma_1} + \left(\frac{L_\gamma}{L_0}\right)^{\gamma_2}\right]^{-1} \times \exp\left[-\frac{(\Gamma - \mu(L_\gamma))^2}{2\sigma^2}\right], \tag{3}$$

where A is a normalization factor, the indices γ_1 and γ_2 govern the evolution of the GLF with the luminosity L_γ, and the Gaussian term takes into account the distribution of the photon indices Γ around their mean $\mu(L_\gamma)$, with a dispersion σ. It turns out that the GLF of the BLLs has a relatively broad distribution in terms of luminosity. For this reason, we allow the mean spectral index to slightly evolve with luminosity from a value μ^*:

$$\mu(L_\gamma) = \mu^* + \beta\left[\log\left(\frac{L_\gamma}{\mathrm{erg\ s^{-1}}}\right) - 46\right]. \tag{4}$$

On the other hand, the FSRQs have a narrower distribution, meaning that the inclusion of this effect would not affect the fit, so we can fix $\mu(L_\gamma) = \mu^*$.

We adopt a luminosity-dependent density evolution (LDDE):

$$e(L_\gamma, z) = \left[\left(\frac{1+z}{1+z_c(L_\gamma)}\right)^{-p_1} + \left(\frac{1+z}{1+z_c(L_\gamma)}\right)^{-p_2}\right]^{-1}, \tag{5}$$

with $z_c(L_\gamma) = z_c^* \times (L_\gamma/10^{48}\mathrm{erg\ s^{-1}})^\alpha$, $p_1(L_\gamma) = p_1^* + \tau \times (\log(L_\gamma) - 46)$, and $p_2(L_\gamma) = p_2^* + \delta \times (\log(L_\gamma) - 46)$. We set δ to 0.64 for both populations (Ajello et al. 2015), while τ is fixed to 3.16 for FSRQs and to 4.62 for BLLs (Ajello et al. 2014).

The SED is modeled as a power law:

$$\frac{\mathrm{d}N}{\mathrm{d}E} \sim \left(\frac{E}{E_0}\right)^{-\Gamma}. \tag{6}$$

For definiteness, the spectral index Γ will be taken to be in the range (1, 3.5) (see also Manconi et al. 2020). Given the SED, the photon flux $S(E_{\min}, E_{\max})$ in a given energy interval is obtained by

$$S(E_{\min}, E_{\max}) = \int_{E_{\min}}^{E_{\max}} \frac{\mathrm{d}N}{\mathrm{d}E} e^{-\tau(E,z)}\, \mathrm{d}E, \tag{7}$$

where $\tau(E, z)$ describes the attenuation by the extragalactic background light (Finke et al. 2010). Unless explicitly stated otherwise, the flux in the following computations of the $\mathrm{d}N/\mathrm{d}S$ and the associated figures always refers to the energy bin from 1 to 100 GeV. The free parameters of the model are summarized in Table 2, together with their best-fit values, obtained as outlined below.

With the physical models of the GLF and SED to hand, we can compute the differential number of blazars per integrated flux and solid angle as

$$\frac{\mathrm{d}N}{\mathrm{d}S} = \int_{0.01}^{5.0} \mathrm{d}z \int_1^{3.5} \mathrm{d}\Gamma\ \Phi[L_\gamma(S, z, \Gamma), z, \Gamma]\, \frac{\mathrm{d}V}{\mathrm{d}z}\, \frac{\mathrm{d}L_\gamma}{\mathrm{d}S}, \tag{8}$$

and the size of the gamma-ray intensity fluctuations between the energy bins i and j can be cast in the following form (assuming that the Poisson noise term is the dominant contribution):

$$C_{\mathrm{P}}^{ij} = \int_{0.01}^{5.0} \mathrm{d}z \frac{\mathrm{d}V}{\mathrm{d}z} \int_1^{3.5} \mathrm{d}\Gamma \int_{L_{\min}}^{L_{\max}} \mathrm{d}L_\gamma\ \Phi(L_\gamma, z, \Gamma) \times S_i(L_\gamma, z, \Gamma)\, S_j(L_\gamma, z, \Gamma)[1 - \Omega(S(L_\gamma, z, \Gamma), \Gamma)]. \tag{9}$$

The term $\Omega(S, \Gamma)$ accounts for the Fermi-LAT sensitivity to detect a source, and it is modeled through a step function becoming equal to one at the flux threshold sensitivity S_{thr}, as described in Manconi et al. (2020; (Section III.B.1). It depends on Γ, and it includes a nuisance parameter $k_{C_{\mathrm{P}}}$, which accounts for the uncertainty in its description. We checked that a smoother, more realistic sensitivity function only has a negligible effect on C_{P}. The bounds in the L_γ integration are $L_{\min} = 7 \times 10^{43}$ erg s^{-1} and $L_{\max} = 1 \times 10^{52}$ erg s^{-1}, for BLLs, taken from Ajello et al. (2014), and $L_{\min} = 1 \times 10^{44}$ erg s^{-1} and $L_{\max} = 1 \times 10^{52}$ erg s^{-1}, for FSRQs, taken from Ajello et al. (2012).

The C_{P}s of the BLLs and FSRQs are additive, i.e., $C_{\mathrm{P}} = C_{\mathrm{P}}^{\mathrm{BLL}} + C_{\mathrm{P}}^{\mathrm{FSRQ}}$. We neglect the (multipole-dependent) clustering term (discussed below in the case of DM), since we checked that, in the multipole range of interest, it is a few orders of magnitude smaller than the C_{P} term.

2.2. The Source Count Distribution

The source count distribution, $\mathrm{d}N/\mathrm{d}S$, is defined as the number of sources per flux and solid angle, and is a function of the flux S. In principle, there could also be a directional dependence, but blazars are observed up to relatively large distances, such that their distribution can be taken as isotropic. On the other hand, populations of blazars are known to evolve with time, i.e., they depend on redshift. Furthermore, blazars do not have a unique SED: for this reason, we adopt a distribution for the photon spectral index Γ, which in Equation (3) is assumed to be Gaussian.

The source count distribution (see Equation (8)) depends on the flux, photon spectral index, and redshift. The latter has been estimated for some of the Fermi-LAT resolved sources—those for which association with a source from another catalog was