The Extragalactic γ Ray Background

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Abstract. One way to understand the nonthermal history of the universe is by establishing the origins of the unresolved and truly diffuse extragalactic γ rays. Dim blazars and radio/γ galaxies certainly make an important contribution to the galactic γ-ray background given the EGRET discoveries, and previous treatments are reviewed and compared with a new analysis. Studies of the γ-ray intensity from cosmic rays in star-forming galaxies and from structure formation shocks, as well as from dim GRBs, are briefly reviewed. A new hard γ-ray source class seems required from the predicted aggregate intensity compared with the measured intensity.

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INTRODUCTION

An isotropic, apparently diffuse flux of γ rays was discovered with SAS-2 in the ≈ 40 – 200 MeV range [45]. EGRET, improving and extending the SAS-2 result, measured isotropic γ-ray emission in the ≈ 30 MeV – 100 GeV range [38] with νF_ν intensity at 1 GeV at the level of ≈ 1 keV/(cm^2-s-sr), and with νF_ν spectral index $\alpha_\nu \approx -0.10 \pm 0.03$ (Fig. 1a). The diffuse isotropic γ-ray background consists of an extragalactic γ-ray background and an uncertain contribution of quasi-isotropic Galactic γ rays produced, for example, by Compton-scattered radiations from cosmic-ray electrons. The model-dependent Galactic contribution [38, 42, 43, 44], and the addition at some level of heliospheric flux [28, 34], means that the actual contribution from extragalactic sources is somewhat uncertain. The data in Fig. 1a compares the extragalactic diffuse γ-ray intensity from EGRET analysis [38] with results using the GALPROP model [44], the latter of which requires an extended (≈ 4 – 10 kpc) nonthermal electron halo to fit the hard ($\alpha_\nu \cong -0.4$) diffuse Galactic γ-ray emission. For our purposes, we consider the apparently diffuse extragalactic γ-ray background (EGRB) of Strong et al. [44] as the conservative upper limit for the superposed intensity of any class of γ-ray sources, with the Sreekumar et al. [38] intensity as an absolute upper limit to the combined residual intensity from all source classes.

The GALPROP fits [42] to the OSSE-COMPTEL-EGRET Milky Way intensity spectra in different directions toward the Galaxy implies the total γ-ray luminosity of the Milky Way galaxy. Scaled to $10^{39}L_{39}$ ergs s^{-1}, the GALPROP analysis gives $L_{39} = (0.71 - 0.92)$ for the > 100 MeV γ-ray luminosity of the Milky Way, a factor ≈ 3 greater than the value $L_{39} = (0.16 - 0.32)$ inferred from COS-B observations [7]. Most of this emission is from secondaries created in cosmic-ray nuclear production processes. The Galactic γ-ray power provides an important yardstick to assess the total contribution of to the unresolved γ-ray background of cosmic-ray emissions from star-forming galaxies, as described in more detail below.

Every γ-ray source class makes a different contribution to the γ-ray background, including transient events below detector threshold, variously oriented relativistic jet sources, and large numbers of individually weak sources. The basic formalism for making such calculations for beamed and unbeamed sources was given in my Barcelona talk [14]. Here I review the various source classes that likely dominate the composition of the diffuse background: blazars and radio/γ galaxies; star-forming galaxies of various types; γ rays from structure-formation shocks; and GRBs.

BLAZARS AND RADIO/γ GALAXIES

Population studies of γ-ray blazars were undertaken soon after the recognition of the γ-ray blazar class with EGRET [16]. Chiang et al. [10] performed a $\langle V/V_{max}\rangle$ analysis assuming no density evolution and showed that luminosity evolution of EGRET blazars was implied by the data. With a larger data set, and using radio data to ensure the sample was unbiased in regard to redshift determination, Chiang & Mukherjee [11] again found that luminosity evolution was

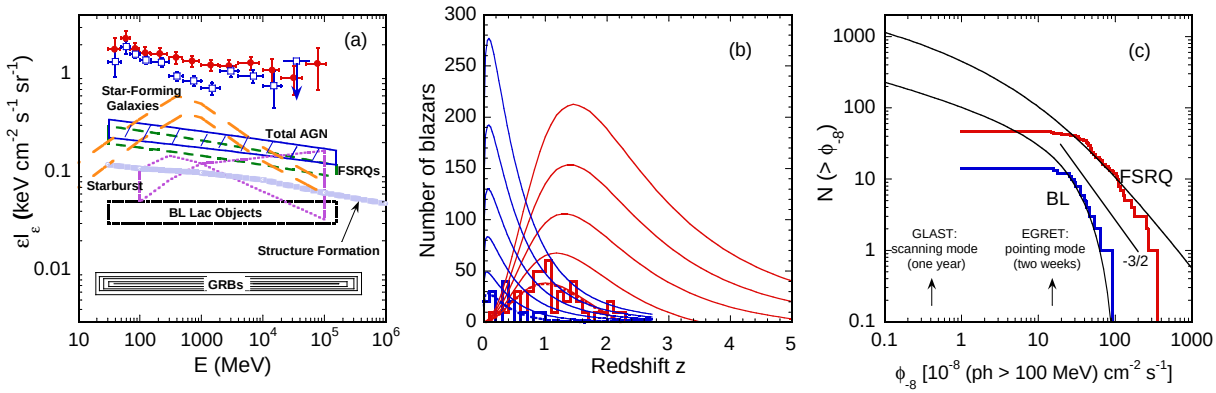

FIGURE 1. (a) Diffuse extragalactic γ-ray background from analyses of EGRET data, shown by filled [38] and open [42] data points, compared to model calculations of the contributions to the EGRB for FSRQs and BL Lac objects, and total AGNs [14], star-forming galaxies [35], starburst galaxies [46], structure shocks in clusters of galaxies [21, 6], and GRBs [12]. (b) Fitted EGRET and predicted redshift distributions of FSRQs and BL Lac objects [12]. (c) Fitted EGRET size distribution, and predictions for different flux levels [12].

required. They obtained best-fit values through the maximum likelihood method that gave an AGN contribution to the EGRET γ-ray background at the level of $\approx 25\%$.

Stecker & Salamon [40] postulated a radio/γ-ray correlation in blazars, and tried to correct for the duty cycle and γ-ray spectral hardening of flaring states. They found that essentially 100% of the EGRET γ-ray background arises from unresolved blazars and AGNs. In later work [41], they predict that GLAST will detect ≈ 5000 blazars to a flux level of $\approx 2\times10^{-9}$ ph$(>100$ MeV$)/($cm^2-s), which will be reached with GLAST after ≈ 4 years. They did not, however, fit the blazar redshift distribution to provide a check on their model, nor distinguish between flat spectrum radio quasar (FSRQ) and BL Lac objects.

The crucial underlying assumption of this approach, which has been developed in recent work [18, 33], is that there is a simple relation between the radio and γ-ray fluxes of blazars. Because a large number of EGRET γ-ray blazars (primarily FSRQs) are found in the 5 GHz, >1 Jy Kühr et al. [23] catalog, a radio/γ-ray correlation is expected. This correlation is not, however, evident in 2.7 and 5 GHz monitoring of EGRET γ-ray blazars [30]. X-ray selected BL objects are also not well-sampled in GHz radio surveys. Studies based on correlations between the radio and γ-ray emissions from blazars must therefore consider the very different properties and histories of FSRQs and BLs and their separate contributions to the γ-ray background.

Treatments of blazar statistics that avoid any radio/γ-ray correlation and separately consider FSRQs and BL Lac objects have been developed by Mücke & Pohl [29] and Dermer [12]. In the Mücke & Pohl [29] study, blazar spectra were calculated assuming an injection electron number index of -2. Distributions in injected particle energy in BL Lac and FSRQ jets were separately considered, with a simple description of density evolution given in the form of a cutoff at some maximum redshift z_{max}. Depending on the value of z_{max}, Mücke & Pohl [29] concluded that as much as $\approx 40-80\%$ of the EGRB is produced by unresolved AGNs, with $\approx 70-90\%$ of the emission from FR 1 galaxies and BL Lac objects.

In my recent study [12], I also use a physical model to fit the EGRET data on the redshift and size distribution of EGRET blazars. The EGRET blazar sample consists of 46 FSRQs and 14 BL Lac objects that were detected in the Phase 1 EGRET all-sky survey [16], with fluxes as reported in the Third EGRET catalog [19]. A blazar is approximated by a relativistic spherical ball entraining a tangled magnetic field and containing an isotropic, power-law distribution of nonthermal electrons. Single electron power-law distributions were used in the study, with indices $p=3.4$ for FSRQs and $p=3.0$ for BL Lac objects, giving spectral indices $\alpha_\nu=-0.2$ and $\alpha_\nu=0.0$, respectively, as shown by observations [31, 50]. Beaming patterns appropriate to external Compton and synchrotron self-Compton processes, and bulk Lorentz factor $\Gamma=10$ and $\Gamma=4$, were used in FSRQs and BL Lac objects, respectively. The comoving directional luminosities l'_e and blazar comoving rate densities (blazar formation rate; BFRs) for the two classes were adjusted to give agreement with the data. The threshold detector sensitivity ϕ_{-8}, in units of 10^{-8} ph$(>100$ MeV$)/($cm^2-s), was nominally taken to be $\phi_{-8}=15$ for the two-week on-axis EGRET sensitivity, and $\phi_{-8}=0.4$ for the one-year all-sky sensitivity of GLAST. Due to incompleteness of the sample near threshold, the EGRET threshold was adjusted to $\phi_{-8}=25$. Because a mono-luminosity function was used, the range in apparent powers is entirely kinematic in this

model, arising from the different, randomly oriented jet directions.

By using a minimalist blazar model, the model parameters were severely constrained. The FSRQ data were fit with $l'_e = 10^{40}$ ergs/(s-sr) and a BFR that was $\approx 15\times$ greater at $z \approx 2-3$ than at present. The BL Lac data, by contrast, could not be fit using a fixed luminosity. A model that could jointly fit the redshift and size distribution of BL Lac objects required that BL Lac objects be brighter and less numerous that in the past, consistent with a picture where FSRQs evolve into BL Lac objects [8, 27].

Fig. 1b shows the fitted EGRET redshift distributions and predicted redshift distributions of γ galaxies and blazars at different GLAST sensitivities [12]. The fits to the EGRET size distributions of FSRQs and BL Lac objects, and extrapolations of the model size distributions to lower flux thresholds, are shown in Fig. 1c. After one year of observations with GLAST ($\phi_{-8} \cong 0.4$), ≈ 800 FSRQs/FR2 and ≈ 200 BL Lac/FR1 γ galaxies and γ-ray blazars are predicted. This is a lower prediction, and additional hard-spectrum blazars to which EGRET was not sensitive could increase this number, but not by more than a factor ≈ 2. The contribution of unresolved blazars below a flux level of $\phi_{-8} \cong 12.5-25$ to the EGRB is shown in Fig. 1a. As can be seen, the total blazar/γ galaxy contribution is less than $\approx 20-30\%$ of the EGRET EGRB intensity, meaning that other classes of sources must make a significant contribution.

STAR-FORMING GALAXIES

The integrated emission from γ rays formed by cosmic-ray interactions in star-forming galaxies will make a "guaranteed" γ-ray background. Pavlidou & Fields [35] calculate this intensity by approximating the diffuse Galactic γ-ray spectrum as a broken power law and assuming that the γ-ray spectrum of a star-forming galaxy is proportional to the supernova rate and thus the massive star-formation rate, which can be inferred from the measured blue and UV luminosity density. Fig. 1a shows their results for a dust-corrected star formation rate (SFR) integrated over all redshifts, and a lower curve where the SFR is integrated to redshift unity.

A different approach [46, 47] to this problem starts by noting that cosmic-ray protons in the Milky Way lose only $\approx 10\%$ of their energy before escaping. This fraction could rise to nearly 100% in starburst galaxies where the target gas density is much higher and the timescale for escape, due primarily to advective galactic winds rather than diffusion in the galaxy's magnetic field, is less than the nuclear loss time. Support for this contention is provided by the observed correlation between far infrared flux—primarily due to starlight reradiated by dust and gas—with synchrotron flux produced by cosmic ray electrons. If both are proportional to the supernova rate, and the radio-emitting electrons lose a large fraction of their energy due to synchrotron cooling, then this correlation is explained [51].

The calculated intensity [46] from starburst galaxies is shown in Fig. 1a. The bulk of this intensity is formed at redshifts $\gtrsim 1$, where the starburst fraction of star-forming galaxies is large. The starburst intensity from Ref. [46] is smaller than the the total star-forming galaxy contribution [35], even when the latter calculation is truncated at $z = 1$. The latter calculation was checked in Ref. [14], based on the γ-ray spectrum of the Milky Way. Stecker [39] argues that the starburst contribution is a factor ≈ 5 lower than diffuse γ-ray and neutrino intensity derived by Loeb and Waxman [26] and Thompson et al. [46] by pointing out that directly accelerated electrons make a strong contribution to the synchrotron flux, and questioning the assumption that protons lose all their energy in starbursts. This criticism is addressed in Ref. [47].

GLAST will clarify this situation through its observations of nearby star-forming galaxies, e.g., LMC, SMC, M31, and M33, the starburst galaxies M82 and NGC 253, and infrared luminous galaxies like Arp 220. These galaxies are predicted to be GLAST sources [35, 48, 15, 46], and will provide benchmarks to correlate γ-ray fluxes with star formation activity.

CLUSTERS OF GALAXIES

Nonthermal radiation from clusters of galaxies is expected for several reasons: cosmic rays will be accelerated through merger shocks from merging subclusters, from accretion shocks as primordial matter continues to accrete on a forming cluster, and from turbulent reacceleration of nonthermal particles by plasma waves in the intracluster medium. In addition, a galaxy cluster often has an energetic AGN in its central cD galaxy that could inject cosmic rays into the cluster medium. Hadronic cosmic rays with energies $\lesssim 10^{19}$ eV will be trapped on timescales longer than the Hubble time, so galaxy clusters become storage volumes for cosmic rays [4]. In spite of these expectations, EGRET did not make a high-significance detection of any galaxy cluster [36].

Hard X-ray tails have also not been detected with high significance from the Coma cluster or any other galaxy cluster. The study of nonthermal emission from clusters of galaxies has consequently stalled, as nonthermal X-ray measurements provide the crucial information to normalize the magnetic field and nonthermal electron spectrum. Predictions based on the marginal detection of the hard X-ray tail from the Coma cluster indicate that Coma will be easily detectable with GLAST in one year of observation and marginally detectable with ground-based γ-ray telescopes in a nominal 50 hour observation [5], though the angular extent of Coma makes such detections more difficult [17].

In view of these uncertainties, any calculation of the integrated contribution from clusters of galaxies to the γ-ray background is likewise highly uncertain. Fig. 1a shows predictions [21, 6] for galaxy cluster emission. GLAST detections of clusters of galaxies will be crucial to provide a better basis for determining this contribution.

GAMMA RAY BURSTS

The contribution of untriggered GRBs to the γ-ray background can be estimated in a number of ways, but all depend on modeling, or inferring from observations, the typical high-energy GRB spectra. For the optimistic case that the TeV flux made by a GRB is $\approx 10\times$ greater than the MeV flux, then the superpositions of GRB emissions are found to make $\approx 10\%$ of the γ-ray background after cascading from high energies into the GeV band [9]. If one instead relies on observations of EGRET spark-chamber GRBs that show that the fluence in the EGRET band is only $\approx 10\%$ of the fluence in the BATSE band, then GRBs are found to give very little ($\lesssim 1\%$) contribution to the γ-ray background [25]. This neglects the contributions of short, hard GRBs and low luminosity GRBs, but since these have small fluences and all-sky rates, they are unlikely to make a significant contribution to the γ-ray background.

It hardly needs to be mentioned that GLAST observations of the high-energy emission from GRBs will provide crucial information to determine the share of the background γ-ray intensity provided by GRBs.

ADDITIONAL CONTRIBUTIONS

A truly diffuse flux of γ rays will be formed by the cascade radiations initiated by photopion and photopair production of ultra-high energy cosmic rays interacting with photons of the extragalactic background light. Because the electromagnetic secondaries are distributed over several orders or magnitude as they cascade to photon energies where the universe becomes transparent to $\gamma\gamma$ processes, this intensity will be well below the Waxman-Bahcall intensity at ≈ 0.03 keV/(cm^2-s-sr). By comparing with the diffuse neutrino intensities calculated in bottom-up scenarios for the ultra-high energy cosmic rays [13, 52], cosmogenic γ rays are not expected to make a large contribution to the EGRB (however, see Ref. [20], though they could for top-down models [37]. This question will definitively be answered by Auger data.

The various source classes that contribute to the extragalactic γ-ray background have hardly been exhausted, but the described classes are expected to be most important. Yet when one adds up the best guesses of the various contributions to the total, as shown in Fig. 1a, a deficit remains at both low ($\lesssim 100$ MeV) and high ($\gg 1$ GeV) energies. Because star-forming and starburst galaxies make such a large contribution to the total, it is possible that their spectra are actually much softer than assumed on the low-energy side, due to nonthermal electron bremsstrahlung and Compton-scattered emissions from γ-ray production by cosmic rays in "thick-target' starburst and infrared luminous galaxies (cf. [32]). This, or soft-spectrum radio galaxies and from the superposition of hard tailes from many weak radio-quiet Seyfert galaxies, could explain the low-energy deficit.

It seems unlikely, however, that star-forming galaxies, whose high-energy radiation originates from cosmic rays accelerated by supernova remnant shocks, could explain the deficit on the high-energy side unless shock injection spectra harder than -2 were postulated. The EGRET effective area dropped rapidly above ≈ 5 GeV due to self-vetoing effects, so it was not sensitive to hard-spectrum sources, in particular, hard spectrum BL Lac objects. But the BL Lac contribution is estimated at the 5% level, and it is difficult to suppose that EGRET was not able to detect a number of such hard-spectrum BL Lac objects. Hard tails on FSRQs originating, e.g., from photohadronic cascade emissions [2], could explain the high-energy discrepancy. Other possibilities are the diffuse contributions from dark matter annihilation [49], or cascade radiations from misaligned blazars [1]. We must furthermore keep in mind the possibility that the model of foreground Galactic emission that must be subtracted from the extragalactic flux is incomplete [22], or that the EGRET internal background was underestimated [3]. Data from GLAST will tell us which, if any, of these suggestions are correct, and whether new, unexpected sources of high-energy γ rays are required to explain the γ-ray background.

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