DETECTING THE ATTENUATION OF BLAZAR GAMMA-RAY EMISSION BY EXTRAGALACTIC BACKGROUND LIGHT WITH THE GAMMA-RAY LARGE AREA SPACE TELESCOPE

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ABSTRACT

Gamma rays with energy above 10 GeV interact with optical–UV photons, resulting in pair production. Therefore, a large sample of high-redshift sources of these gamma rays can be used to probe the extragalactic background starlight (EBL) by examining the redshift dependence of the attenuation of the flux above 10 GeV. The Gamma-Ray Large Area Space Telescope (GLAST), the next-generation high-energy gamma-ray telescope, will have the unique capability to detect thousands of gamma-ray blazars to redshifts of at least $z = 4$, with sufficient angular resolution to allow identification of a large fraction of their optical counterparts. By combining established models of the gamma-ray blazar luminosity function, two different calculations of the high-energy gamma-ray opacity due to EBL absorption, and the expected GLAST instrument performance to produce simulated fluxes and redshifts for the blazars that GLAST would detect, we demonstrate that these gamma-ray blazars have the potential to be a highly effective probe of the optical–UV EBL.

Subject heading: galaxies: active — gamma rays: observations — instrumentation: detectors — intergalactic medium

1. INTRODUCTION

In the last few years, the study of galaxy formation and evolution has seen tremendous progress. Instruments at many different wavelengths have begun to penetrate to the relevant redshifts. One important prediction of models of galaxy formation and evolution is the nature of the radiation field produced by star formation. One way to probe the resulting extragalactic background light (EBL) is to measure the attenuation through pair production of gamma rays from distant sources. However, without a large sample of sources distributed across a wide redshift range, it is difficult to distinguish between extragalactic absorption and characteristics peculiar to individual sources. The Large Area Telescope (LAT) instrument on the Gamma-Ray Large Area Space Telescope (GLAST) will observe gamma rays with energies from 20 MeV to greater than 300 GeV. The GLAST LAT will be the first instrument able to probe the intergalactic radiation field by observing the absorption of gamma rays from a large number of extragalactic point sources as a function of redshift over a wide range. Ground-based telescopes can measure the attenuation of TeV emission by intergalactic IR radiation (Stecker, DeJager, & Salamon 1992; MacMinn & Primack 1996; Madau & Phinney 1996). However, these telescopes will measure the spectra of a relatively small number of sources, making it more difficult to resolve the question of whether differences between sources are due to intergalactic attenuation or intrinsic peculiarities. Furthermore, the high-pair production opacity of the IR radiation limits TeV probes of the EBL to a narrow, low-redshift range. GLAST, on the other hand, will observe thousands of sources, and will measure less drastic attenuation of GeV photons by optical and UV radiation. The energy range and capabilities of GLAST are thus ideal for probing the EBL to cosmological distances.

This paper reports our first modeling of the ability of GLAST to measure the EBL absorption. In order to do this, we need (1) models of the intergalactic radiation field, (2) the luminosity function of extragalactic gamma-ray sources, and (3) parameters of the instrument. In § 2.1, we briefly review models for the intergalactic radiation field and the resulting gamma-ray opacity as a function of redshift. In § 2.2, we describe the two gamma-ray blazar luminosity functions used. In § 2.3, we describe the parameters used to simulate GLAST. In § 3, we discuss the simulation procedure, including the two different models of blazar input spectra and the two models for the intergalactic radiation field. In § 4, we present our results and conclusions.

2. FRAMEWORK

2.1. Extragalactic Background Light

Gamma rays with $E > 10$ GeV traveling through intergalactic space will interact through pair production with the extragalactic background starlight (EBL) emitted by galaxies. The total center-of-mass energy must be high enough to produce the electron-positron pair, and, for a wide range of EBL models, the attenuation becomes significant only above ~10 GeV. The cross section is maximized when the EBL photon energy $\epsilon_{\text{EBL}} \sim 1/2(1000 \text{ GeV}/E_{\nu})$ eV, with $E_{\nu}$ in GeV (Stecker, DeJager, & Salamon 1992). For 10 GeV to TeV gamma rays this corresponds to $\epsilon_{\text{EBL}}$ in the optical-UV range. Salamon & Stecker (1998) calculated the opacity of high-energy gamma-rays to redshift $z = 3$. To estimate the stellar emissivity and spectral energy distributions versus redshift,
they adapted the analysis of Fall, Charlot, & Pei (1996), consistent with the Canada-France Redshift Survey, and included corrections for metallicity evolution. They found that the stellar emissivity peaks between \( z = 1 \) and 2 before falling off, leading to a significant redshift-dependent absorption below \( z = 3 \). Other models, e.g., by Primack et al. (1999), provide for significant attenuation at even larger redshifts. More recently, Bernstein, Freedman, & Madore (2002a, 2000b) have made the first direct measurement of the optical-UV EBL integrated over redshift. As shown in § 3, our technique is a powerful discriminator among models, giving information about the era of galaxy formation and evolution.

2.2. Gamma-Ray Blazars

2.2.1. Blazar Luminosity Function

The Energetic Gamma Ray Experiment Telescope (EGRET) detected more than 60 blazar-type quasars (Mukherjee et al. 1997) emitting gamma rays with \( E > 100 \) MeV. These sources are flat-spectrum radio-loud quasars (FSRQs) and BL Lac objects, often exhibiting nonthermal radio continuum spectra, violent optical variability, and/or high optical polarization. They are also highly variable and powerful gamma-ray sources. The EGRET blazars whose optical redshifts have been measured lie between \( z = 0.03 \) and 2.28. The redshift distribution is consistent with the observed distribution of FSRQs, which extends up to \( z = 3.8 \). However, since the luminosity function determines the statistical power of our technique versus redshift, and since this function is still relatively unconstrained, we use two different models for the blazar luminosity function.

The first model, by Stecker & Salamon (1996), makes the assumption that blazars seen in gamma-rays above 100 MeV are also seen in the radio as FSRQs. This model assumes that the gamma-ray and radio luminosity functions are linearly related as

\[
\rho_r(L_r, z) = \eta \rho_v(L_r, z),
\]

where \( \eta \) is a parameter of the model and

\[
\rho_v(L_r, z) = 10^{-8.15} \left( \frac{L_r}{L_v(z)} \right)^{0.83} + \left( \frac{L_r}{L_v(z)} \right)^{1.96}^{-1},
\]

with \( \log_{10} L_v(z) = 25.26 + 1.18z - 0.28z^2 \). The units of the comoving density \( \rho \) are Mpc\(^{-3} \) per unit interval of \( \log_{10} L \), and the units of \( L \) are W Hz\(^{-1} \) sr\(^{-1} \). Using the cosmological parameters \( \Omega_M = 1, \Omega_k = 0, \) and \( H_0 = 50 \) km s\(^{-1} \) Mpc\(^{-1} \), the model is constrained to predict the number of blazars observed by EGRET.

The number of sources with redshift in the interval \( z + \Delta z \) seen at the Earth with an \( E > 100 \) flux MeV in the interval \( F + \Delta F \) is given by (Stecker & Salamon 1996)

\[
\frac{dN}{dF} dz \Delta z \Delta F = 4 \pi R_0^2 \Delta F r_\gamma \Delta (\log_{10} L),
\]

with \( R_0 = (2c/H_0)[1 - (1 + z)^{-1/2}] \), where \( H_0 \) is the Hubble expansion rate. Combining the choice of parameters given by Stecker & Salamon (1996) with a GLAST flux sensitivity of \( 1.5 \times 10^{-9} \) photons cm\(^{-2} \) s\(^{-1} \), ~9000 blazars are expected to be observed with redshifts up to \( z \sim 4 \).

The second model, by Chiang & Mukherjee (1998), does not assume a correlation between luminosities at gamma-ray energies and other wavelengths. This model parametrizes the luminosity function as

\[
\frac{dN}{dL_B} \Delta L_B \Delta L_B = \begin{cases} 
\left( \frac{L_0}{L_B} \right)^{-\gamma_1} & \text{for } L_0 \leq L_B \\
\left( \frac{L_0}{L_B} \right)^{-2.2} & \text{for } L_0 > L_B 
\end{cases},
\]

with de-evolved luminosity \( L_0 = L/(1 + z)^3 \) and a maximum cutoff redshift of \( z_{\text{max}} = 5 \). The energy range of this integrated luminosity is \( E > 100 \) MeV. The best fit found for this broken power law is parametrized by \( \gamma_1 \leq 1.2, L_B = 1.1 \times 10^{46} \) erg s\(^{-1} \), and \( \beta = 2.7 \), with the cosmological parameters \( \Omega_M = 1, \Omega_k = 0, \) and \( H_0 = 75 \) km s\(^{-1} \) Mpc\(^{-1} \). Each model was separately fitted in a self-consistent fashion to the EGRET data to produce the luminosity functions. More recent cosmological data suggest a nonzero value for \( \Omega_k \). The impact on the luminosity function, however, is small: we therefore retain the original model, along with the fit to the data, for our calculations. Of course, one of the important goals of the GLAST mission will be to constrain the luminosity function.

2.2.2. Blazar Spectra

The spectra of the blazars observed by EGRET are well characterized in the \( E > 100 \) MeV range by power laws with an average photon spectral index of \(-2.15 \pm 0.04 \) (Mukherjee et al. 1997). The spectra of some individual blazars have a measured index significantly different from the mean value, suggesting true scatter in the distribution of blazar spectra, which our simulation takes into account as described below. More importantly, most of the EGRET blazars have not been detected by TeV telescopes; for many of these sources, this implies a spectral break or rolloff at some energy between the EGRET and TeV energy ranges. Intergalactic attenuation, the very effect explored in this paper, would account for the lack of detection of high-redshift objects, but there are relatively low-redshift blazars that are bright in the EGRET range and undetected in the TeV range. More tellingly, most of the TeV blazars belong to the same subset of blazars, the X-ray–selected BL Lac objects (XBLs). Since only a small fraction of the EGRET blazars are XBLs, this implies that the non-XBL blazars may have spectra with intrinsic rolloffs independent of any intergalactic attenuation effects. Finally, blazars that have been detected in both the GeV and TeV ranges have TeV fluxes that are lower than simple extrapolations of the EGRET power laws would suggest. Of course, such an extrapolation over such a wide range of energies is unreasonable. Most of the models for blazar spectra attribute both the GeV and TeV emission to the same inverse Compton component of the emission. However, with little observational data in the 30–300 GeV range, no firm conclusions can be drawn about the precise shape of the spectra. Indeed, this is one of the motivations for the next generation of experiments.

Our technique, as described in § 3, is to form the ratio of the observed fluxes for \( E > 10 \) and \( E > 1 \) GeV,

\[
\frac{F(E > 10 \text{ GeV})}{F(E > 1 \text{ GeV})}.
\]

This ratio is simple, robust, and insensitive to rolloffs above ~50 GeV for most EBL models, as shown in § 3.1. We attempt
to bracket the range of possible spectra by first analyzing a sample of blazars whose power-law spectral indices are normally distributed around a mean of $-2.15$ with standard deviation $0.04$, representing a situation in which there is a range of spectral indices but no intrinsic rolloff in this energy range. To model intrinsic rolloffs, we then repeat the analysis with a sample of blazars whose unredshifted spectra have a broken power law with mean index $-2.15$ below $50$ GeV and $-3.15$ above, again with a standard deviation of $0.04$ in each case.

2.3. GLAST

GLAST is under development with a planned launch in 2007 (Michelson 2001). The Large Area Telescope (LAT) of GLAST will observe gamma rays with energies from $20$ MeV to greater than $300$ GeV. GLAST will have a much larger effective area than EGRET, especially at higher energies (peak effective area $>8000$ cm$^2$ at $>1$ GeV), a larger field of view, and subarcminute-scale source localization. GLAST should be able to reach a $5\sigma$ point-source flux sensitivity of less than $1.5 \times 10^{-9}$ photons cm$^{-2}$ s$^{-1}$ for $E > 100$ MeV within $5$ yr. As noted above, using the distribution of blazars observed by EGRET and extrapolating to lower fluxes, it is estimated that GLAST will detect thousands of blazars. Improved angular resolution should allow a high percentage of optical identifications and redshift measurements, depending on the available ground-based resources. Improved high-energy performance should yield accurate flux determinations above $10$ GeV for many of these sources. Note that our modeling is based on the generic parameters outlined in the GLAST Science Requirements document (Michelson 2001); the performance of the flight instrument may be substantially better.

3. PROCEDURE

To simulate the gamma-ray sources observable by GLAST, we need a reasonable extrapolation of the EGRET source distribution to the GLAST flux limit. We used the two luminosity functions described in § 2.2.1 for this purpose, but our main conclusions do not depend significantly on this choice. We note that any predictions made now will be supplanted by the data GLAST itself provides.

Before any observational selection, according to the luminosity function by Stecker & Salamon (1996), $\sim 12,000$ blazars in principle will have fluxes in the range detectable by GLAST. Each one was assigned a random luminosity and redshift according to this model. With the luminosity function by Chiang & Mukherjee (1998) we generated $10,000$ blazars, between redshifts $z = 0$ and $5$ according to Figure 6 of their paper. For both samples, the flux of each blazar was then calculated according to

$$F = \frac{L}{4\pi d_l^2(z)} (1 + z)^{2-\alpha},$$

where $\alpha$ is the photon spectral index and $d_l$ is the cosmological luminosity distance $d_l = (2c/H_0)(1 + z)[1 - (1 + z)^{-1/2}].$

Only blazars with observed flux greater than $1.5 \times 10^{-9}$ photons cm$^{-2}$ s$^{-1}$ for $E > 100$ MeV are allowed in the sample. The $E > 10$ GeV flux of each blazar was calculated by adding two effects. First, each blazar was given a random, normally distributed spectral index, $-2.15 \pm 0.04$. An index of $-2.15$ yields a flux ratio $F(E > 10$ GeV$)/F(E > 1$ GeV) of $\sim 0.07$; also included was the redshift-dependent absorption above $10$ GeV. The form of the dependence was parameterized from Figure 6 of Salamon & Stecker (1998), with metallicity corrections. In this EBL model, $\Omega_M = 1$, $\Omega_L = 0$, and the value of $H_0$ scales out. We set the absorption for $z > 3$ for this model equal to the absorption at $z = 3$, both because it is a conservative assumption and because it is physically plausible (little stellar emissivity and smaller scale and path lengths, for $z > 3$).

To produce observed fluxes from these intrinsic fluxes, each blazar was assigned a random position on the sky and, assuming an exposure equivalent to $2$ full yr, Galactic and extragalactic backgrounds were added. The Galactic backgrounds were derived from the diffuse model used in EGRET analysis (Hunter et al. 1997). To take into account the extragalactic background, we added a second, fixed, background component, with intensity $4 \times 10^{-6}$ photons cm$^{-2}$ s$^{-1}$ sr$^{-1}$ for $E > 100$ MeV and a power-law index of $-2.15$, under the assumption that GLAST may resolve a significant fraction of the EGRET isotropic background (Salamon & Stecker 1998). This component represents the sum of the flux from unresolved blazars and any truly diffuse background contribution. Any blazar within $10'$ of the Galactic plane and any blazar whose observed flux was less than $5\sigma$ above the background flux at $E > 1$ GeV was removed from both samples, leaving $\sim 9100$ blazars (Stecker & Salamon 1996) or $\sim 8200$ blazars (Chiang & Mukherjee 1998). Figure 1 shows a histogram of the number of blazars in each $0.5$ redshift bin. The model by Chiang & Mukherjee (1998) predicts a population of blazars that are intrinsically brighter when compared to the model by Stecker & Salamon (1996). In that case, GLAST would detect more blazars at higher redshift, as can be observed from the graph. We note that with no EBL attenuation, for $z > 3$ and a requirement for more than $5$ detected photons ($E > 10$ GeV), GLAST would see $\sim 60$ blazars using the Stecker & Salamon luminosity function or $\sim 700$ blazars using the Chiang & Mukherjee luminosity function.

3.1. Calculating the Flux Ratios

The integrated fluxes of each blazar for $E > 1$ GeV and $E > 10$ GeV were used to generate observed fluxes using Poisson distributions equivalent to $2$ full yr of exposure. For

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1 See also http://glast.gsfc.nasa.gov/SRD.
each blazar, we calculated the ratio between these fluxes. The error in each flux ratio was set to

$$
\sigma_{\text{ratio}} = \frac{1}{F(E > 1 \text{ GeV})}
\times \sqrt{\frac{\sigma_E^2}{F(E > 10 \text{ GeV})} + \left[ \frac{F(E > 10 \text{ GeV})}{F(E > 1 \text{ GeV})} \sigma_{\text{F}(E > 1 \text{ GeV})} \right]^2},
$$

where $\sigma_E$ is the statistical error of the flux measurement in each energy range. The crosses in Figure 2 show the weighted mean ratio in each redshift bin. To avoid the bias of small-number Poisson statistics toward lower values, the flux ratio of each source was weighted by the Poisson error of the $E > 1 \text{ GeV}$ flux, rather than the formal, propagated error of the flux ratio. The diamonds show the same ratio when the intergalactic absorption is removed from the observed blazar fluxes. In all cases, the error bars are statistical, obtained by computing the rms scatter within each redshift bin and dividing by $\sqrt{N}$. The analytically derived flux ratio using the opacity model of Salamon & Stecker (1998) is plotted as a solid curve. For comparison, the dashed lines in Figure 2 show the same results with no intergalactic absorption.

We repeated the entire analysis with the blazar spectra changed from single power laws with mean index $-2.15$, to broken power laws with mean index $-2.15$ below $50 \text{ GeV}$ (at the source) and $-3.15$ above. The results are plotted as crosses in Figure 3. Although fewer blazars have a detected flux above $10 \text{ GeV}$, the effects of absorption are still apparent. Note that sources with no detectable flux above $10 \text{ GeV}$ (zero photons) still provide important information; indeed, neglecting them introduces a bias. The modified $\chi^2$ statistic used here (Mighell 1999) accounts for these sources.

The ratio obtained without EBL absorption is presented as diamonds, along with the analytically derived flux ratio (dashed line). As can be easily seen, this flux ratio is not constant as a function of redshift. This is a consequence of defining the break in the index for a given energy at the source.

### 3.2. Other EBL Models

Primack and coworkers combined theoretical modeling with observational data to develop semianalytic models of
galaxy formation and evolution (Primack et al. 1999). Their models permit a physical treatment of the processes of galaxy formation and evolution in a cosmological framework, including gravitational collapse, mergers, etc., rather than relying on pure luminosity evolution of the galaxies existing today. We use their calculations of opacities to gamma rays at redshifts up to z = 5. The cosmological parameters used are ΩM = 0.4, ΩΛ = 0.6, and H0 = 60 km s^{-1} Mpc^{-1}. The luminosity functions use a different value for H0, but for our purposes, this difference does not significantly affect the results; as shown by Blanch & Martinez (2001), the gamma-ray horizon has a relatively weak dependence on H0. Note that these opacities, with their different cosmological parameter sets, should not be thought of as predictions, but rather as another set of reasonable values to illustrate the discriminating power of our technique. The results are shown as triangles in Figures 2 and 3, along with the lines representing the analytical prediction. The fact that the flux seems to be more highly attenuated is not important. What is more interesting is that the decrease in flux ratio from z = 2.5 to 5 is observable. This indicates, assuming the availability of gamma-ray sources and sufficient EBL density, that EBL absorption can effectively probe galaxy formation at those redshifts, a regime of intense theoretical interest. More recently, Oh (2001) performed an independent calculation of the opacity of gamma-ray blazar emission to pair production by UV photons as a function of redshift. While not addressing the detectability of high-redshift blazars by GLAST in detail, he obtains attenuation factors that vary strongly with redshift in a manner roughly consistent with the calculations we have used.

4. RESULTS AND CONCLUSIONS

Extragalactic attenuation of gamma-rays by low-energy background photons produces a distortion in the spectra of gamma-ray blazars that increases with increasing redshift. Because we cannot distinguish the difference between extragalactic attenuation and intrinsic effects in individual blazar spectra, statistical analysis of a large sample of blazars such as those presented in this paper is a powerful tool to study EBL absorption. Although AGILE, the next GeV mission (Tavani et al. 2001), will produce a significant increase in the total number of blazars and therefore refine the blazar luminosity function and evolution, GLAST will be the first mission to observe a large sample of high-redshift blazars with sufficient statistics to separate intrinsic differences between blazars from redshift dependence of EBL absorption. Our results indicate that the redshift dependence of the attenuation should be easily detectable by GLAST, even when the diffuse background is taken into account and possible high-energy intrinsic rolloffs are considered.

Selection effects, both from GLAST itself and from optical coverage of redshift determinations, will primarily affect sources with low flux. These sources will have poorly measured flux ratios, and will suffer from optical selection effects because of their more poorly determined positions. Other biases include the locations of optical telescopes, source clustering, and other effects. It will be important to catalog these effects explicitly; in particular, insuring adequate optical coverage may require active preparation and participation.

GLAST will be able to measure the differences in blazar attenuation in the cosmologically interesting redshift range from z = 1 up to 5. This is in contrast to ground-based observations of TeV attenuation by IR radiation, which will only be able to measure differences well below z = 1, where the IR becomes opaque. As the energy threshold of the ground-based experiments drops over time, their redshift range will increase but remain limited to low redshifts except for exceptional, statistically insignificant special cases, especially given their generally small fields of view. More than establishing that EBL attenuation occurs, GLAST will be able to distinguish between different EBL models. This would validate EBL attenuation as a direct cosmological probe.

We emphasize that this analysis will require redshift determinations of a large fraction of GLAST blazars. This is another example of the importance of cross-wavelength studies: by using optical measurements of blazar redshifts, gamma-ray measurements can uniquely probe the optical-UV EBL. A redshift measurement for thousands of high-redshift sources is not a trivial undertaking, but the effort will be well rewarded.

Even after observation of a redshift-dependent effect, the possibility would remain that the spectral evolution of gamma-ray blazars might coincidentally mimic redshift-dependent EBL absorption. For example, if blazars that formed in the early universe suffered more internal attenuation than blazars that formed later, the same effect could be produced. Note that blazars are variable, and there are some indications that their spectra can become harder when they flare (Sreekumar et al. 1996). Evolution in flaring probability could produce the same effect as actual spectral evolution from a statistical standpoint (e.g., a higher percentage of high-redshift blazars might be observed in a quiescent phase), although one would expect the GLAST flux limit to produce a selection effect in the opposite direction. In any case, observation of a redshift-dependent spectral softening will provide an important constraint. Theorists will have to decide the likelihood of an evolutionary conspiracy.

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