The Imprint of the Extragalactic Background Light in the Gamma-Ray Spectra of Blazars

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The light emitted by stars and accreting compact objects through the history of the universe is encoded in the intensity of the extragalactic background light (EBL). Knowledge of the EBL is important to understand the nature of star formation and galaxy evolution, but direct measurements of the EBL are limited by galactic and other foreground emissions. Here, we report an absorption feature seen in the combined spectra of a sample of gamma-ray blazars out to a redshift of $z \sim 1.6$. This feature is caused by attenuation of gamma rays by the EBL at optical to ultraviolet frequencies and allowed us to measure the EBL flux density in this frequency band.

The bulk of the intergalactic gas in the universe must have been reionized between the epoch of cosmic recombination, when the universe was only 300,000 years old ($z \sim 1100$), and 1 billion years later ($z \sim 6$), as indicated observationally by the spectra of distant quasistellar objects (*1*). However, the sources, modes, and nature of this cosmic reionization are largely unknown because most of this redshift range has yet to be explored. Photoionization by ultraviolet (UV) radiation, produced by the first stars and galaxies of the universe, represents the primary suspect for the ionizing process (*2*, *3*). Direct detection of the UV radiation fields is thus of fundamental importance, but at present is extremely difficult (*3*).

An indirect but powerful means of probing the diffuse radiation fields is through γ-γ absorption of high-energy gamma rays (*4*–*6*). In this process, a gamma-ray photon of energy E_γ and an extragalactic background light (EBL) photon of energy $E_{\rm EBL}$ annihilate and create an electron-positron pair. This process occurs for head-on collisions when, for example, $E_\gamma \times E_{\rm EBL} \geq 2(m_e c^2)^2$, where $m_e c^2$ is the rest mass energy of the electron. This introduces an attenuation in the spectra of gamma-ray sources above a critical gamma-ray energy of $E_{\rm crit}(z) \approx 170(1+z)^{-2.38}$ GeV (*7*, *8*).

The detection of the gamma-ray horizon (i.e., the point beyond which the emission of gamma-ray sources is strongly attenuated) is one of the primary scientific drivers of the Fermi Gamma-Ray Space Telescope (*9*–*11*). Several attempts have been made in the past, but none detected the long-sought EBL attenuation (*12*–*14*). So far, limits on the EBL density have been inferred from the absence of absorption features in the spectra of individual blazars (*13*, *15*), distant galaxies with bright gamma-ray emission powered by matter accreting onto central, massive black holes. Although this feature is indeed difficult to constrain for a single source, we show that it is detected collectively in the gamma-ray spectra of a sample of blazars as a cutoff that changes amplitude and energy with redshift. We searched for an attenuation of the spectra of blazars in the 1 to 500 GeV band using the first 46 months of observations of the Large Area Telescope (LAT) on board the Fermi satellite. At these energies, gamma rays are absorbed by EBL photons in the optical to UV range. Thanks to the large energy and redshift coverage, Fermi-LAT measures the intrinsic (i.e., unabsorbed) spectrum up to ~100 GeV for any blazar at $z < 0.2$ and up to ~15 GeV for any redshift.

The LAT has detected >1000 blazars to date (*16*). We restricted our search to a subset of 150 blazars of the BL Lacertae (BL Lac) type that are significantly detected above 3 GeV because of the expected lack of intrinsic absorption (*17*). The sample covers a redshift range of 0.03 to 1.6 (*18*, *19*). The critical energy is therefore always ≥25 GeV, which means that the spectrum measured below this energy is unabsorbed and a true representation of the intrinsic spectrum of the source. We thus determined the intrinsic source spectrum relying on data between 1 GeV and the critical energy $E_{\rm crit}$ and extrapolated it to higher energies. By combining all the spectra, we were able to determine the average deviation, above the critical energy, of the measured spectra from the intrinsic ones, which ultimately provides a measurement of the optical depth $\tau_{\gamma\gamma}$.

The analysis was performed using the Fermi Science Tools (*20*). We determined the spectral parameters of each blazar by maximizing the likelihood of a given source model. The model comprised the Galactic and isotropic diffuse components and all sources in the second Fermi LAT catalog (*21*) within a region of interest (ROI) of 15° radius. We modeled the spectra of the sources in our sample as parabolic in the logarithmic space of energy and flux [see equation 2 in (*21*) for a definition]. Their spectra were modified by a term $e^{-\tau_{\gamma\gamma}(E,z)}$ that describes the absorption of gamma-ray photons on the EBL. In the above, we defined $\tau_{\gamma\gamma}(E,z) = b \times \tau^{model}_{\gamma\gamma}(E,z)$, where the $\tau^{model}_{\gamma\gamma}(E,z)$ is the optical depth predicted by EBL models (*7*, *22*–*25*) and b is a scaling variable, left free in the likelihood maximization. In particular, this allowed us to assess the likelihood of two important scenarios: (i) there is no EBL attenuation ($b = 0$), or (ii) the model prediction is correct ($b = 1$).

We combined the data from all the ROIs in a global fit that determined the common parameter b for a given EBL model (see table S1). All those models with a minimal EBL density based on (or compatible with) resolved galaxy counts (*2*, *7*, *24*–*27*) were found to be acceptable descriptions of the Fermi data (i.e., are consistent with $b = 1$ within ≈ 25%) (see also Fig. 1), yielding a significance of the absorption feature of up to ~6 SD. Models that predict a larger intensity of the EBL, particularly in the UV (*22*, *23*), would produce a stronger-than-observed attenuation feature and are therefore incompatible with the Fermi observations. Our measurement points to a minimal level of the optical-UV EBL up to redshift $z \approx 1.6$, which combined with the upper limits (*15*, *28*, *29*) derived at lower redshift (using observations of blazars at TeV energies) on the near-infrared EBL highlights the conclusion that most of the EBL intensity can be explained by the measured galaxy emission.

Our measurement relies on the accuracy of the extrapolation of the intrinsic spectra of the sources above the critical energy (*30*). This in turn depends on a precise description of the gamma-ray spectra by our source parametrization. To verify that this is the case and to exclude the possibility that the detected absorption feature is intrinsic to the gamma-ray sources (*17*), we performed the analysis in three independent redshift intervals ($z < 0.2$, $0.2 \leq z < 0.5$, and $0.5 \leq z < 1.6$). The deviations from the intrinsic spectra in the three redshift intervals are displayed in Fig. 2. In the local universe ($z < 0.2$), EBL absorption is negligible in most of the Fermi-LAT energy band ($E_{crit} \geq 120$ GeV). The lowest redshift interval therefore reveals directly the intrinsic spectra of the sources and shows that our spectral parametrization is accurate (*18*). The absorption feature is clearly visible above the critical energy in the higher redshift bins. Its amplitude and modulation in energy evolve with redshift as expected for EBL absorption. In principle, the observed attenuation could be due to a spectral cutoff that is intrinsic to the gamma-ray sources. The absence of a cutoff in the spectra of sources with $z < 0.2$ would require that the properties of BL Lacs change with redshift or luminosity. It remains an issue of debate whether such evolution exists (*31*–*34*). However, in case it were present, the intrinsic cutoff would be expected to evolve differently with redshift than we observe. To illustrate this effect, we fitted the blazar sample assuming that all the sources have an exponential cutoff at an energy E_0. From source to source, the observed cutoff energy changes because of the source redshift and because we assumed that blazars as a population are distributed in a sequence such as that proposed in (*31*–*34*). E_0 was fitted to the data globally like b above. As

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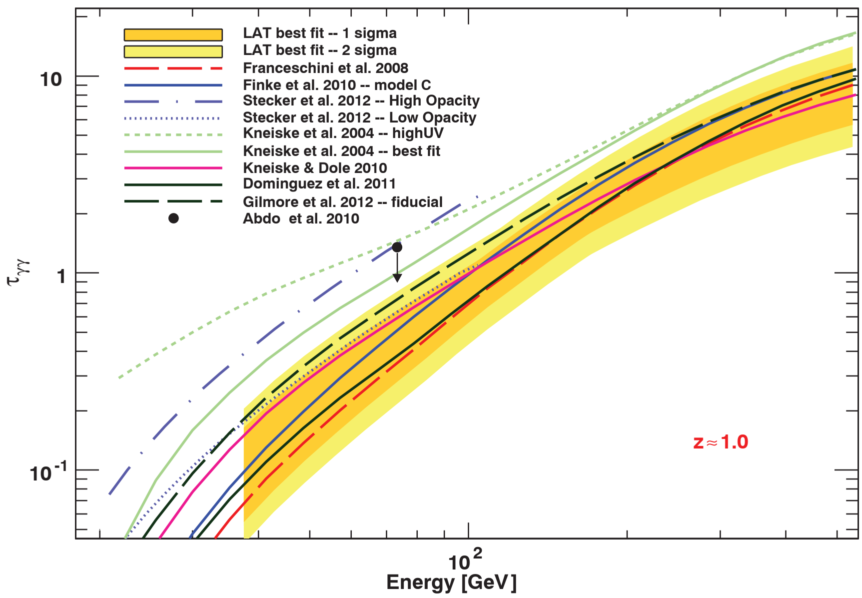

Fig. 1. Measurement, at the 68 and 95% confidence levels (including systematic uncertainties added in quadrature), of the opacity $\tau_{\gamma\gamma}$ from the best fits to the Fermi data compared with predictions of EBL models. The plot shows the measurement at $z \approx 1$, which is the average redshift of the most constraining redshift interval (i.e., $0.5 \leq z < 1.6$). The Fermi-LAT measurement was derived combining the limits on the best-fit EBL models. The downward arrow represents the 95% upper limit on the opacity at $z = 1.05$ derived in (*13*). For clarity, this figure shows only a selection of the models we tested; the full list is reported in table S1. The EBL models of (*49*), which are not defined for $E \geq 250/(1 + z)$ GeV and thus could not be used, are reported here for completeness.

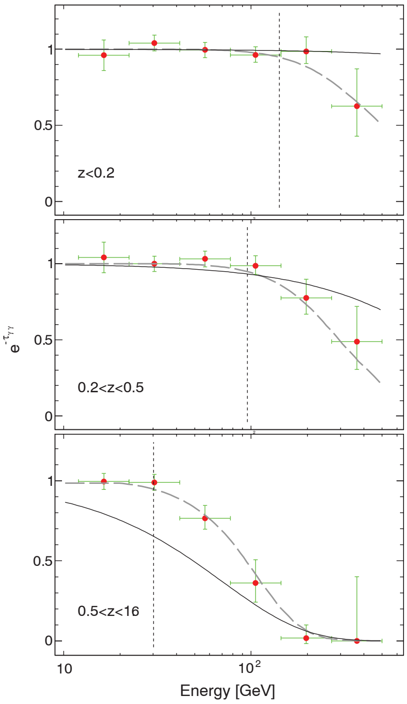

Fig. 2. Absorption feature present in the spectra of BL Lac objects as a function of increasing redshift (data points, from top to bottom). The dashed curves show the attenuation expected for the sample of sources by averaging, in each redshift and energy bin, the opacities of the sample [the model of (*7*) was used] and multiplying this average by the best-fit scaling parameter *b* obtained independently in each redshift interval. The vertical line shows the critical energy E_{crit} below which ≤ 5% of the source photons are absorbed by the EBL. The thin solid curve represents the best-fit model, assuming that all the sources have an intrinsic exponential cutoff and that blazars follow the blazar sequence model of (*32*, *33*).

apparent from Fig. 2, it appears difficult to reconcile the observed feature with an intrinsic characteristic of the blazars' spectra. We therefore associate the spectral feature to the EBL absorption.

At energies ≤ 100 GeV, gamma rays observed at Earth and coming from redshift ≥ 1 interact mostly with UV photons of ≥ 5 electron volts. An UV background in excess of the light emitted by resolved galaxies can be produced locally by active galactic nuclei (AGN) or at higher redshift ($z \approx 7$ to 15) by low-metallicity massive stars (*35*). By comparing the results from the best-fit EBL models, we measured the UV component of the EBL to have an intensity of 3(±1) nW m^{-2} sr^{-1} at $z \approx 1$. A contribution to the UV background from AGN as large as the one predicted by (*36*) (i.e., ≈ 10 nW m^{-2} sr^{-1}) and used in the EBL model of (*22*) is thus excluded by our analysis at high confidence. However, the recent prediction (*37*) of the UV background from AGN (≈ 2 nW m^{-2} sr^{-1}) is in agreement with the Fermi measurement. Direct measurements of the extragalactic UV background are hampered by the strong dust-scattered Galactic radiation (*38*). The agreement between the intensity of the UV background as measured with Fermi and that due to galaxies individually resolved by the Hubble Space Telescope (*39*) (3 ± 1 nW m^{-2} sr^{-1} versus 2.9-3.9 nW m^{-2} sr^{-1}, respectively) shows that the room for any residual diffuse UV emission is small. This conclusion is reinforced by the good agreement of the Fermi measurement and the estimate of the average UV background, at $z \geq 1.7$, of 2.2 to 4.0 nW m^{-2} sr^{-1} using the proximity effect in quasar spectra (*40*).

Zero-metallicity population-III stars or low-metallicity population-II stars are thought to be the first stars to form in the universe and formally marked the end of the dark ages when, with their UV light, these objects started ionizing the intergalactic medium (*41*). These stars, whose mass might have exceeded 100 times the mass of our Sun ($M_\odot$), are also believed to be responsible for creating the first metals and dispersing them in the intergalactic medium (*42*–*44*). A very large contribution of population-III stars to the near-infrared EBL had already been excluded by (*15*). Our measurement constrains, according to (*45*, *46*), the redshift of maximum formation of low-metallicity stars to be at $z \geq 10$ and its peak comoving star-formation rate to be lower than 0.5 $M_\odot$ Mpc^{-3} year^{-1}. This upper limit is already of the same order of the peak star-formation rate of 0.2 to 0.6 $M_\odot$ Mpc^{-3} year^{-1} proposed by (*47*) and suggests that the peak star-formation rate might be much lower, as proposed by (*48*).

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Supplementary Materials

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