An Empirical Determination of the EBL and the Gamma-ray Opacity of the Universe

Floyd W. Stecker
NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA and
Department of Physics and Astronomy, University of California, Los Angeles

I present the results of a new approach to the intensity and photon density spectrum of the intergalactic background light as a function of redshift using observational data obtained in many different wavelength bands from local to deep galaxy surveys. This enables an empirical determination of both the EBL and its observationally based uncertainties. Using these results one can place 68% confidence upper and lower limits on the opacity of the universe to $\gamma$-rays, free of the theoretical assumptions that were needed for past calculations. I compare our results with measurements of the extragalactic background light, upper limits obtained from observations made by the Fermi Gamma-ray Space Telescope, and new observationally based results from Fermi and H.E.S.S. using recent analyses of blazar spectra.

1. INTRODUCTION

Past work on estimating the spectral and redshift characteristics of the intergalactic photon density, generically referred to as the EBL, have depended on various assumptions as to the evolution of stellar populations and dust absorption in galaxies. A detailed review of the problem has been given by Dwek & Krennrich [1]. There have also been attempts to probe the EBL from studies of blazar spectra [2, 3] an approach originally suggested by Stecker, De Jager & Salamon [4]. In this paper, I present the results of a new, fully empirical approach to calculating the EBL, and subsequently, the $\gamma$-ray opacity of the Universe from pair production interactions of $\gamma$-rays with the EBL. This approach of M.A. Malkan, S.T. Scully and myself, hitherto unattainable, is now enabled by very recent data from deep galaxy surveys spanning the electromagnetic spectrum from millimeter to UV wavelengths and therewith using galaxy luminosity functions for redshifts up to $z = 8$. This new approach, in addition to being an alternative to the approaches mentioned above, is totally model independent; it does not make assumptions as to galaxy dust or star formation characteristics or as to blazar emission models. It is also an approach uniquely capable of delineating empirically based uncertainties on the determination of the EBL. More details of the work presented here have now been published [5]. (See also Ref. [6].)

2. GALAXY EMISSIVITIES AND LUMINOSITY DENSITIES

The observationally determined co-moving radiation energy density $u_\nu(z)$ is derived from the co-moving specific emissivity $\mathcal{E}_\nu(z)$, which, in turn is derived from the observed galaxy luminosity function (LF) at redshift $z$. The galaxy luminosity function, $\Phi_e(L)$, is defined as the distribution function of galaxy luminosities at a specific frequency or wavelength. The specific emissivity at frequency $\nu$ and redshift $z$ (also referred to in the literature as the luminosity density, $\rho_{L\nu}$), is the integral over the luminosity function

$$\mathcal{E}_\nu(z) = \int_{L_{\min}}^{L_{\max}} dL \Phi(L\nu; z)$$  \hspace{1cm} (1)

In view of the well known difficulties in predicting galaxy LFs based on galaxy formation models [6], our working philosophy was to depend only on observational determinations of galaxy LFs in deriving specific emissivities.

There are many references in the literature where the LF is given and fit to Schechter parameters, but where $\rho_{L\nu}$ is not given. In those cases, we could not determine the covariance of the errors in the Schechter parameters used to determine the dominant statistical errors in their analyses. Thus, we could not ourselves accurately determine the error on the emissivity from equation (1). We therefore chose to use only the papers that gave values for $\rho_{L\nu}(z) = \mathcal{E}_\nu(z)$ with errors. We did not consider cosmic variance, but this uncertainty should be minimized since we used data from many surveys.

The co-moving radiation energy density $u_\nu(z)$ is the time integral of the co-moving specific emissivity $\mathcal{E}_\nu(z)$,

$$u_\nu(z) = \int_z^{z_{\max}} dz' \mathcal{E}_\nu(z') \frac{dt}{dz} e^{-\tau_{\gamma\nu}(\nu, z, z')}$$  \hspace{1cm} (2)

where $\nu' = \nu(1 + z')/(1 + z)$ and $z_{\max}$ is the redshift corresponding to initial galaxy formation [8], and

$$\frac{dt}{dz}(z) = H_0(1 + z)\sqrt{\Omega_\Lambda + \Omega_m(1 + z)^3}^{-1}$$  \hspace{1cm} (3)

with $\Omega_\Lambda = 0.72$ and $\Omega_m = 0.28$. 

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The opacity factor for frequencies below the Lyman limit is dominated by dust extinction. Since we were using actual observations of galaxies rather than models, dust absorption is implicitly included. The remaining opacity $\tau_\nu$ refers to the extinction of ionizing photons with frequencies above the rest frame Lyman limit of $\nu_{Ly\alpha} = 3.29 \times 10^{15}$ Hz by interstellar and intergalactic hydrogen and helium. It has been shown that this opacity is very high, corresponding to the expectation of very small fraction of ionizing radiation in intergalactic space compared with radiation below the Lyman limit \[8, 9\]. In fact, the Lyman limit cutoff is used as a tool; when galaxies disappear when using a filter at a given waveband (e.g., "U-dropouts", "V-dropouts") it is an indication of the redshift of the Lyman limit.

We have therefore replaced equation \[2\] with the following expression

$$u_\nu(z) = \int_z^{z_{\text{max}}} dz' \mathcal{E}_\nu(z') \frac{dt}{dz'} \mathcal{H}(\nu(z') - \nu_{Ly\alpha}),$$

where $\mathcal{H}(x)$ is the Heavyside step function.

### 3. EMPIRICAL SPECIFIC EMISSIVITIES

We have used the results of many galaxy surveys to compile a set of luminosity densities (LDs), $\rho_L(z) = \mathcal{E}_\nu(z)$, at all observed redshifts, and at rest-frame wavelengths from the far-ultraviolet, FUV = 150 nm to the $I$ band, $I = 800$ nm. The LDs were obtained with a wide variety of instruments in many different deep fields \[3\]. Figure 1 shows the redshift evolution of the luminosity $\mathcal{E}_\nu(z)$ for the various wavebands based on those published in the literature. In order to determine the redshift evolution of the LD in each of the bands out to a redshift of $\sim 8$ where only UV data are available, we utilized observed color relations to transform data from other bands. We have chosen to include all data possible at $z > 1.5$ in order to fill in the observational gaps for various wavebands, mostly at higher redshifts. We used the redshift-dependent observations of average galaxy colors where appropriate in our analysis. In the redshift ranges where they overlap, the colored (observational) data points shown in Figure 1 for the various wavelength bands agree quite well (within the uncertainties) with the black data points that were extrapolated from the shorter wavelength bands using our color relations. The observationally determined LDs, combined with the color relations, extend our coverage of galaxy photon production from the FUV to NIR wavelengths in the galaxy rest frame. Our final results are not very sensitive to errors in our average color relations because the interpolations that we made were only over very small fractional wavelength intervals, $\Delta \lambda(z)$. We have directly tested this by using numerical trial runs.

### 4. THE PHOTON DENSITIES WITH EMPIRICAL UNCERTAINTIES

The 68% confidence band upper and lower limits of the EBL were determined from the observational data on $\rho_L$. We made no assumptions about luminosity density evolution. We derived a luminosity confidence band in each waveband by using a robust rational fitting function characterized by

$$\rho_L = \mathcal{E}_\nu(z) = \frac{ax + b}{cx^2 + dx + e} \quad (5)$$

where $x = \log(1+z)$ and $a, b, c, d, e$ are free parameters.

The 68% confidence band was then computed from Monte Carlo simulation by finding $10^5$ realizations of the data and then fitting the function to the form given by eq. \[5\]. In order to best represent the tolerated confidence band, particularly at the highest redshifts, we chose to equally weight all FUV points in excess of a redshift of 2. Our goal was not to find the best fit to the data, but rather to find the limits tolerated by the current observational data.

With the confidence bands established, we took the upper and lower limits of the bands to be our high and low EBL constraints respectively. We then interpolated each of these cases separately between the various wavebands to find the upper and lower limit rest frame LDs. The calculation was extended to the Lyman limit using the derivative derived from our color relationship between the near and far UV bands. The co-moving radiation energy density was then determined from equation \[4\]. This result was used as input for the determination of the optical depth of the universe to $\gamma$-rays. Our resultant $z = 0$ EBL is shown in Figure 2 and compared with the present data, as discussed in Ref. \[3\].
Figure 1: The observed specific emissivities in our standard astronomical fiducial wavebands. The lower right panel shows all of the observational data used. In the other panels, non-band data have been shifted using observed color relations in order to fully determine the specific emissivities in each waveband. The symbol designations are FUV: black filled circles, NUV: magenta open circles, U: green filled squares, B: blue open squares, V: brown filled triangles, R: orange open triangles, I: yellow open diamonds. Grey shading: derived 68% confidence bands.

5. THE OPTICAL DEPTH FROM $\gamma - \gamma$ INTERACTIONS WITH UV-IR PHOTONS

The photon density

$$n(\epsilon, z) = u(\epsilon, z)/\epsilon$$

(6) with $\epsilon = h\nu$, $h$ being Planck's constant, were calculated using equation [2].

The cross section for photon-photon scattering to electron-positron pairs can be calculated using quantum electrodynamics [10]. The threshold for this interaction is determined from the frame invariance of the square of the four-momentum vector that reduces
to the square of the threshold energy, \( s \), required to produce twice the electron rest mass in the c.m.s.,

\[
s = 2\epsilon E_\gamma (1 - \cos \theta) = 4m_e^2\tag{7}
\]

This invariance is known to hold to within one part in \( 10^{15} \) [12, 13]. With the co-moving energy density \( u_\nu(z) \) evaluated, the optical depth for \( \gamma \)-rays owing to electron-positron pair production interactions with photons of the stellar radiation background can be determined from the expression [4]

\[
\tau(E_0, z_e) = \frac{c}{\epsilon} \int_0^{z_e} \frac{dz}{dz} \int_0^\infty \frac{d\nu}{\nu} \int_0^x \frac{dx}{2} x^2 (1 + z)^3 \\
\times \left( \frac{u_\nu(z)}{\hbar \nu} \right) \sigma_{\gamma\gamma}[s = 2E_0h\nu x(1 + z)],
\]

where \( E_0 \) is the observed \( \gamma \)-ray energy at redshift zero, \( \nu \) is the frequency at redshift \( z \), \( z_e \) is the redshift of the \( \gamma \)-ray source at emission, \( x = (1 - \cos \theta) \), \( \theta \) being the angle between the \( \gamma \)-ray and the soft background photon.

The pair production cross section \( \sigma_{\gamma\gamma} \) is zero for center-of-mass energy \( \sqrt{s} < 2m_e c^2 \), \( m_e \) being the electron mass. Above this threshold, the pair production cross section is given by

\[
\sigma_{\gamma\gamma}(s) = \frac{3}{16} \sigma_T (1 - \beta^2) \\
\times \left[ 2\beta(\beta^2 - 2) + (3 - \beta^4) \ln \left( \frac{1 + \beta}{1 - \beta} \right) \right],
\]

where \( \sigma_T \) is the Thompson scattering cross section and \( \beta = (1 - 4m_e^2 c^4/s)^{1/2} \) [11].

It follows from equation (7) that the pair-production cross section energy has a threshold at \( \lambda = 4.75 \mu m \cdot E_\gamma(\text{TeV}) \). Since the maximum \( \lambda \) that we consider here is in the rest frame I band at 800 nm at redshift \( z \), and we observe \( E_\gamma \) at redshift 0, so that its energy at interaction in the rest frame is \((1 + z)E_\gamma \), we then get a conservative upper limit on \( E_\gamma \) of \( \sim 200(1 + z)^{-1} \) GeV as the maximum \( \gamma \)-ray energy affected by the photon range considered here. Allowing for a small error, our opacities are good to \( \sim 250(1 + z)^{-1} \) GeV. The 68% opacity ranges for \( z = 0.1, 0.5, 1, 3 \), and 5 are plotted in Figure 3.

The widths of the grey uncertainty ranges in the LDs shown in Figure 1 increase towards higher redshifts, especially at the longest rest wavelengths. This reflects the decreasing amount of long-wavelength data and the corresponding increase in uncertainties about the galaxies in those regimes. However, these uncertainties do not greatly influence the opacity calculations. Because of the short time interval of the emission from galaxies at high redshifts their photons do not contribute greatly to the opacity at lower redshifts. Figure 3 shows that the opacities determined for redshifts of 3 and 5 overlap within the uncertainties.

6. Results and Implications

We have determined the EBL using local and deep galaxy survey data, together with observationally produced uncertainties, for wavelengths from 150 nm to 800 nm and redshifts out to \( z > 5 \). We have presented
Figure 3: The empirically determined opacities for redshifts of 0.1, 0.5, 1, 3, 5. The dashed lines are for $\tau = 1$ and $\tau = 3$.

Figure 4: An energy-redshift plot of the $\gamma$-ray horizon showing our uncertainty band results compared with the Fermi plot of their highest energy photons from FSRQs (red), BL Lacs (black) and GRBs (blue) vs. redshift.

This compares to our value of $17.5 \pm 4.9$ nW m$^{-2}$sr$^{-1}$ at 0.9 $\mu$m.

My colleagues M.A. Malkan and S.T. Scully and I are presently continuing our studies of the photon density spectrum as a function of redshift into the infrared range using surveys from Hubble, Spitzer, Herschel and other sources. Such studies, together with ongoing complementary $\gamma$-ray observations of extragalactic sources with Fermi and future observations using the Čerenkov Telescope Array, which will be sensitive to energies above 10 GeV, one can look forward to a obtaining better understanding of both the EBL and other potential aspects of $\gamma$-ray propagation in the Universe, such as those explored in Refs. 17–19.

Results Online

Our results in numerical form are available at the following link: http://csma31.csm.jmu.edu/physics/scully/opacities.html

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