STAR FORMATION HISTORY, DUST ATTENUATION, AND EXTRAGALACTIC BACKGROUND LIGHT

Vikram Khaire and Raghunathan Srikanth
Inter-University Centre for Astronomy and Astrophysics (IUCAA), Post Bag 4, Pune 411007, India; vikramk@iucaa.ernet.in
Received 2014 November 27; accepted 2015 February 25; published 2015 May 18

ABSTRACT

At any given epoch, the extragalactic background light (EBL) carries imprints of integrated star formation activities in the universe until that epoch. On the other hand, in order to estimate the EBL when direct observations are not possible, one requires an accurate estimation of the star formation rate density (SFRD) and the dust attenuation \( A_\nu \) in galaxies. Here, we present a “progressive fitting method” that determines the global average SFRD(z) and \( A_\nu(z) \) for any given extinction curve by using the available multiwavelength, multiepoch galaxy luminosity function measurements. Using the available observations, we determine the best-fit combinations of SFRD(z) and \( A_\nu(z) \), in a simple fitting form, up to \( z \sim 8 \) for five well-known extinction curves. We find, irrespective of the extinction curve used, the \( z \) at which the SFRD(z) peaks is higher than the \( z \) above which \( A_\nu(z) \) begins to decline. For each case, we compute the EBL from ultraviolet to the far-infrared regime and the optical depth \( \tau_\gamma \) encountered by the high-energy \( \gamma \)-rays due to pair production upon collisions with these EBL photons. We compare these with measurements of the local EBL, \( \gamma \)-ray horizon, and \( \tau_\gamma \) measurements using Fermi-Large Area Telescope. All these and the comparison of independent SFRD(z) and \( A_\nu(z) \) measurements from the literature with our predictions favor an extinction curve similar to that of the Large Magellanic Cloud Supershell.

Key words: cosmic background radiation – cosmology: theory – dust, extinction – galaxies: general – gamma rays: diffuse background – radiative transfer

1. INTRODUCTION

The extragalactic background light (EBL) at any epoch is a diffuse isotropic background radiation, defined here over the wavelength range 0.1 to 1000 \( \mu m \), excluding the cosmic microwave background radiation (CMBR), believed to be contributed mainly by sources such as galaxies and QSOs. The knowledge of how the intensity and shape of the EBL evolves is very important for understanding the galaxy evolution in the universe.

Direct measurements of the EBL are possible only in the local universe (Dwek & Arendt 1998; Dole et al. 2006; Matsuoka et al. 2011). However, there are large uncertainties associated with the removal of foreground contributions from the unresolved point sources and zodiacal light (see Hauser & Dwek 2001). The local EBL can be inferred by adding the light from resolved sources (Madau & Pozzetti 2000; Xu et al. 2005; Hopwood et al. 2010), but the convergence of the number of sources is in dispute (Bernstein et al. 2002; Levenson & Wright 2008). However, with the aid of rapidly developing \( \gamma \)-ray astronomy, in principle, it is possible to place strong constraints on the intermediate redshift \( (z<2) \) EBL.

The high-energy \( \gamma \)-rays, by interacting with the EBL photons, can annihilate themselves and produce electron–positron pairs. Ultrarelativistic electron–positron pairs, the byproduct of this interaction, are expected to inverse-Compton-scatter the CMBR and produce secondary \( \gamma \)-rays. These secondary \( \gamma \)-rays are not yet detected by the Fermi satellite, implying either the presence of a small intergalactic magnetic field that scatters the produced pairs (Neronov & Vovk 2010; Tavecchio et al. 2011; Arlen et al. 2012; Takahashi et al. 2012) or the produced pairs dissipate their energy into the intergalactic medium (IGM) via the electromagnetic pair cascade (see, e.g., Miniati & Elyiv 2013; Schlickeiser et al. 2013). Nevertheless, this process of pair production attenuates the \( \gamma \)-rays originating from distant sources while traveling through the IGM (Gould & Schréder 1966; Jelley 1966). The amount of attenuation suffered by the \( \gamma \)-rays emitted by sources at different emission redshifts depends on the number density of the EBL photons encountered while traveling from the source to the Earth. Thus a well-measured \( \gamma \)-ray attenuation \( \tau_\gamma \) can be used to put constraints on the evolution of the shape and amplitude of the EBL. This was initially suggested by Stecker et al. (1992), and the first few limits on the IR part of the EBL were placed by Dwek & Slavin (1994) and de Jager et al. (1994) using TeV \( \gamma \)-ray observations of the blazar Mrk 421.

With the aid of new-generation ground-based \( \gamma \)-ray Imaging Atmospheric Cherenkov telescopes and the Fermi satellite, many high-energy \( \gamma \)-ray sources have been detected. The observed spectrum of distant \( \gamma \)-ray sources is used to determine the \( \tau_\gamma \). However, the difficulty in doing so arises from the fact that the intrinsic spectral energy distribution (SED) of each source is unknown. Recently, Ackermann et al. (2012) circumvented this difficulty and reported measurements of \( \tau_\gamma \) up to \( z \sim 1.5 \) with the observed \( \gamma \)-ray energies from 10 to 500 GeV using the stacked spectra of \( \gamma \)-ray blazars selected from the sample of objects observed with Large Area Telescope (LAT) on board the Fermi satellite. It is expected that \( \tau_\gamma \) will be found to be increasing with increasing redshift because these \( \gamma \)-rays travel longer distances through EBL photons to reach Earth. The observation of this cosmological evolution in \( \tau_\gamma \) has been reported recently by Sanchez et al. (2013). The \( \gamma \)-ray horizon for \( \gamma \)-ray photons with the observed energy \( E_\gamma \) is defined as the emission redshift of \( \gamma \)-rays beyond which they encounter \( \tau_\gamma > 1 \). Recently, by using a physically motivated modeling of intrinsic SEDs of 15 blazars, Domínguez et al. (2013) reported the \( \gamma \)-ray horizon measurements. Domínguez & Prada (2013), using such \( \gamma \)-ray horizon measurements, have demonstrated the capability of \( \gamma \)-ray astronomy to measure the Hubble constant. Recently, Scully
et al. (2014) and Stecker et al. (2012) used their EBL model to constrain the redshift of $\gamma$-ray blazars. In some sense, the backbone of this rapidly developing $\gamma$-ray astronomy is the EBL. Therefore, it is very important to have an EBL estimate consistent with different observations over a large redshift range.

To estimate the EBL, one needs the specific emissivity (sometimes referred to as the luminosity density) at each frequency and redshift. The EBL in optical wavelengths is predominantly contributed by the stellar emission and, in the infrared (IR) wavelengths, by dust emission from galaxies. Therefore, for the correct estimation of the EBL one has to determine the comoving specific galaxy emissivity at different frequencies and redshifts, $\rho_{i}(z)$, as accurately as possible. The EBL models are generally classified into different categories depending on the method adopted to obtain the $\rho_{i}(z)$. For example, some of the models, say, the first kind of models, start with simulating the galaxy evolution in the framework of the standard cosmological model, taking into account the dark matter halo formation and some prescription to relate baryons to the star formation in them. These models then predict the $\rho_{i}(z)$ forward in time (Primack et al. 2005; Gilmore et al. 2009, 2012; Inoue et al. 2013). There is a second type of models that construct the grid of $\rho_{i}(z)$ measurements in different wavebands and redshift and then apply the interpolation and the extrapolation to obtain the $\rho_{i}(z)$ at each $\nu$ and $z$ (Stecker et al. 2006; Franceschini et al. 2008; Domínguez et al. 2011; Helgason & Kashlinsky 2012; Stecker et al. 2012). There is a third kind of model, where the cosmic star formation history and the SED of the stellar population of galaxies are convolved to obtain the $\rho_{i}(z)$ (Kneiske et al. 2004; Finke et al. 2010; Haardt & Madau 2012). The $\rho_{i}(z)$ obtained in this way depends on the star formation history of the galaxies over the cosmic time and absorption and scattering by the dust present in them. The main uncertainties in the first and third approach are related to the the amount of dust corrections, which is usually quantified by the dust attenuation magnitude, $A_{\nu}$, at frequency $\nu$ and a wavelength-dependent dust extinction curve. It is general practice to assume a form of $A_{\nu}(z)$ and an extinction curve to obtain the $\rho_{i}(z)$ from the star formation history. Irrespective of the approach one adopts, all the methods are expected to reproduce the measured $\rho_{i}(z)$ using the observed luminosity functions.

Here, in this paper, we address the issue of self-consistently determining the dust correction and the star formation history that will reproduce the observed emissivity. We present a novel “progressive fitting method,” which, for a given extinction curve by using the $\rho_{i}(z)$, determines a unique combination of cosmic star formation rate density (SFRD) and $A_{\nu}(z)$. We apply this method to observationally determined $\rho_{i}(z)$, using the available multiwavelength, multipoch galaxy data from the literature. We determine the combinations of SFRD($z$) and $A_{\nu}(z)$ for a set of five well-known extinction curves and compare the results with the different independent measurements of SFRD($z$) and $A_{\nu}(z)$ available in the literature. This allows us to determine the average extinction curve that can be used to convert the emissivity into the SFRD($z$). We provide the simple fitting forms of these combinations of SFRD($z$) and $A_{\nu}(z)$ for each extinction curve with their 1σ upper and lower limits. We self-consistently determine the amount of stellar light absorbed by dust with the help of these combinations of $A_{\nu}(z)$ and SFRD($z$) obtained for different extinction curves and then estimate the far-infrared (FIR) emission from galaxies using the local galaxy FIR templates and the energy conservation arguments. In this way we obtain the specific emissivity from UV to FIR and then use the standard prescription to calculate the EBL, the $\tau_{i}$, and the $\gamma$-ray horizon and compare these results with the different available measurements. We conclude that the combination of $A_{\nu}(z)$ and SFRD($z$) obtained using the extinction curve of the Large Magellanic Cloud Supershell (LMC2) and the inferred local FIR emissivity are consistent with the different measurements, and we call the EBL obtained using its fiducial model for the EBL. The EBL obtained in this way, by exploring different well-known extinction curves and corresponding combinations of self-consistent $A_{\nu}(z)$ and SFRD($z$), includes better treatment of dust correction and gives a general picture of how the FIR part of the EBL depends on it.

The outline of this paper is as follows. In Section 2 we present the standard radiative transfer equation used for calculating the EBL from the inferred emissivities. In Section 2.1, we describe the QSO contribution to the total emissivity used by us. In Section 2.2, we describe the standard procedure to obtain the galaxy emissivity using the SFRD($z$) and $A_{\nu}(z)$. In Section 3, we summarize the galaxy emissivity measurements from the literature that we use in our study and describe our “progressive fitting” technique, which determines a unique combination of $A_{\nu}(z)$ and SFRD($z$) for an assumed extinction curve. In Section 4, we make a detailed comparison of SFRD($z$) and $A_{\nu}(z)$ obtained using our technique for five different extinction curves with those determined from the independent observations. We explain in detail the method we used to calculate the FIR emissivity from galaxies in Section 5. Then we use these inferred galaxy emissivities to calculate the EBL at different $z$. We present our EBL predictions and compare them with the other EBL estimates from the literature in Section 6. In Section 7, we describe the basics of the pair production mechanism used for calculating the $\tau_{i}$ for our EBL models and compare our results with the other independent measurements. We conclude with the discussion related to the uncertainties in estimating the star formation history, $A_{\nu}(z)$, and the EBL in Section 8 and summarize the results in Section 9. Throughout the paper we use cosmology with $\Omega_{b} = 0.07$, $\Omega_{m} = 0.3$, and $H_{0} = 70$ km $s^{-1}$ Mpc$^{-1}$.

2. COSMOLOGICAL RADIATIVE TRANSFER

In this section, we provide a general outline for the basic EBL calculations. The number density of background photons at a frequency $\nu_{0}$ and redshift $z_{0}$ is given by

$$n(\nu_{0}, z_{0}) = \frac{4\pi I_{\nu_{0}}(z_{0})}{hc},$$

(1)

where $h$ is the Planck’s constant and $I_{\nu_{0}}$ is the specific intensity of the EBL (in units of erg cm$^{-2}$ s$^{-1}$ Hz$^{-1}$ sr$^{-1}$) at a frequency $\nu_{0}$. Following the standard procedure (see, e.g., Haardt & Madau 2012, referred to as HM12 from now onward), we assume that QSOs and galaxies are the sole contributors to the EBL at all wavelengths. We do not consider contributions to the EBL from nonstandard sources such as decaying dark matter or dark energy. From the observed luminosity functions of QSOs and galaxies at a redshift $z$ and a frequency $\nu$, one can calculate the proper space-averaged specific volume emissivity...
\( \epsilon_\nu (z) \) (in units of erg s\(^{-1}\) Hz\(^{-1}\) Mpc\(^{-3}\)). Then, the radiative transfer equation, which gives the specific intensity, \( I_0 (z_0) \), of the EBL as seen by an observer at a redshift \( z_0 \) and a frequency \( \nu_0 \), can be written as (Peebles 1993; Haardt & Madau 1996)

\[
I_0 (z_0) = \frac{1}{4\pi} \int_{z_0}^{\infty} dz \frac{d}{dz} \left( \frac{1 + z}{1 + z_0} \right)^3 \epsilon_\nu (z) e^{-\tau_{gal}(\nu_0, z_0, z)}. \quad (2)
\]

Here, \( d\ell/dz \) is the cosmological FRW line element, \( \nu = \nu_0 (1 + z)/(1 + z_0) \) is a frequency of the radiation that originated from a redshift \( z \), and \( \tau_{gal}(\nu_0, z_0, z) \) is the effective IGM optical depth encountered by the radiation emitted at a frequency \( \nu \) while traveling through the IGM from an emission redshift \( z \) to a redshift \( z_0 \) where it has been observed at a frequency \( \nu_0 \). The hydrogen and helium gas present in the IGM and in galaxies dominate \( \tau_{gal} \) at \( \lambda \leq 0.091 \mu m \) through photoabsorption. However, in the optical wavelengths it was believed that the main contribution to the opacity comes from the attenuation by the dust associated with high H\(_1\) column density intervening systems. Based on the available QSO spectroscopic observations, one can conclude that this effect is indeed negligible (see Srianand & Kembhavi 1997; York et al. 2006; Frank & Péroux 2010; Khare et al. 2012; Ménard & Fukugita 2012). Here, as we are interested in calculating the EBL at \( \lambda > 0.1 \mu m \), we will consider \( \tau_{gal} = 0 \) in Equation (2). This assumption has negligible effect on the computed EBL, and it does not affect the \( \tau \) significantly over the \( \gamma \)-ray energy range of our interest.

### 2.1. QSO Contribution to Emissivity

The proper specific volume emissivity of the radiating sources can be written as

\[
\epsilon_\nu (z) = \epsilon_{\nu, Q} (z) + \epsilon_{\nu, G} (z), \quad (3)
\]

where \( \epsilon_{\nu, Q} \) and \( \epsilon_{\nu, G} \) are the proper specific volume emissivity of QSOs and galaxies, respectively. For QSOs, we use the parametric form for \( \epsilon_{\nu, Q} \) as given in HM12 at 912 Å, which is consistent with the QSO luminosity function of Hopkins et al. (2007),

\[
\frac{\epsilon_{912, Q}(z)}{(1 + z)^3} = 10^{24.6} (1 + z)^{4.68} \frac{\exp(-0.28z)}{\exp(1.77z) + 26.3}, \quad (4)
\]

in units of ergs s\(^{-1}\) Mpc\(^{-3}\) Hz\(^{-1}\). To obtain \( \epsilon_{\nu, Q} \) at different wavelengths, we use an SED given by the broken power law, \( L_\nu \propto \nu^{-0.44} \) for \( \lambda > 1300 \AA \) and \( L_\nu \propto \nu^{-1.57} \) for \( \lambda < 1300 \AA \) (Vanden Berk et al. 2001; Telfer et al. 2002). It is well known that stellar emission from galaxies dominates the EBL in the optical regime in all redshifts. Therefore, we place more emphasis on estimating \( \epsilon_{\nu, G} \) accurately. We discuss this in detail in the following section.

### 2.2. Galaxy Contribution to Emissivity

We need to compute the galaxy emissivity, \( \epsilon_{\nu, G} (z) \), which is consistent with the observed luminosity functions of galaxies at different wavelengths and redshifts. The luminosity function, \( \phi_\nu (L, z) \), observed at different \( z \) and frequency \( \nu \) is usually specified in the form of a Schechter function. The comoving luminosity density, \( \rho_\nu (z) \), for galaxies, which is nothing but the space-averaged comoving specific emissivity,

\[
\rho_\nu (z) = \frac{\epsilon_{\nu, G} (z)}{(1 + z)^3},
\]

is given by the integral,

\[
\rho_\nu = \int_{\nu_{min}}^{\nu_{max}} L_\nu \phi_\nu (L) dL = \phi_\nu ^* L_*^* \Gamma (\alpha + 2, L_{min}/L_*^*). \quad (5)
\]

Here, \( \phi_\nu ^* \), \( L_*^* \), and \( \alpha \) are the Schechter parameters, \( L_{min} \) is the luminosity corresponding to the faintest galaxy at a redshift \( z \), and \( \Gamma \) is the incomplete gamma function. We dropped the subscript \( z \) in the above equation for clarity. The \( \rho_\nu \) depends on the choice of \( L_{min} \). In principle, one can always take \( L_{min} = 0 \) for \( \alpha > -2.0 \) where the integral in Equation (5) converges. Generally, for galaxies at \( z < 2.5 \), one finds \( \alpha > -1.3 \) (Cucciati et al. 2012). In this case, the change in \( \rho_\nu \), when one changes the \( L_{min} \) from 0 to 0.01L\(_*^*\), is less than 10%. We discuss the effect of adopting different \( L_{min} \) values in Section 8.

The \( \rho_\nu (z) \) measurements are used to determine the global star formation history (see Lilly et al. 1996; Madau et al. 1996) of the universe, provided that the magnitude of the dust attenuation, \( A_v (z) \), at any frequency \( \nu_0 \) and redshift \( z \) is known. The average SFRD, in units of M\(_{\odot}\) yr\(^{-1}\) Mpc\(^{-3}\), is connected to \( \rho_\nu \) through the relationship (Kennicutt 1998),

\[
\text{SFRD} (z) = \zeta_{nu} \times \rho_\nu (z) 10^{0.4A_v(z)}. \quad (6)
\]

Here, \( \zeta_{nu} \) is a constant conversion factor that depends on \( \nu_0 \) and the initial mass function (IMF) assumed for galaxies. However, note that the relation given in Equation (6) is an approximation, as \( \rho_\nu (z) \) can also have contributions from the old stellar population where the stars that are formed earlier are still shining at \( z \).

The derived SFRD(z) and the SED produced from the instantaneous burst of star formation can be used to obtain the luminosity density at different \( \nu \) and \( z \). For an assumed IMF and metallicity \( Z \), the population synthesis models provide an SED in terms of the specific luminosity, \( L (\tau, Z) \) (in units of ergs s\(^{-1}\) Hz\(^{-1}\) per unit mass of stars formed) at different ages, \( \tau \), of the stellar population. Because the timescales involved in the process of star formation (10\(^{-10}\)–10\(^{9}\) yr) are relatively small, the SED from the instantaneous starburst can be directly convolved with the global SFRD(z) to obtain the \( \rho_\nu (z_0) \) by solving the following convolution integral (see, e.g., Kneiske et al. 2002, HM12),

\[
\rho_\nu (z_0) = C_\nu (z_0) \int_{z_0}^{\text{max}} \text{SFRD}(z) \delta \left[ t(z_0) - t(z), Z \right] \frac{dt}{dz} dz, \quad (7)
\]

where \( \tau = t(z_0) \) is the age of the stellar population at the redshift \( z_0 \) that went through an instantaneous burst of star formation at a redshift \( z \). \( C_\nu (z_0) \) is the dust correction factor at \( z_0 \) and \( dt/dz = [(1 + z)H(z)]^{-1} \). The fact that the burst of star formations occurs at all epochs, \( t \), but with the average star formation rates equal to the global SFRD(t), is captured by the product of SFRD(z) and \( \delta \left[ t(z_0) - t(z), Z \right] \) in the convolution integral. We use \( \text{max} = \infty \), as often used in the literature (e.g., Gilmore et al. 2009; Inoue et al. 2013, HM12). Later in Section 8, we discuss the validity of the \( \text{max} = \infty \) assumption and the effect of using different \( z_{\text{max}} \). The dust correction
factor, \( C_\nu(z_0) \), for \( \lambda < 912 \text{ Å} \) is assumed to be equal to the escape fraction of hydrogen-ionizing photons from galaxies, as given in HM12. For \( \lambda > 912 \text{ Å} \), we use \( C_\nu(z_0) = 10^{-0.4} \text{ Å} (z_0) \), where \( A_\nu(z_0) \), which is normalized at \( \nu_0 \), is given by

\[
A_\nu(z_0) = A_{\nu_0}(z_0) \frac{k_\nu}{k_{\nu_0}}.
\]

(8)

Here, \( k_\nu \) is a frequency-dependent dust extinction curve.

3. METHOD TO DETERMINE SFRD(\( z \)) AND \( A_{\nu_0}(z) \)

In this section, we summarize the \( \rho_\nu(z) \) measurements from the literature and the progressive fitting method, which determines a unique combination of SFRD(\( z \)) and \( A_{\nu_0}(z) \) for an assumed extinction curve using \( \rho_\nu(z) \). By construct, this combination of SFRD(\( z \)) and \( A_{\nu_0}(z) \) reproduces the emissivity measurements.

3.1. Compiled Luminosity Density Measurements

Motivated by the previous works of Stecker et al. (2012) and Helgason et al. (2012), we have compiled available observations of the galaxy luminosity functions and the corresponding \( \rho_\nu \) at different rest wavelengths and \( z \). In Table 1, we have given references along with the rest wavelength and a redshift range over which the luminosity functions have been determined. In Table 5 in the Appendix, we list the faint end slopes of the luminosity functions with the rest wavelength and redshift, along with the \( L_{\text{min}} \) values we used to determine \( \rho_\nu \). In general, we preferred the references where the luminosity functions are determined in different wavebands from the FUV (centered at \( \lambda = 0.15 \mu\text{m} \)) to the K (2.2 \( \mu\text{m} \)) band and with the largest possible coverage in redshift. This compilation has luminosity functions determined in the FUV band up to \( z = 8 \), in the NUV and H band up to \( z = 3.5 \), and for all other bands the measurements are available up to \( z \sim 2.5 \). We take the \( \rho_\nu(z) \) with the errors from the references where it is explicitly calculated. We use luminosity functions given in other references and compute \( \rho_\nu(z) \) (using Equation (5)) with \( L_{\text{min}} = 0.01 L_\odot \). Because there are more measurements of the \( \rho_\nu \) in the FUV band and covering a large \( z \) range, we choose \( \nu_0 = \nu_{\text{FUV}} \), the frequency we use to determine SFRD(\( z \)) as a frequency corresponding to the FUV band.

### Table 1
Details of the Observed Galaxy Luminosity Functions Used to Obtain the \( \rho_\nu \) in Our Study

| Reference | Waveband* | Redshift Range | Plotting Symbol^b |
|-----------|-----------|----------------|-------------------|
| Schiminovich et al. (2005) | FUV | 0.2–2.95 | cyan triangle |
| Reddy & Steidel (2009) | FUV | 1.9–3.4 | orange triangle |
| Bouwens et al. (2007) | FUV | 3.8–5.9 | red diamond |
| Bouwens et al. (2011) | FUV | 6.8–8 | red diamond |
| Dahlen et al. (2007) | FUV | 0.92–2.37 | blue square |
| Cucciati et al. (2012) | FUV | 0.05–4.5 | green circle |
| Tresse et al. (2007) | FUV, NUV, U, V, B, R, I | 0.05–2 | red circle |
| Wyder & Treyer (2005) | NUV | 0.05 | black triangle |
| Faber et al. (2007) | B | 0.2–1.2 | orange star |
| Dahlen et al. (2005) | U, B, R | 0.1–2 | blue square |
| Stefanon & Marchesini (2013) | J, H | 1.5–3.5 | green square |
| Pozzetti et al. (2003) | J, K | 0.2–1.3 | orange triangle |
| Arnouts et al. (2007) | K | 0.2–2 | green diamond |
| Cirasuolo et al. (2007) | K | 0.25–2.25 | blue triangle |

Notes.

* Central wavelengths corresponding to different wavebands are as follows: FUV = 0.15 \( \mu\text{m} \), NUV = 0.28 \( \mu\text{m} \), U = 0.365 \( \mu\text{m} \), B = 0.445 \( \mu\text{m} \), V = 0.551 \( \mu\text{m} \), R = 0.658 \( \mu\text{m} \), \( I = 0.806 \mu\text{m} \), J = 1.27 \( \mu\text{m} \), H = 1.63 \( \mu\text{m} \), and K = 2.2 \( \mu\text{m} \).

^b These plotting symbols are used in Figures 5 and 17 for the \( \rho_\nu \) obtained using different luminosity functions.

3.2. Progressive Fitting Method

We use a population synthesis model, “\textsc{Starburst99}” (Leitherer et al. 1999), to obtain the specific luminosity from the stellar population of a typical galaxy, \( L(t, Z) \), at an age \( t \) and a metallicity \( Z \) with an instantaneous burst of star formation. In these simulations, we consider a constant metallicity of \( Z = 0.008 \) over all \( z \). Later in Section 8, we also discuss the effect of using different values of metallicity. We use the Salpeter IMF with an exponent of 2.35 and the stellar mass range from 0.1 to 100 \( M_\odot \). For this particular galaxy model, we find the conversion factor for connecting \( \rho_{\text{FUV}}(z) \) and SFRD(\( z \)) (see Equation (6)) to be \( \zeta_0 = 1.25 \times 10^{-28} \). As described before, the reference frequency \( \nu_0 \) that we use corresponds to the frequency of the FUV band. Note that this conversion factor \( 1.25 \times 10^{-28} \) is 11% smaller than widely used, 1.4 \( \times 10^{-28} \), quoted by Kennicutt (1998). This difference is mainly because of the updated population synthesis model and the assumed metallicity.

We fit a functional form to the compiled \( \rho_{\text{FUV}} \) data and obtained its parameter using the \textsc{mpfit} IDL routine2 that uses \( \chi^2 \) minimization. At high redshifts, we take 20% errors on the \( \rho_{\text{FUV}} \) calculated from the luminosity function given by

1 \textsuperscript{http://www.stsci.edu/science/starburst99/docs/default.htm}

2 \textsuperscript{http://www.stsci.edu/science/starburst99/docs/default.htm}
Figure 1. The $\rho_{\text{FUV}}$ as a function of $z$ fitted with a functional form given in Equation (9). Solid, dashed, and dotted-dashed curves are the median, high, and low fits, respectively. Data are taken from the references listed in Table 1 for the FUV band.

Bouwens et al. (2011). We convert the asymmetric errors into symmetric errors by taking their average. To fit $\rho_{\text{FUV}}(z)$, we use the following functional form, which was originally used by Cole et al. (2001) to fit the SFRD($z$),

$$
\rho_{\text{FUV}}(z) = \frac{a + b z}{1 + (z/c)^d}.
$$

(9)

There is a large scatter in the $\rho_{\text{FUV}}(z)$ data. Therefore, along with this fit (hereafter, the median fit), we construct 1σ upper- and lower-limit fits (hereafter we refer to them as the high and low $\rho_{\text{FUV}}$ fits, respectively). These $\rho_{\text{FUV}}$ fits multiplied by $1.25 \times 10^{-28}$ are nothing but the different SFRD($z$) with $A_{\text{FUV}}(z) = 0$ (see Equation (6)), which are plotted in Figure 1. The values of fitting parameters for the median $\rho_{\text{FUV}} \times 1.25 \times 10^{-28}$ fit are $a = (6 \pm 1) \times 10^{-2}$, $b = (11 \pm 2) \times 10^{-2}$, $c = 4.41 \pm 0.58$, and $d = 3.15 \pm 0.62$. We construct 1σ high and low $\rho_{\text{FUV}}$ fits by adding and subtracting the error in each parameter from its respective best-fit value (see, Figure 1). We determine the combinations of SFRD($z$) and $A_{\text{FUV}}(z)$ for all three (low, median, and high) $\rho_{\text{FUV}}$ fits with different extinction curves, as discussed below.

The average extinction curve for high-redshift galaxies is one of the key unknowns in astronomy. However, the mean extinction curves for our galaxy, SMC, and LMC and for some low-redshift starburst galaxies are well known (Lequeux et al. 1982; Clayton & Martin 1985; Calzetti et al. 1994). It is a general practice to use the average extinction curve determined for the nearby starburst galaxies by Calzetti et al. (2000) \footnote{Note that sometimes this is also called an attenuation curve or an obscuration curve (Calzetti 2001). However, in this paper, along with the other four extinction curves we call it an extinction curve for uniformity.} for the high-redshift galaxies. Here, along with the Calzetti et al. (2000) extinction curve, we use extinction curves determined for the SMC, LMC, and LMC supershell (LMC2) from Gordon et al. (2003) and for the Milky Way (MW) from Misselt et al. (1999). In particular, this set of extinction curves encompasses a wide range of dust properties typically present in the astronomical domain. Because we are using $\rho_{\text{FUV}}$ measurements for determining the SFRD($z$), we normalize all the extinction curves, $k_{\nu}$, at $\nu$ corresponding to the FUV band (0.15 $\mu$m). In Figure 2, we have plotted the $k_{\nu}/k_{\text{FUV}}$ for different extinction curves as a function of $\lambda^{-1}$, along with the respective measured data points from Gordon et al. (2003) for SMC, LMC, and LMC2. In Figure 2, we also mark the different $\lambda^{-1}$ for the wavebands at which we have compiled the $\rho$ measurements to determine the $A_{\text{FUV}}$ and the SFRD.

From Equation (6) it is clear that SFRD($z$) and $A_{\text{FUV}}(z)$ are degenerate quantities, and different combinations of them can give the same $\rho_{\text{FUV}}$. However, the measured $\rho_{\lambda}$ values at different frequencies other than the FUV band, along with the assumed extinction curve, break this degeneracy. Here we introduce a novel method that, by using the mult wavelength and multiepoch luminosity functions, determines the $A_{\text{FUV}}(z)$ and SFRD($z$) uniquely for an assumed extinction curve. In this method we initially fix the $A_{\text{FUV}}$ and SFRD at some higher redshifts, and then, using this we progressively determine $A_{\text{FUV}}$ and SFRD at lower redshifts. This “progressive fitting method” is described below in detail.

Combining Equations (6)–(8), the $\rho_{\nu}(z_{0})$ can be written as

$$
\rho_{\nu}(z_{0}) = 1.25 \times 10^{-28} \times 10^{\left[-A_{\text{FUV}}(z_{0}) \frac{\nu}{1.5}\right]} \times \int_{z_{0}}^{\infty} \rho_{\text{FUV}}(z) 10^{0.4A_{\text{FUV}}(z)} \\
\times k_{\nu}(t(z_{0}) - t(z), Z) \frac{dz}{dz}. \quad (10)
$$

Figure 2. Extinction curves normalized at the FUV band for SMC, LMC, LMC Supershell (LMC2), Milky Way (MW), and nearby starburst galaxies by Calzetti et al. (2000). Here, triangles, squares, and diamonds represent the mean extinction curve measurements from Gordon et al. (2003) normalized at the FUV band for SMC, LMC2, and LMC, respectively. Different wavebands are marked with the vertical dashed lines to show the difference in different extinction curves at those wavelengths.
For a given extinction curve, $k_\nu$, and our $\rho_{\text{FUV}}(z)$ fits, the only unknown in the above equation is $A_{\text{FUV}}(z)$ for $z \geq z_0$. Therefore, to obtain the $\beta_i(z_0)$ one needs to know the $A_{\text{FUV}}(z)$ for all $z \geq z_0$. The procedure we followed to obtain the $A_{\text{FUV}}(z)$ for each extinction curve, $k_\nu$, using the $\rho_{\text{FUV}}(z)$ measurements is given below:

1. We choose the highest possible redshift $z_{\text{th}}$ where we have $\rho_{\text{FUV}}(z)$ measurements in most of the wavebands.
2. For all $z \geq z_{\text{th}}$, we assume a functional form for $A_{\text{FUV}}(z)$.
3. We fix the normalization of this function and hence the value of $A_{\text{FUV}}(z_{\text{th}})$ by matching the predicted $\rho_{\text{FUV}}(z_{\text{th}})$ with the measured ones at different wavebands (other than the FUV band), using least-squares minimization. This fixes the $A_{\text{FUV}}(z)$ for $z \geq z_{\text{th}}$. Then we call $z_{\text{th}}$ as $z_1$.
4. We choose the next redshift $z_0 < z_1$, which is the next nearby lower redshift where we have multwavavelength $\rho_{\text{FUV}}(z_0)$ measurements.
5. We assume $A_{\text{FUV}}(z)$ is constant and equal to $A_{\text{FUV}}(z_0)$ in between the redshifts $z_0$ and $z_1$. For $z \geq z_1$ we use $A_{\text{FUV}}(z)$, as determined earlier. Then we calculate the $\rho_{\text{FUV}}(z)$ for different values of $A_{\text{FUV}}(z_0)$.
6. We compare the resultant $\rho_{\text{FUV}}$ with the measured one at different wavebands and determine the best-fit $A_{\text{FUV}}(z_0)$ by least-squares minimization. This fixes the $A_{\text{FUV}}(z)$ for $z \geq z_0$. Then we call this $z_0$ as $z_2$.
7. We repeat steps 4 to 6 until we reach the lowest $z$ where we have multwavavelength $\rho_{\text{FUV}}(z)$ measurements. This provides us the best-fit values of $A_{\text{FUV}}(z)$ and SFRD($z$) over the whole redshift range for a given extinction curve.

In Figure 3 we show the $A_{\text{FUV}}(z)$ obtained (histograms) using the progressive fitting method described above for different extinction curves. We fit a continuous function through the resultant $A_{\text{FUV}}(z)$ using a functional form that is the same as the one we used to fit the $\rho_{\text{FUV}}(z)$ measurements (given in Equation (9)). For fitting this functional form we use the MPFIT IDL routine by taking 10% errors for all. To demonstrate the procedure described here, in Figure 3, we also show the resultant $A_{\text{FUV}}(z)$ obtained using the high, low, and median $\rho_{\text{FUV}}$ fits (histograms), along with its fitted functional form for different extinction curves. Because we show Figure 3 for the purpose of demonstrating our "progressive fitting method," for clarity, we do not show $A_{\text{FUV}}(z)$ obtained for the MW extinction curve. Note that this resultant $A_{\text{FUV}}(z)$ will directly give the corresponding SFRD($z$) (see Equation (6)). We also fit SFRD($z$) using the same functional form (see Equation (9)).

Our aim is to obtain the combinations of $A_{\text{FUV}}(z)$ and SFRD($z$) that will reproduce the measured $\rho_{\text{FUV}}(z)$ obtained using the observed luminosity functions at different wavebands and different $z$. The $\rho_{\text{FUV}}$ measurements are taken from different references, and they have different biases and error estimates. Therefore, to minimize the uncertainty and determine the $A_{\text{FUV}}$ over a large $z$ range uniquely, we have to choose $\rho_{\text{FUV}}$ measurements that span many wavebands and a large $z$ range and possibly reported by the same group, so that the effect of various biases will be minimum. Fortunately, this requirement is satisfied by the $\rho_{\text{FUV}}$ measurements reported in Tresse et al. (2007), where the $\rho_{\text{FUV}}$ is measured over seven different wavebands (from FUV to I band) and at the same redshift bins spanning up to $z = 2$. Therefore, to obtain a robust $A_{\text{FUV}}(z)$ and SFRD($z$) combination we choose the observed $\rho_{\text{FUV}}(z)$ given by Tresse et al. (2007) and take $z_{\text{th}} = 2$. We assume that the form of the $A_{\text{FUV}}(z)$ for $z \geq 2$ becomes $1/(1 + z)$ and is independent of the extinction curve used. We show later that this assumed form gives $A_{\text{FUV}}(z)$ consistent with other independent measurements. This trend of decreasing
$A_{\text{FUV}}$ at higher $z$ has been previously observed (see, e.g., Takeuchi et al. 2005; Bouwens et al. 2009; Cucciati et al. 2012; Burgarella et al. 2013). This is consistent with the picture of a gradual buildup of dust in galaxies with cosmic time, as evident from the fact that galaxies at very high redshifts ($z > 5$) are bluer than the $z \sim 2-4$ galaxies (Bouwens et al. 2009).

We calculate the $A_{\text{FUV}}(z)$ and corresponding SFRD($z$) for all five extinction curves used in this paper using the low, high, and median $\rho_{\text{FUV}}(z)$ fits. As we show later, we use the $\rho_z(z)$ obtained using the combinations of $A_{\text{FUV}}(z)$ and SFRD($z$) to estimate the $\rho_z(z)$ at FIR wavelengths and the EBL at different redshifts. We denote the obtained combinations of $A_{\text{FUV}}(z)$ and SFRD($z$), the $\rho_z(z)$, and the EBL using different extinction curves as the “smc,” “Imc,” “Imc2,” “mw,” and “cal” models, based on the SMC, LMC, LMC2, MW, and Calzetti et al. (2000) extinction curves used, respectively. For most comparisons we use our default models, which are obtained using median fits through the $\rho_{\text{FUV}}$ Points. We use the predictions of the high and low fits only when we discuss the spread. For clarity in the subsequent discussions, whenever we use the “high” (low) model,” we mean the relevant quantity (e.g., $\rho_z$, $A_{\text{FUV}}$, SFRD, and EBL) obtained with the high (low) $\rho_{\text{FUV}}$ fit and the “model” extinction curve. When we denote only “model,” we mean the relevant quantity obtained using the median $\rho_{\text{FUV}}$ fit and that “model” extinction curve.

In the following section we discuss the resultant $\rho_z(z)$, $A_{\text{FUV}}(z)$, and SFRD($z$) determined using the method described in this section.

4. DUST ATTENUATION AND STAR FORMATION HISTORY

4.1. Reproducing $\rho_z(z)$ Measurements

In Figure 4, we plot the $\rho_z$ obtained using the convolution integral (Equation (7)) for the best-fit combinations of SFRD and $A_{\text{FUV}}$ at different $z$, along with the measurements of Tresse et al. (2007). Note that to obtain the $A_{\text{FUV}}$ by least-squares minimization we use the $\rho_z$ measurements of Tresse et al. (2007) in all wavebands except at the FUV band. However, these $\rho_{\text{FUV}}$ measurements, along with many others reported in the literature up to $z = 8$ (see Tables 1 and 5), go into fitting the $\rho_{\text{FUV}}$ (as shown in Figure 1). All our five models show very good agreement with the measurements of Tresse et al. (2007) in all wavebands (including the FUV band). The difference in the strength of the 2175 Å absorption feature arises because of using different extinction curves.

In Figure 5, along with the compiled measurements, we plot the $\rho_z$ at the FUV band obtained by using the combination of the SFRD($z$) and the $A_{\text{FUV}}(z)$ for the low, median, and high “Imc2” model. There are negligible differences in the $\rho_{\text{FUV}}$ obtained for different models. Therefore, for clarity, we do not show the similar $\rho_{\text{FUV}}$ plots for other models.

For the high $z$ and all other wavebands, we show our estimated $\rho_z$, along with the compiled measurements in Figure 17 in the Appendix (see Table 1 for the references and plotting symbols). Even though we use measurements of $\rho_z$ up to $z \sim 2$ and up to the wavelength corresponding to the I band to obtain the $A_{\text{FUV}}(z)$, our estimated $\rho_z$ matches well with the various measurements up to $z \sim 4$ from the NUV to the K band. This implies that our determined combinations of the $A_{\text{FUV}}(z)$ and the SFRD($z$) are valid over a large $z$ range and suggests that our assumption of decreasing dust attenuation at high $z$ is also valid. However, note that at the high redshifts (i.e., $z > 4$) there are no measurements of $\rho_z$ except at the FUV band. In the H band, our calculated $\rho_z(z)$ is slightly overestimated than the measured ones. However, as there are very few measurements we do not attempt to address this disagreement.

The good matching between the observations and the model predictions suggests that we have a consistent combination of the $A_{\text{FUV}}(z)$ and SFRD($z$) for each extinction curve under consideration. The evolution of our best-fit $A_{\text{FUV}}$ and the corresponding SFRD with $z$ is discussed in the next section.

4.2. Redshift Evolution of $A_{\text{FUV}}$

Understanding the dust attenuation and its wavelength and redshift dependences is very important to derive the intrinsic SFRD($z$) accurately. Dust attenuation is measured by using either of the SED fitting techniques, the Balmer decrement method, or by comparing the FUV and the IR luminosity function measurements. It has also been noticed that at any given $z$, the derived $A_{\text{FUV}}$ may also depend on the galaxy luminosity and the stellar mass of the galaxy (see, e.g., Bouwens et al. 2012). Recently, it has been shown that the shape of the extinction curve strongly depends on the distribution of dust in the galaxies and the viewing geometries where scattering plays an important role (Chevallard et al. 2013). As our main purpose is to calculate the EBL, we are mainly interested in the volume-averaged star formation rates and emissivity. Therefore, to calculate the average dust correction as a function of $z$, for simplicity we do not consider the dependence of $A_{\text{FUV}}$ on galaxy luminosity or stellar mass and the dependence of $k_e$ on scattering and viewing geometries. In this section, we compare $A_{\text{FUV}}(z)$ obtained for different extinction curves with the $A_{\text{FUV}}$ measurements in the literature based on other independent approaches.

The fitting parameters for $A_{\text{FUV}}(z)$ for different extinction curves are given in Table 2. In Figure 6, we plot the range of $A_{\text{FUV}}(z)$ for different extinction curves, along with the measurements of Takeuchi et al. (2005), Cucciati et al. (2012), Burgarella et al. (2013), and Bouwens et al. (2012). Takeuchi et al. (2005) and Burgarella et al. (2013) determined the $A_{\text{FUV}}$ using the ratio of the FUV to FIR band luminosity density. Cucciati et al. (2012) have calculated the $A_{\text{FUV}}$ using the Calzetti et al. (2000) extinction curve and used the SED fitting technique. At very high redshifts, Bouwens et al. (2012) determined the effective dust extinction using the UV-continuum slope $\beta$ distribution and the IRX-$\beta$ relationship (see Meurer et al. 1999). We take the effective extinction calculated for the luminosity function integrated up to $\sim 17.7$ magnitude from Bouwens et al. (2012, from Table 6 of their paper).

The shaded region in Figure 6 is obtained by using the low, high, and median $\rho_{\text{FUV}}$ fits to determine the $A_{\text{FUV}}$. Since the SFRD is directly related to the $\rho_{\text{FUV}}$ and $A_{\text{FUV}}$, when we use the low (high) $\rho_{\text{FUV}}$ fits, to obtain the same $\rho_z$ at different wavebands we need higher (lower) SFRD and hence higher (lower) $A_{\text{FUV}}$. In other words, the low (high) $\rho_{\text{FUV}}$ implies that galaxies are more red (blue), which suggests that these galaxies should have more (less) dust extinction. This trend is evident from Figure 6, where the dotted and dashed curves show the $A_{\text{FUV}}$ obtained using the low and high $\rho_{\text{FUV}}$ fits, respectively.
The shaded region in Figure 6 represents the allowed range of $A_{\text{FUV}}$. For each assumed extinction curve, we obtain a different allowed range for the $A_{\text{FUV}}$, and the difference is prominent at redshifts $z < 1$. For redshifts $1 < z < 2$, we find that the $A_{\text{FUV}}$ values remain constant or show a mild decrease with increase in $z$. At high redshifts, i.e., $z > 2$, our assumption of decreasing dust attenuation plays a role in obtaining a similar allowed range of the $A_{\text{FUV}}$ for all assumed extinction curves. As can be seen from Figure 6, the allowed $A_{\text{FUV}}$ range for $z > 2$ nicely follows that of other independent measurements, rendering support to our assumption. Apart from the $A_{\text{FUV}}$ determined for the “mw” model, for all the other models we find a moderate increase in the $A_{\text{FUV}}$, with redshift up to $z = 1$ from $z = 0$. This trend of increasing FUV band dust attenuation magnitude has been detected previously (see Takeuchi et al. 2005; Cucciati et al. 2012; Burgarella et al. 2013), as shown in Figure 6. However, at $z \leq 0.8$, our estimated $A_{\text{FUV}}(z)$ for the “cal,” “mw,” and “lmc” models are higher than these measurements. The $A_{\text{FUV}}$ determined for the “smc” model matches well in all redshifts, except that it underpredicts $A_{\text{FUV}}$ at $1 < z < 2$. Overall, a good match with these measurements of the $A_{\text{FUV}}$ is obtained over the large $z$ range for the “lmc2” model.

From the very good agreement between the $A_{\text{FUV}}(z)$ determined for the “lmc2” model and the measurements of Burgarella et al. (2013) and Takeuchi et al. (2005), we...
calculated for the UV wavelengths for all SEDs. They concluded that the SED of the MW and Calzetti extinction curves provide poor fits to the UV wavelengths for all SEDs. We assume that the SFRD is a smooth and continuous function of $z$ and fit it with the same functional form (using Equation (9)) we are using to fit the $\rho_{\text{FUV}}$ and $\alpha_{\text{FUV}}$. The fitting parameters for the SFRD$(z)$ are given in Table 1 for the FUV band. The $\rho_{\text{FUV}}$ calculated for different models have negligible difference with respect to each other. Therefore, as a representative for all other models, we show $\rho_{\text{FUV}}$ only for the “lmc2” model.

![Figure 5. The FUV band comoving luminosity density with $z$. Solid, dashed, and dotted lines represent $\rho_{\text{FUV}}$ calculated at the FUV band using the median, high, and low “lmc2” models, respectively. The plotting symbols and corresponding references are mentioned in Table 1 for the FUV band. The $\rho_{\text{FUV}}$ calculated for different models have negligible difference with respect to each other. Therefore, as a representative for all other models, we show $\rho_{\text{FUV}}$ only for the “lmc2” model.

conclude that the average extinction curve, which is applicable for galaxies over a wide range of redshifts, is most likely to be similar to the LMC2 extinction curve.

Recently, Kriek & Conroy (2013), using the SED of the galaxies, investigated the dust extinction curves for 32 different spectral classes of galaxies over $0.5 \leq z \leq 2$. They found that
In Figure 8 we plot our SFRD obtained using the LMC2 extinction curve, along with the SFRD determined by Madau & Dickinson (2014). The shaded region in Figure 8 represents the SFRD range covered when we use low and high “lmc2” dust curves. Our best-fit SFRD $z(\nu)$ in units $\text{M}_\odot \text{yr}^{-1} \text{Mpc}^{-3}$, obtained using different extinction curves. Dotted, solid, and dashed lines represent values of the best-fit $A_{\text{FUV}}$ obtained using the low, median, and high models, respectively. Green circles represent the $A_{\text{FUV}}$ determined through SED fitting by Cucciati et al. (2012) using Calzetti extinction curves. Red diamonds and blue squares represent the $A_{\text{FUV}}$ measured through the $\rho_{\text{FIR}}$ to $\rho_{\text{FUV}}$ ratio by Burgarella et al. (2013) and Takeuchi et al. (2005), respectively. Cyan triangles are from Bouwens et al. (2012).

References and plotting symbols used here are provided in Table 3. The SFRD obtained using the LMC2 extinction curve shows good agreement with the different dust-independent measurements.
models to determine the SFRD and $A_{\text{FUV}}$. Madau & Dickinson (2014) used the $\rho_{\text{FUV}}$ measurements from the literature and converted them into the SFRD, using the conversion constant, $\zeta = 1.15 \times 10^{-28}$, which is 10% smaller than what we use. For the dust correction they use the $A_e$ provided by the different surveys from where the luminosity functions are used to obtain the $\rho_{\text{FUV}}$. They calculate the $\rho_{\text{FUV}}$ by integrating the luminosity function from $L_{\text{min}} = 0.032 z^4$, whereas in our case we directly take the $\rho_{\text{FUV}}$ given in different references, where it is often calculated with $L_{\text{min}} = 0$ (for the $L_{\text{min}}$ values used here, see Table 5 in the Appendix). Madau & Dickinson (2014) use the same IMF we used, but take different metallicities and consider metallicity evolution with $z$. As compared to our preferred SFRD(z) for the LMC2 model, the SFRD of Madau & Dickinson (2014) shows rapid increase and decrease in low and high $z$, respectively. However, the difference between both is within 0.1–0.2 dex for $z < 5$. The peak of SFRD(z) of our preferred “Imz2” model matches exactly with that of Madau & Dickinson (2014). The peak of our SFRD(z) is at $z = 1.9_{-0.3}^{+0.2}$, which is also consistent with the peak of SFRD reported by Cucciati et al. (2012).

For comparing the SFRD(z) shapes, we also plot the fit to the SFRD measurements compiled from the different observational data reported in the literature given by Behroozi et al. (2013) (see Figure 2 and Table 4 of their paper). Behroozi et al. (2013) provide the fit for the recent data and the old data used by Hopkins & Beacom (2006). Both of these fits are obtained for the Chabrier (2003) IMF and show a rapid increase at low $z$ as compared to our SFRD(z). At high $z$, the fit through the compiled SFRD data used by Hopkins & Beacom (2006) shows a slow decrease, whereas the Behroozi et al. (2013) fit shows a rapid decrease as compared to our SFRD. The peak of the compiled SFRD measurements of Behroozi et al. (2013) for the old and new measurements is at $z = 1.7$, which is consistent with our SFRD(z) peak within the allowed uncertainties. The main differences between our SFRD(z) estimated here and the compiled SFRD measurements of Behroozi et al. (2013) and SFRD(z) estimated by Madau & Dickinson (2014) is that we self-consistently calculate the $A_{\text{FUV}}(z)$, which gives SFRD(z) consistent with $\rho_{\text{FUV}}$ measurements at different wavebands and redshifts.

Having obtained the best-fit $A_{\text{FUV}}(z)$ and SFRD(z), we use the stellar population synthesis models to calculate the emissivity from the UV to NIR regime. However, to generate the complete EBL, in addition to this we need the IR emissivity. We predict the IR emissivity using our best-fit $A_{\text{FUV}}(z)$ and SFRD(z), which is explained in the following section.

5. GALAXY EMISSIVITY IN INFRARED

The old stellar population, the interstellar gas, and dust are the main sources which contribute to the IR emission form galaxies. The IR emission from old stars peaks around 1–3 $\mu$m, and a very few per cent of the total IR output of a galaxy is emitted by atoms and molecules that constitute the interstellar gas. The main source of the IR emission at $\lambda > 3$ $\mu$m is thermal emission from dust grains heated by the local stellar light in the UV and optical wavelength range. The amplitude and shape of this emission from the NIR to FIR wavelengths depend on the temperature, size distribution, and the composition of the dust grains (e.g., Dale et al. 2012; Magdis et al. 2012, 2013). However, like the extinction curves, these quantities are unknown for distant galaxies. Therefore, instead of assuming the dust properties to model the NIR to FIR emission of a typical galaxy, we use the observed IR templates and make use of the $A_{\text{FUV}}$ for different models determined here.

We use the average IR templates of Rieke et al. (2009) from 5 $\mu$m to 30 cm obtained for infrared galaxies having different total infrared luminosity, $L_{\text{TIR}}$. They have assembled the SEDs of 11 local luminous and ultraluminous infrared galaxies, and for generating the templates at lower luminosity they have combined the templates of Dale et al. (2007) and Smith et al. (2007). The shape of each template is moderately different for different $L_{\text{TIR}}$. Therefore, we have to choose an appropriate template for calculating the IR emission. Because at any $z$ most of the total luminosity is contributed by galaxies with luminosity $L^*(z)$, we choose templates of Rieke et al. (2009) obtained for $L_{\text{TIR}} = L_{\text{TIR}}^*(z)$. We use $L_{\text{TIR}}^*(z)$ values for different redshifts, using the total IR luminosity function given in Gruppioni et al. (2013) up to $z = 4$. To obtain the $L_{\text{TIR}}^*(z)$ values for the high redshifts (in units of $L_\odot$), we fit a second-degree polynomial through log($L_{\text{TIR}}^*$), using the MPFIT IDL routine. The best-fit second-degree polynomial is log($L_{\text{TIR}}^*$) = $10.0 + 1.18z - 0.18z^2$. To compute the FIR spectrum we interpolate the templates of Rieke et al. (2009) for corresponding values of $L_{\text{TIR}}^*(z)$ given by the above polynomial fit. For all redshifts $z > 7$ we use the interpolated template of Rieke et al. (2009) with $L_{\text{TIR}} = 10^9 L_\odot$. However, this lower limit has no effect on the shape of the IR template because it is just a template for the lowest luminosity ($10^{9.75} L_\odot$) given by Rieke et al. (2009) scaled to give the $L_{\text{TIR}} = 10^9 L_\odot$.

We use the energy conservation to calculate the IR emission. We assume that the average energy absorbed by dust from the FUV to NIR regime per Mpc$^3$ per second at any redshift $z_0$, $E_{\text{abs}}(z_0)$, is emitted in the NIR to FIR regime as a thermal emission, with the assumed SED taken from the appropriate IR template at $z_0$, as explained above. The $E_{\text{abs}}(z_0)$ is given by

$$E_{\text{abs}}(z_0) = \int_0^{\infty} dv \left[ 1 - \frac{C_v(z_0)}{z_0} \int_{z_0}^{\infty} \text{SFRD}(z) L_{\text{TIR}}(t_0(z), z) dz \right] (11)$$

Note that the range of wavelengths used to define $L_{\text{TIR}}$ is different in Rieke et al. (2009) (5–1000 $\mu$m) and Gruppioni et al. (2013) (8–1000 $\mu$m). We take this into account and scale the Rieke et al. (2009) templates with the definition of Gruppioni et al. (2013), which we use for IR emission from galaxies.

| Reference         | Technique | Redshift Range | Plotting Symbols |
|-------------------|-----------|----------------|------------------|
| Shim et al. (2009)| H-α      | 0.7–1.9        | cyan diamond     |
| Tadaki et al. (2011)| H-α | 2.2           | red diamond      |
| Sobral et al. (2013)| H-α | 0.4–2.3       | green diamond    |
| Ly et al. (2011)  | H-α      | 0.8           | orange diamond   |
| Condon et al. (2002) | 1.4 GHz | 0.02         | cyan squares     |
| Smolčič et al. (2009) | 1.4 GHz | 0.1–1.3         | red and orange squares |
| Rajopakam et al. (2010) | FIR | 0–1.3         | blue circles     |
| Burgarella et al. (2013) | FIR | 0–4           | red circles      |
where $C_r(z_0) = 10^{-0.4 \mu m(z_0)}$ and $t_F$ and $t_I$ are the frequencies corresponding to 0.992 and 10 $\mu m$. Photons in this wavelength range heat the interstellar dust effectively. Hard photons at $\lambda < 0.992 \mu m$ are mainly photoabsorbed by the interstellar hydrogen and helium. We assume that $E_{abs}(z_0)$ is emitted at the same time in IR from 5 to 1000 $\mu m$. We scale the IR template with total IR luminosity, $L_{IR}(z_0)$, to match the value of $E_{abs}(z_0)$ in between wavelengths from 5 to 1000 $\mu m$. Then we do a power law extrapolation to this scaled IR template at $\lambda < 5 \mu m$. We use a second-degree polynomial to smoothly connect the NIR part of the SED with the IR part of the extrapolated template at the connecting points.\footnote{The connecting points are usually in between 2 to 4 $\mu m$.} Note that here we assume the efficiency of dust to re-emitting in the NIR to FIR wavelengths is 100%.

In Figure 9, we show the emissivity of galaxies from the UV to FIR at $z = 0$ for the different extinction curves assumed. As expected, apart from the 2175 Å absorption feature the emissivity up to $\lambda = 0.8 \mu m$ is quite the same for all models. However, from the NIR to FIR wavelengths the emissivity is different for different models. This is because the absorbed energy by the interstellar dust depends on the extinction curve and the $A_{FUV}$. In Figure 9, we also show the local emissivity from different surveys and at different wavelengths, such as in the optical from SDSS by Montero-Dorta & Prada (2009); in the NIR wavelength from the 2MASS and 6dF by Jones et al. (2006); in the IR to FIR from surveys such as Infrared Space Observatory (ISO) FIRBACK, IRAS, and SCUBA by Soifer & Neugebauer (1991), Takeuchi et al. (2006), and Serjeant & Harrison (2005); and at 8 $\mu m$ from the Spitzer Space Telescope survey by Huang et al. (2007). Our predicted local emissivity from the NIR to FIR ($\lambda > 2 \mu m$) range in the case of the “mw” and “cal” models gives higher intensity by a factor of 2 than the local emissivity measurements from these different surveys. Our local emissivity for the “lmc” and “smc” models is marginally higher and lower from these measurements, respectively. Our “lmc2” model gives a local emissivity that is in very good agreement with these measurements.

In principle, dust can be assumed to have lower efficiency to re-emit. In that case, the models that give higher IR emissivity can be scaled down to reproduce the measurements. However, there is no room for scaling up the IR emission from the models that give lower IR emissivity. Therefore, the “smc” model cannot be scaled up to match the local emissivity measurements.

We use the emissivity of galaxies from the UV to FIR range obtained here to calculate the EBL, which is discussed in detail in the following section.

### 6. EBL Calculation

We solve the cosmological radiative transfer equation (Equation (2)) numerically to compute the EBL. In this equation the source term, $\epsilon_s$, is the sum of the QSO and galaxy emissivities. We take the QSO emissivity, $\epsilon_{s,Q}(z)$, and the SED as given in Section 2. We use the galaxy emissivity from the combinations of the SFRD($z$) and $A_{FUV}(z)$ for different dust extinction curves and corresponding dust emission, as described in the previous sections. In the following sections, we compare our estimated EBL from the UV to FIR regime with the direct measurements of the local EBL and other estimates of the EBL reported in the literature.

#### 6.1. Local EBL

First, we compute the EBL at $z = 0$ for our five different models, which are plotted in Figure 10. Apart from the wavelengths near the 2175 Å absorption, different EBLs are quite indistinguishable from each other for $\lambda < 0.8 \mu m$. As expected, we see a clear difference appearing at higher wavelengths between different models. Apart from the extinction curves, the difference is also because of the differences in the $A_{FUV}$ values for the different models (see Figure 6). Therefore, even though the estimated EBL in the UV and optical parts are similar (because of the way we determine SFRD and $A_{FUV}$), there are clear differences in the IR wavelengths where the dust re-emission is important.

The shaded area in Figure 10 represents the range of the allowed EBL intensity determined by the local EBL observations. The data used in Figure 10 are taken from the compilation of Dwek & Krennrich (2013, see their Figure 7). The lower limits are determined by the intensity of the integrated galaxy light (IGL). The IGL is obtained by adding the light emitted by resolved galaxies in deep surveys. In principle, the IGL should converge to the total EBL at $z = 0$. However, because of the problem in the convergence of number counts and sensitivity of the surveys to resolve fainter galaxies, the IGL gives a lower limit to the EBL. Here, we use the IGL measurements in the UV from GALEX, in the optical from HST, and in the IR from Spitzer, ISO, and Herschel (Totani et al. 2001; Fazio et al. 2004; Xu et al. 2005; Levenson et al. 2007; Béthermin et al. 2010; Berta et al. 2010). The upper limits on the local EBL come from the direct measurements of the EBL. An important uncertainty in the direct measurements is the removal of strong foreground zodiacal light caused by the interplanetary dust and the stellar emission from the MW.
consistent with different independent measurements. The shaded region by Zemcov et al. (2014) represents the range of the allowed EBL intensity from observations. The lower limits of the EBL where we use the emissivity consistent with the observed multiwavelength galaxy luminosity functions. The “lmc2” model, which also provides $A_{\text{FUV}}(z)$ and $\text{SFRD}(z)$ consistent with different independent measurements, produces the IR background ($1 < \lambda < 100 \mu m$) consistent with the lower limits, whereas other models produce slightly higher background intensity but are well within the allowed range and closer to the lower limits. In the FIR regime ($\lambda > 100 \mu m$), the estimated background for the “lmc2” and “lmc” models goes through the observed points. The EBL for the “mw” and “cal” models is just consistent or slightly higher than the observed upper limits at $\lambda > 100 \mu m$. In summary, the available local EBL measurements in the NIR to FIR regime do not support the average dust extinction observed in the case of SMC. However, these measurements cannot discriminate between the EBL obtained with other extinction curves.

Recently, using the rocket-borne instrument Cosmic Infrared Background Experiment, Zemcov et al. (2014) measured the fluctuation amplitude of the IR background at 1.1 and 3.6 $\mu m$. One of the plausible explanations for the large fluctuation found at these wavelengths is that it arises from the intrahalo light (IHL) produced by the tidally striped old stars in the halos of the galaxy (Cooray et al. 2004; Thacker et al. 2014). Using these fluctuations measured over large scales, Zemcov et al. (2014) give the model-dependent total EBL contributed by IHL. In Figure 10, we show their computed values of the total EBL, which is a sum of their estimated IHL and the compiled measurements of IGL by Franceschini et al. (2008). As expected, because we do not include the additional contributions such as the IHL in our emissivities, we find that our estimated EBL for all models is lower than predicted by Zemcov et al. (2014). Except for the “smc” model, the EBL obtained for all other models at $\lambda \leq 2.4 \mu m$ are within $2\sigma$ lower than the total EBL predicted by Zemcov et al. (2014). We find that only for the “smc” model is it more than $2.5\sigma$ lower at all wavelengths. At $\lambda \geq 3.6 \mu m$ our “lmc,” “mw,” and “cal” models match with the EBL predicted by Zemcov et al. (2014) within $1\sigma$. In light of these recent developments, it will be interesting to consider the IHL contribution to IR, the signal arising from the epoch of reionization (Cooray et al. 2004; Kashlinsky et al. 2004) and the FIR light from dusty galaxies (Amblard et al. 2010; Thacker et al. 2013; Viero et al. 2013), which we will attempt in the near future.

From the very good agreement with the local emissivity (see Figure 9) and with different independent measurements of the $A_{\text{FUV}}(z)$ and $\text{SFRD}(z)$ (see Figures 6 and 7), for the EBL calculations we prefer our “lmc2” model over other models.

### 6.2. High-$z$ EBL

In Figure 11, we plot the EBL at redshifts 0, 0.5, 1, and 1.5 for our preferred “lmc2” model. We also show the range covered by the high and low “lmc2” model by a gray shaded region and the range covered by all five median models by a vertical striped region. The fact that we made sure the $\text{SFRD}(z)$
and $A_{FUV}(z)$ determined for different extinction curves should give the same observed emissivity has resulted in the narrow spread in the striped region for $l < 3 \mu m$, especially at high redshifts. For comparison, in Figure 11, we also show the previous estimates of the EBL reported in the literature (Franceschini et al. 2008; Finke et al. 2010; Kneiske & Dole 2010; Domínguez et al. 2011; Gilmore et al. 2012; Helgason & Kashlinsky 2012; Inoue et al. 2013; Scully et al. 2014, HM12). Below we compare our EBL predictions with the previous EBL estimates that use observational data such as galaxy number counts and galaxy luminosity functions to obtain the EBL directly.

Helgason & Kashlinsky (2012) and Stecker et al. (2012) reconstructed the EBL using the multiwavelength and multi-epoch luminosity functions. We also use a similar compilation of the luminosity functions but up to the K band. Therefore, our EBL matches very well with the EBL predictions of Helgason & Kashlinsky (2012) up to $\lambda \sim 3 \mu m$, as shown in Figure 11. For $\lambda > 3 \mu m$, Helgason & Kashlinsky (2012) predicts a higher EBL intensity than do we. The EBL model of Scully et al. (2014) extends the model of Stecker et al. (2012) up to $5 \mu m$ and provides $1\sigma$ upper and lower limits on the EBL as well as $\gamma$. Our EBL predictions are consistent with their lower and upper limit EBL for $\lambda > 1 \mu m$. The EBL estimated by Domínguez et al. (2011) is based on the observed K-band luminosity function with the galaxy SEDs based on the multiwavelength observations from the SWIRE library. For $z < 1$ and $\lambda < 3 \mu m$, our EBL is consistent with the predictions of Domínguez et al. (2011), which show slightly lower EBL intensities in the UV and slightly higher EBL intensities in the NIR. At high $z$ this difference is more prominent. Franceschini et al. (2008) used different multi-wavelength survey data, which include the luminosity functions, number counts, and the redshift distribution of different galaxy types, and the relevant data are fitted and interpolated to obtain the EBL. Our estimated EBL matches well with the EBL of Franceschini et al. (2008) up to the NIR wavelengths. At $z > 1$, in the UV regime their EBL gives a factor of $\sim 1.5$ lower intensity than our EBL. However, in the FIR wavelengths, our EBL gives around a factor of $\sim 2$ smaller EBL intensity as compared to the EBL of Franceschini et al. (2008) and Domínguez et al. (2011). In summary, as expected, our EBL at $\lambda < 3 \mu m$ is consistent with the models that use direct observations to obtain the EBL but gives a lower EBL in the NIR to FIR regime. Below we mention some of the general trends in different EBL estimates that can be seen from Figure 11.
Given that there are more observations of the EBL as well as the luminosity functions of galaxies in the local universe, almost all the different independent models including our “lmc2” model converge very well, span narrower range at $z = 0$ in the UV to NIR regime, and pass through observed lower limits of EBL. However, at the NIR and FIR wavelengths the spread between different estimates is relatively higher. All the EBL estimates differ from each other at high $z$ and the difference is as high as a factor of ~4. Our local EBL passes very well through the lower limit EBL data compiled by Kneiske & Dole (2010). Most of the EBL models for $0.4 < \lambda < 2 \mu m$ give similar intensity up to $z < 1.5$.

Our local EBL is very much similar to the estimates of HM12. However, at higher $z$, the UV background ($\lambda < 0.4 \mu m$) intensity of HM12 is higher than our EBL. This will have implications on the values of the escape fraction for H-ionizing photons, which indirectly plays an important role in interpreting the He II Lyman-α effective optical depth measurements near the epoch of helium reionization (see Khaire & Srianand 2013).

Having obtained the EBL at different $z$ from UV to FIR, we calculate its effect on the transmission of high-energy γ-rays through the IGM and compare it with the different observations in the following section.

7. GAMMA-RAY ATTENUATION

Two photons with sufficient energy upon collision can annihilate into an electron–positron pair. The condition on the energies of photons ($E_1$ and $E_2$) for this process of pair production is given by

$$\sqrt{2E_1E_2(1 - \cos \theta)} > 2m_e c^2,$$  \hspace{1cm} (12)

where $\theta$ is the collision angle, $m_e$ is the mass of the electron, and $c$ is the speed of light. Thus γ-rays with an energy $E_\gamma$ can annihilate themselves with the background extragalactic photons having energy greater than a threshold energy $E_{th}$.

$$E_{th} = \frac{2m_e^2 c^4}{E_\gamma(1 - \cos \theta)}.$$  \hspace{1cm} (13)

The cross-section for this process is

$$\sigma(E_1, E_2, \theta) = \frac{3\sigma_f}{16} \left(1 - \beta^2\right)$$

$$\times \left[2\beta\left(\beta^2 - 2\right) + \left(3 - \beta^4\right) \ln \left(\frac{1 + \beta}{1 - \beta}\right) \right].$$  \hspace{1cm} (14)

where

$$\beta = \sqrt{1 - \frac{2m_e^2 c^4}{E_1E_2(1 - \cos \theta)}},$$

and $\sigma_f$ is the Thompson-scattering cross-section. The pair production cross-section given in Equation (14) has a maximum value $\sigma(E_1, E_2, \theta)_{\text{max}} = 0.25 \sigma_f$ and the corresponding value of $\beta = 0.7$.

If the number density of the background photons at redshift $z$ and energy $E_{bg}$ is $n(E_{bg}, z)$ (from Equation (1)), then as a result of pair production the optical depth encountered by the γ-ray photons emitted at redshift $z_0$ and observed at energy $E_\gamma$ on the Earth (i.e., $z = 0$) is given by

$$\tau_\gamma(E_\gamma, z_0) = \frac{1}{2} \int_0^{C_{\text{th}}} dz \frac{dl}{dz} \int_{E_{\text{min}}}^{\infty} dE_{bg} n(E_{bg}, z)$$

$$\times \sigma(E_\gamma(1 + z), E_{bg}, \theta).$$  \hspace{1cm} (15)

Here,

$$E_{\text{min}} = E_{th}(1 + z)^{-1} = \frac{2m_e^2 c^4}{E_\gamma(1 + z)(1 - \cos \theta)}.$$  \hspace{1cm} (16)

The above equation in terms of the maximum wavelength of the EBL, which is going to attenuate observed γ-rays of energy $E_\gamma$, can be simplified as

$$\lambda_{\text{max}}(z) = \frac{23.74 E_\gamma(1 + z)(1 - \cos \theta)}{E_\gamma},$$

where $E_\gamma$ is in GeV. The cross-section for the pair production will be maximum at $\lambda(z) = 12.06 E_\gamma(1 + z)(1 - \cos \theta)$.

The specific number density of the EBL photons is directly related to the optical depth $\tau_\gamma$ encountered by γ-rays while traveling through the IGM as explained above. For the EBL estimated here, we calculate $\tau_\gamma$ using Equation (15) over an energy range from GeV to TeV. In the following subsection, we compare our calculated of $\tau_\gamma$ with those obtained using different EBL estimates reported in the literature.

7.1. The γ-ray Opacity at Different $z$

The optical depth encountered by γ-rays while traveling from the emission redshifts $z_0$ to Earth (i.e., $z = 0$) and observed at γ-ray energies from the GeV to TeV range is plotted in Figure 12 for different emission redshifts. We plot $\tau_\gamma$ calculated for our median “lmc2” model along with the $\tau_\gamma$ for its low and high counterparts in a dark gray shaded region. We also show the range of $\tau_\gamma$ covered by all five median models by a light gray shaded region. The extent of the light gray shaded region for different $z$ up to the γ-ray energy of 0.6 TeV shows that the $\tau_\gamma$ is indistinguishable for all five EBL models. This is because the maximum effective wavelength of the EBL photons that interact with γ-rays of energy less than 0.6 TeV is less than 3 μm where, by construct, our different EBL models predict similar intensities (see Figure 11). The spread of the shaded region for γ-ray energy >0.6 TeV points to the fact that our EBL intensity at FIR wavelengths is different for different models.

For comparison, in Figure 12, we also plot the $\tau_\gamma$ obtained by other estimates of EBL given in the literature. To clearly show the differences between $\tau_\gamma$ calculated for other EBL estimates and for our “lmc2” EBL model, we plot the ratio of the former to the latter in the bottom panel of Figure 12. Differences in the $\tau_\gamma$ obtained for various EBL estimates can be directly understood from the differences in the EBLs, as shown in Figure 11. Here, we mention some of the general trends seen in the various $\tau_\gamma$ estimates and then compare our $\tau_\gamma$ with the models that used direct observations of galaxy properties to construct the EBL.

The difference between the $\tau_\gamma$ at energies from GeV to TeV for various EBL estimates increases with $z$. The difference is more in the TeV energy range where the EBL photons that effectively attenuate the γ-rays are from the FIR part of the
EBL: the large scatter in different EBL estimates in the FIR wavelengths (see Figure 11) is responsible for that. However, for the observationally relevant γ-rays, which are the ones with 0.1 < τ < 2 in the corresponding energy range, the differences between τi estimates are quite small. The difference in τi for γ-ray energies from 0.1 to 3 TeV is small and within 30% for various estimates for emission redshifts z < 1.5. In general, our EBL gives lower τi compared to most of the other estimates. The τi obtained for the lower limit EBL of Scully et al. (2014) at z = 0.01 is a factor of ~2 higher at Eγ < 0.2 TeV. The τi obtained for the EBL by Inoue et al. (2013) at z ≥ 1 is within 10% of our estimate at 0.2 < Eγ < 40 TeV. However, note that the τi at Eγ > 10 TeV in our model is quite small because we do not consider the CMBR in our EBL model (see Stecker et al. 2006). The τi in the energy range 0.05 < Eγ < 2 TeV estimated by Helgason & Kashlinsky (2012) up to 25 μm is within 15% of our τi. The τi calculated using the EBL generated by Franceschini et al. (2008) and Domínguez et al. (2011) for 0.1 < Eγ < 4 TeV is within 30% of our τi. However, at high energies, τi differs more from this, which is evident from the differences in the FIR part of the EBL inbetween their models and our “lmc2” model (see Figure 11).

7.2. The γ-ray Horizon

The γ-ray horizon is defined as the maximum redshift of the γ-ray source that can be detected through γ-rays of the observed energy, Eγ, with τi ≤ 1. This is nothing but the γ-ray source redshift z0 for γ-rays of the observed energy, Eγ, on Earth corresponding to τi (Eγ, z0) = 1. In Figure 13, we plot the γ-ray horizon for different source redshifts for our different EBL models where the gray shaded area shows the range spanned by the high and low “lmc2” model.

It can be directly seen from Figure 13 that our universe is transparent for the γ-rays with energies less than 10 GeV. The γ-rays with energy Eγ < 30 GeV can be observed from sources at z ∼ 3 without significant attenuation. Due to the differences in the IR part of the EBL, the γ-ray horizon redshift for our models differs in TeV energies. The well-measured τi at TeV energies at low z can, in principle, distinguish between the different EBL models presented here.

In Figure 13, we also plot the measurements of the γ-ray horizon by Domínguez et al. (2013) where they model the multiwavelength observations of blazars to determine the γ-ray horizon, which is EBL-independent. Apart from the “smc” model, all of our other models show good agreement with these γ-ray horizon measurements. This is evident from the χ^2 statistics. The reduced χ^2 values are 13.1, 1.7, 0.5, 0.4, and 0.4 for our “smc,” “lmc2,” “lmc,” “mw,” and “cal” models, respectively. This indicates that for the “smc” model, the predicted NIR to FIR part of the EBL intensity is less and inconsistent with the available γ-ray horizon measurements.

Note that the reduced χ^2 quoted above includes only observational and systematic errors. We notice that even when we allow for the EBL obtained using high and low models for
“smc,” it does not give γ-ray horizon consistent with the measurements. If we include the average deviation in the γ-ray horizon in the case of the “lmc2” model, due to its higher and lower limits of the EBL obtained by using the high and low models as the errors in the prediction of the γ-ray horizon, the reduced χ² for “lmc2” becomes 0.92. It is evident from Figure 13 that, even though we could rule out the “smc” model, purely based on the available γ-ray horizon measurements alone, we cannot distinguish between the other four models. Given the uncertainties involved in modeling the intrinsic SEDs of the γ-ray sources, the contribution of IHL to the galaxy emissivity in the NIR, and the small spread of the γ-ray horizon predicted in our remaining four models, it may be challenging to distinguish them based on more such measurements.

7.3. Fermi Measurements of τ

Recently, Ackermann et al. (2012) reported the average measurements of τ in a large redshift range using a sample of 150 blazars observed with the *Fermi*-LAT. Because it is difficult to determine τ in an individual blazar spectrum, they divided their blazar sample into three redshift bins, z < 0.2, 0.2 < z < 0.5 and 0.5 < z < 1.6. Then they stacked spectra in each redshift bin and determined the intrinsic SED of blazars by extrapolating the stacked spectrum from the lower energies where various EBL estimates suggest that τ is negligible. Using these stacked spectra, Ackermann et al. (2012) reported the measurements of τ for the observed γ-ray energies from 10 to 500 GeV in the redshift range of 0 < z ≤ 1.6. Based on the good agreement between the EBL measured by *Fermi* and that expected from the lower limits determined from the IGL measurements, they argued that there is negligible room for residual emission from other sources. The γ-rays in this observed energy range from 10 to 500 GeV will be attenuated effectively by the EBL photons of the rest wavelength, λ < 3.1 μm for z < 1.6, λ < 1.8 μm for z < 0.5, and λ < 1.4 μm for z < 0.2, where the cross-section of pair production is maximum (at θ = π). This is the wavelength range where, by construct, all five of our models give similar EBL.

For comparison with the measurements of Ackermann et al. (2012), we calculate τ in a way that mimics stacking of individual blazar spectra as done by them. We take the number distribution of blazars as a function of redshift for the 150 blazars used by Ackermann et al. (2012) and calculate e⁻τ for each blazar at a corresponding z and at different energies, Eγ. Then we take the average of e⁻τ over the same number of blazars in the redshift bins. This average is equivalent of obtaining e⁻τ by stacking the individual blazar spectrum in a redshift bin. In Figure 14, we plot our estimates of the γ-ray optical depth, along with the measurements of Ackermann et al. (2012), in terms of the transmission, e⁻τ, for our “lmc2” EBL model. The range in e⁻τ covered by all five EBL models with their high and low counterparts is shown by the gray shaded region in Figure 14. For all of our EBL models, the e⁻τ fits well in low (z ≤ 0.2) and high (0.5 < z ≤ 1.6) redshift bins. However, in the intermediate redshifts, our estimated τ is slightly higher than that reported in Ackermann et al. (2012). This excess optical depth is not statistically significant, given the large uncertainties in the measurements of τ. However, if these measurements are indeed very accurate, then to account for this we need the EBL intensity to be a factor of 2 lower than
predicted by our models at $z < 0.5$ in the optical to NIR regime. This requires a factor of 2 reduction in $\rho_\star$ at $\lambda < 1.8\,\mu$m for $z < 0.5$. One can, in principle, reduce the $\rho_\star$ by increasing $L_{\text{min}}$ (in Equation (5)). However, how much $\rho_\star$ can be reduced depends upon the $\alpha$ and the luminosity of the faintest galaxy detected to determine the luminosity functions. It can be seen from Table 5 that the values of $\alpha$ at $z < 0.5$ are high, and therefore to reduce $\rho_\star$ by a factor of 2 one needs to take $L_{\text{min}} > 0.2L_\odot$. However, in this wavelength range (UV to NIR), given the fact that our EBL models are consistent with the observational lower limits on local EBL, there is not much room available to reduce the EBL intensity. This reiterates the findings of Ackermann et al. (2012) that the observed luminosity densities of galaxies are just sufficient to reproduce the $\tau_z$ measurements.

Note that to obtain intrinsic blazar spectra, the continuum extrapolation from the lower energy to higher energy is a practical solution, but may not be the valid one. Therefore, the minor discrepancy mentioned above does not conclude anything significantly. However, it will be more interesting for constraining various EBL models if the errors on $\tau_z$ are reduced significantly.

8. EFFECT OF UNCERTAINTIES ON MODEL PARAMETERS

In this paper, we use a progressive fitting method to determine the combinations of $A_{\text{FUV}}(z)$ and SFRD$(z)$ for five different extinction curves using multiwavelength multiepoch luminosity functions. We use these $A_{\text{FUV}}(z)$ and SFRD$(z)$ to obtain the IR emissivity and generate the EBL. The progressive fitting method uses the convolution integral (see Equation (7)) to obtain the $\rho_\star$. The convolution integral involves the stellar emission from the population synthesis model, which depends on the assumed input parameters such as metallicity, IMF, and age of the galaxy. In this section, we investigate the possible uncertainties arising from the scatter in these input parameters involved in the modeling as compared to that arising purely from uncertainties in the $\rho_\star$ measurements. In particular, we concentrate on the assumed $z_{\text{max}}$, which corresponds to the age of the galaxies in the convolution integral, and the metallicity.

8.1. Maximum Redshift $z_{\text{max}}$ in the Convolution

The convolution integral (Equation (7)) gives the $\rho_\star(z_0)$ by convolving the SFRD$(z)$ with the intensity output of an instantaneous burst of star formation, which has occurred at epoch $t$, corresponding to redshift $z$. The population synthesis models give the specific intensity, $I_\star(\tau)$, where $\tau$ is an age of the stellar population that goes through the starburst at $z$ and is shining at $z_0$. In the calculations discussed above we have taken the maximum redshift, $z_{\text{max}} = \infty$, which means, in principle, the $\rho_\star(z_0)$ will have the contribution from very old stars up to the ages of $t_{\text{max}}$, equal to the light travel time from the Big Bang to redshift $z = z_0$, which is less than 13.6 Gyr, depending on $z_0$. Note that the actual contribution from very old stars (age $>10$ Gyr) that went through the starburst at time $t$ is negligible because the SFRD$(z)$ at $z$ corresponding to these earlier epochs $t$ is negligible. Here, we are investigating the validity of the $z_{\text{max}} = \infty$ assumption and the effect of taking different values of $z_{\text{max}}$ (or corresponding maximum age of galaxy, $t_{\text{max}}$) on our derived quantities such as $A_{\text{FUV}}$ and SFRD$(z)$, mainly at low redshifts where the age of the universe is large. If we take sufficiently small values of $t_{\text{max}}$, a contribution from the old stellar population, which shines at the optical and NIR wavelengths, will be less. Therefore, galaxies will be bluer than one expects. It requires a large dust attenuation to make them red and match the $\rho_\star$ measurements at the NIR wavelengths. With this small $t_{\text{max}}$, if we follow the progressive fitting method described in Section 3.2, we obtain large $A_{\text{FUV}}(z)$ and hence large SFRD$(z)$ at low redshifts. This is demonstrated in the case of the "cal" and "lmc2" model in Figure 15 where we show the SFRD$(z)$ and $A_{\text{FUV}}(z)$ determined by stopping the convolution integral after a time, $t_{\text{max}} = t_0$, for different values of $t_0$, ranging from 1 to 10 Gyr. We take $t_{\text{max}}$ equal to the age of the universe when the age is smaller than $t_0$. We see similar trends for all five models, but for the sake of presentation we show results in Figure 15 only for the "cal" and "lmc2" models. It is clear from Figure 15 that the lower the value of $t_{\text{max}}$, the higher the values will be of the inferred SFRD$(z)$ and $A_{\text{FUV}}(z)$.

In Figure 15, we also plot the independent measurements shown in Figures 6 and 7. These measurements of the $A_{\text{FUV}}$ show that it increases from $z = 0$ to a peak at $z \sim 1$ and then decreases at higher $z$ (Takeuchi et al. 2005; Cucciati et al. 2012; Burgarella et al. 2013). To obtain such a shape of $A_{\text{FUV}}$, as shown in Figure 15, one needs $t_{\text{max}} > 5$ Gyr. We find that the SFRD$(z)$ and $A_{\text{FUV}}(z)$ are insensitive to $t_{\text{max}}$ when it is $\geq 10$ Gyr. Therefore, to obtain the SFRD$(z)$ and $A_{\text{FUV}}(z)$ consistent with the trend seen in different independent observations one needs to consider the stellar population ages $\geq 10$ Gyr, which is consistent with $z_{\text{max}} = \infty$ and the estimated age 11 Gyr of MW (Krauss & Chaboyer 2003).

8.2. Metallicity

Another source of possible uncertainty in determining the SFRD$(z)$ and $A_{\text{FUV}}(z)$ can be related to the redshift evolution of metallicity, which we do not consider. We use constant $Z = 0.008$ metallicity for all redshifts. HM12 and Madau & Dickinson (2014) use the metallicity evolution as $Z(z) = Z_\odot 10^{-0.15(z-2)}$, suggested by Kewley & Kobulnicky (2001), where $Z_\odot = 0.020$. This evolution gives $Z = 0.008$ at $z = 2.6$. To see the effect of using different metallicity, we determine the SFRD$(z)$ and $A_{\text{FUV}}(z)$ for metallicity $Z = 0.020$ and $Z = 0.004$. Our results are plotted in Figure 16 for the "cal" and "lmc2" models. We also show the range covered by the $A_{\text{FUV}}$ and SFRD when obtained for the respective high and low models for our fiducial metallicity, $Z = 0.008$ (the same as in Figures 6 and 7). Note that the low and high models use $1\sigma$ low and high fits through the $\rho_{\text{FUV}}$ measurements used to determine the $A_{\text{FUV}}$ and SFRD. It is clear from Figure 16 that the higher (lower) metallicity gives higher (lower) $A_{\text{FUV}}(z)$ and SFRD$(z)$. We see similar trends for all five models, but for the sake of presentation we show them only for the "cal" and "lmc2" models. The difference between the $A_{\text{FUV}}(z)$ obtained for these metallicities (as high as a factor of 5 in $Z$) is well within the allowed range of the $A_{\text{FUV}}$ and SFRD obtained using our fiducial $Z = 0.008$. This suggests that the scatter in the $A_{\text{FUV}}(z)$ and SFRD$(z)$ arising due to a change in metallicity (as high as a factor of 5) is smaller than the scatter one obtains in the $A_{\text{FUV}}(z)$ and SFRD$(z)$ due to scatter in the $\rho_{\text{FUV}}$ measurements at a constant metallicity.
The analysis presented here shows that the effect of the metallicity evolution is subdominant as compared to those arising from uncertainties in the $r_{\text{FUV}}$ measurements. Therefore, our assumption of constant metallicity is valid and compatible with the current $r_m$ measurements.

### 8.3. IMF and $L_{\min}$

In this paper, we consider the Salpeter (1955) IMF in the population synthesis model with stellar mass range from 0.1 to $100M_\odot$. Even though there are other IMFs such as Kroupa & Weidner (2003), Chabrier (2003), and Baldry & Glazebrook (2003), because most of the star formation rates reported in the literature use Salpeter IMF, we also prefer it for our work. Note that the different IMFs can change the combination of $A_{\text{FUV}}(z)$ and SFRD$(z)$, but the fact that we use the progressive fitting method to obtain these combinations will ensure that the emissivities and EBL will remain the same in the UV to NIR wavelengths (the wavelengths where we have multiwavelength, multipoch luminosity functions). However, the

**Figure 15.** The $A_{\text{FUV}}(z)$ (top panel) and SFRD$(z)$ (in units of $M_\odot \text{yr}^{-1}\text{Mpc}^{-3}$; bottom panel) for different ages of the stellar populations contributing in the convolution integral (Equation (7)) for our “cal” and “lmc2” models. The time, $t_0 < 13.6$ Gyr, is the age with our fiducial $z_{\text{max}} = \infty$ limit. Different data points plotted in the top and bottom panels are the same as in Figures 6 and 7, respectively. Legends are scattered over the entire plot.

**Figure 16.** The $A_{\text{FUV}}(z)$ (top panel) and SFRD$(z)$ (in units of $M_\odot \text{yr}^{-1}\text{Mpc}^{-3}$; bottom panel) for different metallicities, $Z = 0.004$, $Z = 0.008$ (fiducial), and $Z = 0.020$, of the stellar populations for our “cal” and “lmc2” models. The gray shaded region represents the range covered in the $A_{\text{FUV}}$ and SFRD determined using the high and low models for our fiducial $Z = 0.008$ (same as shown in Figures 6 and 7).
different IMFs, and, hence, different $A_{\text{FUV}}(z)$ and SFRD($z$) will give a different FIR emissivity and FIR part of the EBL (see, e.g., Primack et al. 2001).

The luminosity densities calculated from the observed luminosity function depend on the values of $L_{\text{min}}$ and the faint end slope, $\alpha$. For most of the $\rho_\alpha$ used here, we use $L_{\text{min}} = 0$. In Table 5 of the Appendix, we list the $\alpha$ and $L_{\text{min}}$ values used to obtain $\rho_\alpha$. We also list the percentage decrease in the $\rho_\alpha$, if we use $L_{\text{min}} = 0.01 L^*$ and $L_{\text{min}} = 0.03 L^*$, instead of the fiducial $L_{\text{min}}$ (see the columns labeled as $\Delta_1$ and $\Delta_2$ in Table 5). The difference is large for small $\alpha$ (i.e., $\alpha < -1.3$). The value $L_{\text{min}} = 0.01 L^*$ is used by HM12 in their UV background calculations. The value of $L_{\text{min}} = 0.03 L^*$ is used by Madau & Dickinson (2014) to obtain the SFRD. It can be directly seen from Table 5 that the choice of $L_{\text{min}}$, between 0 to 0.03 $L^*$ can change the $\rho_\alpha$ up to 30%. This difference is large for the $\rho_\alpha$ measurements of Tresse et al. (2007) at high $z$ and higher wavebands, where $\alpha$ is small. Because of the sensitivity limit of the survey, Tresse et al. (2007) could not determine $\alpha$ for $z > 1.2$. Therefore, at high $z$, the $\alpha$ is extrapolated from the low redshift measurements. However, note that the errors estimated on the $\rho_\alpha$ values by Tresse et al. (2007) include uncertainties arising from the different values of $\alpha$, which is larger than the difference due to the $L_{\text{min}}$ values mentioned here.

By increasing the values of $L_{\text{min}}$, we can obtain lower $\rho_\alpha$, which will give rise to the EBL with lower intensity. Because our EBL generated using the $\rho_\alpha$ with $L_{\text{min}} = 0$ passes through the lower limits on the local EBL obtained from the IGL measurements in the FUV to NIR bands (see Figure 10), we do not consider the higher values of $L_{\text{min}}$.

9. SUMMARY

In this paper, we estimate the EBL, which is consistent with the observed multiwavelength and multiepoch luminosity functions up to $z \sim 8$. To achieve that we introduce a novel method, which determines the unique combination of the dust attenuation magnitude at the FUV band, $A_{\text{FUV}}(z)$, and the SFRD($z$), for a given extinction curve. It allows us to investigate the mean extinction curve, which can be used to determine the global average quantities such as EBL, SFRD ($z$), and $A_{\text{FUV}}(z)$. The main results of our work are summarized below.

1. We introduce a “progressive fitting method,” which uses multiwavelength and multiepoch luminosity functions to determine a unique combination, $A_{\text{FUV}}(z)$ and SFRD($z$), for a given extinction curve. The combination of $A_{\text{FUV}}(z)$ and SFRD($z$), by construct, reproduces emissivity consistent with the observed luminosity functions.

2. We compiled the observed luminosity functions from the FUV to K band and up to $z \sim 8$. Using this, we determine the combinations of $A_{\text{FUV}}(z)$ and SFRD($z$) from the “progressive fitting method” for a set of well-known extinction curves observed for MW, SMC, LMC, LMC2, and for the nearby starburst galaxies given by Calzetti et al. (2000).

3. With the help of these combinations of $A_{\text{FUV}}(z)$ and SFRD($z$), for each extinction curve we calculate the average energy absorbed by the interstellar dust in the UV to NIR wavelengths. This allowed us to estimate the NIR to FIR emissivity using the principle of energy conservation and the IR emission templates of local galaxies.

4. Out of all five extinction curves, we find that the $A_{\text{FUV}}(z)$, SFRD($z$), and local emissivity obtained using the LMC2 extinction curve reproduces different independent measurements. This enables us to conclude that, out of five well-measured extinction curves for nearby galaxies, the average extinction curve, which is applicable for galaxies over a wide range of redshifts, is most likely to be similar to the LMC2 extinction curve.

5. We use the emissivity obtained for each extinction curve from the UV to IR wavelengths and calculate the EBL for each. We compare these with the different EBL estimates reported in the literature and with the lower and upper limits placed on the local EBL from various observations.

6. For the different EBLs estimated here, we calculate the optical depths, $\tau$, encountered by the high-energy $\gamma$-rays due to electron–positron pair production upon collision with the EBL photons. We compare the $\tau$ computed for our EBL with those from different EBL estimates reported in the literature and with the measurements of Ackermann et al. (2012). We also calculate the $\gamma$-ray horizon and compare it with recently reported measurements of Domínguez et al. (2013).

7. We find that the IR part of the local EBL and the corresponding $\gamma$-ray horizon in the TeV energies estimated using the SMC extinction curve are inconsistent with various measurements. However, these measurements are consistent with results obtained from all the other extinction curves.

8. We discuss the uncertainties in the $A_{\text{FUV}}(z)$, SFRD($z$), and EBL estimates related to the standard assumptions such as metallicity, faint end slope of the luminosity function, and age of the stellar population contributing to the emissivity.

We fit the $A_{\text{FUV}}(z)$ and SFRD($z$), using a functional form given in Equation (9), and the fitting parameters obtained for each extinction curve are provided in Tables 2 and 4. From the very good agreement with various measurements we conclude that the LMC2 extinction curve should be used to calculate the global averaged quantities such as the EBL, SFRD, and $A_{\text{FUV}}$. The “progressive fitting method” used here to obtain the $A_{\text{FUV}}(z)$ and SFRD($z$) requires luminosity functions observed over different wavebands and redshifts. Therefore, surveys such as Tresse et al. (2007) and Ilbert et al. (2005), which determine the luminosity functions uniformly over large redshifts and different wavebands, are very important. Currently, our method is limited by the lack of good observations in different wavebands and at high redshifts.

We wish to thank Lawrence Tresse, Kari Helgason, Peter Behroozi, Marco Ajello, Hansa Padmanabhan, Tirthankar Roy Choudhury, and Sunder Sahayananth for providing relevant data and useful discussions. We thank an anonymous referee for useful comments, which helped us to improve the paper. V. K. thanks CSIR for providing support for this work.
Figure 17. The NUV to K band comoving luminosity density calculated using the best-fit combination of SFRD(z) and A_{FUV}(z) obtained using different extinction curves k (v). For the references and plotting symbols, see Table 1. Solid, dashed, and dotted-dashed lines represent values of the best-fit $\rho_c$ calculated for the SFRD(z) obtained using the low, median, and high models, respectively. From top to bottom, the extinction curves used are Calzetti et al. (2000), Milky Way, LMC, LMC2, and SMC, respectively.
Figure 17. (Continued.)
Figure 17. (Continued.)
Table 4
Fitting Parameters for the SFRD($z$)\(^a\)

| Extinction Curve | $\rho_{\text{UV}}$ Fit\(^b\) | $a$ (10\(^{-2}\)) | $b$ (10\(^{-2}\)) | $c$ | $d$ |
|------------------|-----------------------------|-----------------|-----------------|---|---|
| SMC Low          | 1.55                        | 7.14            | 2.53            | 3.10 |
| SMC Median       | 1.38                        | 6.24            | 2.65            | 3.01 |
| SMC High         | 1.50                        | 5.12            | 3.08            | 3.09 |
| LMC2 Low         | 2.54                        | 10.9            | 2.22            | 3.07 |
| LMC2 Median      | 2.01                        | 8.48            | 2.50            | 3.09 |
| LMC2 High        | 1.67                        | 7.09            | 2.74            | 3.02 |
| Milky Way Low    | 6.27                        | 15.2            | 2.14            | 3.16 |
| Milky Way Median | 5.78                        | 11.2            | 2.28            | 3.02 |
| Milky Way High   | 5.03                        | 8.33            | 2.59            | 2.99 |
| Calzetti Low     | 4.44                        | 15.8            | 2.06            | 3.11 |
| Calzetti Median  | 3.62                        | 12.0            | 2.20            | 2.97 |
| Calzetti High    | 3.23                        | 8.78            | 2.54            | 2.97 |

Notes.
\(^a\) The fitting form is SFRD($z$) = $a + b / (1 + z/c)^d$. $M_\odot$ yr\(^{-1}\) Mpc\(^{-3}\).
\(^b\) Note that, as explained in the text, the models with low and high $\rho_{\text{UV}}$ fit need not give higher and lower SFRD($z$) than the median model for all $z$, respectively.

Table 5
Observations of the Galaxy Luminosity Function

| Reference        | Band | $z$  | $\alpha$ | $L_{\text{min}}$ (L\(^*\)) | $\Delta_1$ | $\Delta_2$ |
|------------------|------|------|----------|-----------------------------|------------|------------|
| Cucciati et al. (2012) | FUV  | 0.125 | $-1.05$ | 0 | 1 | 3 |
| Tresse et al. (2007) | FUV  | 0.14  | $-1.13$ | 0 | 1 | 4 |
| Cucciati et al. (2012) | FUV  | 0.3   | $-1.17$ | 0 | 2 | 5 |
| Schiminovich et al. (2005) | FUV  | 0.3   | $-1.19$ | 0 | 2 | 5 |
| Tresse et al. (2007) | FUV  | 0.5   | $-1.07$ | 0 | 1 | 3 |
| Schiminovich et al. (2005) | FUV  | 0.5   | $-1.6$  | 0 | 15 | 25 |
| Tresse et al. (2007) | FUV  | 0.51  | $-1.6$  | 0 | 15 | 25 |
| Tresse et al. (2007) | FUV  | 0.69  | $-1.6$  | 0 | 15 | 25 |
| Cucciati et al. (2012) | FUV  | 0.7   | $-0.9$  | 0 | 0 | 1 |
| Schiminovich et al. (2005) | FUV  | 0.7   | $-1.6$  | 0 | 15 | 25 |
| Cucciati et al. (2012) | FUV  | 0.9   | $-0.85$ | 0 | 0 | 1 |
| Tresse et al. (2007) | FUV  | 0.9   | $-1.6$  | 0 | 15 | 25 |
| Schiminovich et al. (2005) | FUV  | 1     | $-1.6$  | 0 | 15 | 25 |
| Tresse et al. (2007) | FUV  | 1.09  | $-1.6$  | 0 | 15 | 25 |
| Cucciati et al. (2012) | FUV  | 1.1   | $-0.91$ | 0 | 0 | 2 |
| Dahlen et al. (2007) | FUV  | 1.125 | $-1.48$ | 0 | 9 | 17 |
| Tresse et al. (2007) | FUV  | 1.29  | $-1.6$  | 0 | 15 | 25 |
| Cucciati et al. (2012) | FUV  | 1.45  | $-1.09$ | 0 | 1 | 4 |
| Dahlen et al. (2007) | FUV  | 1.55  | $-1.6$  | 0 | 15 | 25 |
| Schiminovich et al. (2005) | FUV  | 1.75  | $-1.48$ | 0 | 9 | 17 |
| Cucciati et al. (2012) | FUV  | 2.1   | $-1.3$  | 0 | 4 | 9 |
| Dahlen et al. (2007) | FUV  | 2.22  | $-1.48$ | 0 | 9 | 17 |
| Reddy & Steidel (2009)\(^a\) | FUV  | 2.3   | $-1.73$ | 0.01 | 0 | 15 |
| Schiminovich et al. (2005) | FUV  | 2.9   | $-1.47$ | 0 | 9 | 16 |
| Cucciati et al. (2012) | FUV  | 3     | $-1.5$  | 0 | 10 | 18 |
| Reddy & Steidel (2009)\(^a\) | FUV  | 3.05  | $-1.73$ | 0.01 | 0 | 15 |
| Bouwens et al. (2011)\(^b\) | FUV  | 3.8   | $-1.73$ | 0.01 | 0 | 15 |

(Continued)
APPENDIX
ADDITIONAL FIGURE AND TABLE

A.1 $\rho_a$ with $z$

In Figure 17, we show our estimated $\rho_a$ along with the compiled measurements for the high $z$ and all other wavebands.

A.2 $L_{\text{min}}$ with $\alpha$

Table 5 lists the faint end slopes of the luminosity functions with the rest waveband and redshift, along with the $L_{\text{min}}$ values we used to determine $\rho_a$.

REFERENCES

Ackermann, M., Ajello, M., Allafort, A., et al. 2012, Sci, 338, 1190
Amblard, A., Cooray, A., Serra, P., et al. 2010, A&A, 518, L9
Arlen, T. C., Vassiliev, V. V., Weisgarber, T., Wakely, S. P., & Yusef Shafi, S. 2012, arXiv:1210.2802
Arnouts, S., Walcher, C. J., le Fèvre, O., et al. 2007, A&A, 476, 137
Baldry, I. K., & Glazebrook, K. 2003, ApJ, 593, 258
Behroozi, P. S., Wechsler, R. H., & Conroy, C. 2013, ApJ, 770, 57
Bernstein, R. A., Freedman, W. L., & Madore, B. F. 2002, ApJ, 571, 56
Berta, S., Magnelli, B., Lutz, D., et al. 2010, A&A, 518, L30
Béthermin, M., Dole, H., Beelen, A., & Aussel, H. 2010, A&A, 512, A78
Bouwens, R. J., Illingworth, G. D., Franx, M., et al. 2009, ApJ, 705, 936
Bouwens, R. J., Illingworth, G. D., Labbe, I., et al. 2011, Natur, 469, 504
Bouwens, R. J., Illingworth, G. D., Oesch, P. A., et al. 2012, ApJ, 754, 83
Buat, V., Noll, S., Burgarella, D., et al. 2012, A&A, 545, A141
Burgarella, D., Buat, V., Gruppioni, C., et al. 2013, A&A, 554, A70
Calzetti, D., Armus, L., Bohlin, R. C., et al. 2000, ApJ, 533, 682
Calzetti, D., Kinney, A. L., & Storchi-Bergmann, T. 1994, ApJ, 429, 582
Chabrier, G. 2003, PASP, 115, 1449
Condon, J. J., Cotton, W. D., & Broderick, J. J. 2002, AJ, 124, 675
Cooray, A., Bock, J. J., Keatin, B., Lange, A. E., & Matsumoto, T. 2004, ApJ, 606, 611
Cucciati, O., Tresse, L., Ilbert, O., et al. 2012, A&A, 539, A31
Dahlen, T., Mobasher, B., Dickinson, M., et al. 2007, ApJ, 654, 172
Dahlen, T., Mobasher, B., Somerville, R. S., et al. 2005, ApJ, 631, 126
Dale, D. A., Amano, G., Engelbracht, C. W., et al. 2012, ApJ, 745, 95
