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DUST ABSORPTION AND THE COSMIC ULTRAVIOLET FLUX DENSITY

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ABSTRACT

We study the evolution of the galaxy UV luminosity density as a function of redshift in the Hubble Deep Field–North (HDF-N). We estimate the amount of energy absorbed by dust and hidden from optical observations by analyzing the HDF-N photometric data with the spectral energy distribution fitting method. According to our results, at redshifts of $1 \leq z \leq 4.5$, the global energy observed in the UV rest frame at $\lambda = 1500$ Å corresponds to only 7%–11% of the stellar energy output, the rest of it being absorbed by dust and reemitted in the far-IR. Our estimates of the comoving star formation rate density in the universe from the extinction-corrected UV emission are consistent with the recent results obtained with Submillimeter Common-User Bolometric Array (SCUBA) at faint submillimeter flux levels.

Subject headings: dust, extinction — galaxies: distances and redshifts — galaxies: evolution — methods: data analysis — techniques: photometric — ultraviolet: ISM

1. INTRODUCTION

The study of galaxy star formation rate density (SFRD) as a function of redshift is of crucial importance to exploring cosmic evolution of galaxies at different epochs and assessing the physical processes involved in galaxy formation. Ultraviolet luminosity in star-forming galaxies relates directly to the number of short-lived, high-mass stars, and this gives, in principle, a measure of the actual SFR. This simple approach has been widely used for high-redshift objects such as Lyman break galaxies, for which rest-frame UV emission can be probed at optical wavelengths (e.g., Connolly et al. 1997; Madau, Pozzetti, & Dickinson 1998; Meurer, Heckman, & Calzetti 1999; Steidel et al. 1999).

Even moderate amounts of dust, however, may significantly suppress the UV flux and, hence, the inferred SFR. A confident assessment of this effect is required in order to correctly interpret high-redshift data and recover the cosmic UV luminosity density as a function of z.

Meurer et al. (1997) and Sawicki & Yee (1998), in their analysis of spectroscopically confirmed $z > 2$ galaxies, found that dust can suppress UV luminosity by a factor of 15–20 (see also Papovich, Dickinson, & Ferguson 2001). Pettini et al. (1998) obtained a factor of about 2.5–6.3 from a sample of five Lyman break galaxies. This is close to the value of about 5 recently proposed by Meurer et al. (1999) and Steidel et al. (1999) using their U drop-out samples.

A firm appraisal of the role of dust would also improve estimates of the contribution of optically selected starburst galaxies to the submillimeter background, as detected by Submillimeter Common-User Bolometric Arrary (SCUBA; see, e.g., Adelberger & Steidel 2000; Barger, Cowie, & Richards 2000).

In this letter we will estimate the comoving luminosity density in the Hubble Deep Field–North (HDF-N; Williams et al. 1996), taking into account dust obscuration. As explained in § 2, our procedure relies on the spectral energy distribution (SED) fitting method to estimate photometric redshift and color excess for each HDF-N galaxy (see Massarotti, Iovino, & Buzzoni 2001a, hereafter Paper I). As we will see, any simplified treatment based on mean corrections for galaxy $E(B-V)$ could lead to a significant underestimate of the UV flux density (§§ 3 and 4) and the inferred cosmic SFRD, compared with the corresponding estimates from the far-IR/submillimeter spectral window (§ 5).

2. SPECTRAL ENERGY DISTRIBUTION FITTING METHOD

For our analysis we use the multicolor photometric catalog of the HDF-N as obtained by Fernández-Soto, Lanzetta, & Yahil (1999). It consists of 1067 objects observed with the *Hubble Space Telescope* (*HST*) Wide Field Planetary Camera 2 at four photometric bands—U_{300}, B_{450}, V_{606}, I_{814}—and with the Kitt Peak National Observatory Infrared Imager (IRIM) camera by Dickinson (1998) in the J, H, K infrared range.

Photometric redshifts and other properties of galaxies in the sample have been reported in Paper I and involved fitting the SED, as derived from the seven-band photometry, with different sets of reference galaxy models. The starburst models by Leitherer et al. (1999, hereafter L99) with metallicity $Z = Z_{\odot}$, $Z_{\odot}/20$ have been complemented by theoretical templates for irregular, spiral, and elliptical galaxies at old and intermediate ages according to the population synthesis codes of Buzzoni (1998; 1989, hereafter BUZ) and Bruzual & Charlot (1993, hereafter BC; we used the 1998 version code). We include in the library also simple stellar population models (by L99) to minimize confusion between dust absorption and aging effects. Further details about the best-fit procedure as well as the preliminary results of its application to the photometric redshift technique can be found in Paper I.

The Calzetti (1999) dust attenuation law has been adopted in our calculations, including grain absorption and scattering. The $E(B-V)$ parameter was assumed to vary in the range 0.0–0.4 mag [we did not consider higher values of $E(B-V)$ in

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TABLE 1
Comoving UV Luminosity Density

Redshift z	ρ_{1500}[a] Apparent	Extinction Corrected
1.0–2.0	2.1 ± 0.1	17 ± 1
2.0–3.5	2.3 ± 0.1	28 ± 3
3.5–4.5	1.0 ± 0.1	12 ± 2

[a] Flux density at 1500 Å is given in units of 10^{26} ergs s^{-1} Hz^{-1} Mpc^{-3}.

order to stay within the range of Calzetti's calibration]. Treatment of the intergalactic medium absorption as a function of redshift follows from Madau (1995) and Scott, Bechtold, & Dobrzycki (2000; see Massarotti et al. 2001b).

The match with the best-fit template models allowed us to estimate, for each HDF-N galaxy, its color excess, its apparent and intrinsic UV luminosity at 1500 Å, and the proper cosmological distance according to its photometric redshift. Spectroscopic redshift was forced in the fit whenever available.

A check on the spectroscopic sample of the HDF-N (Cohen et al. 2000) confirms that our SED fitting procedure provides a very consistent estimate of z within a relative accuracy $\Delta z/(1+z) \sim 0.04$ (see Massarotti et al. 2001b for a discussion).

3. THE COMOVING UV LUMINOSITY DENSITY

The comoving luminosity density, $\rho_{(1500)}$, was computed in the range $1 \leq z \leq 4.5$ by summing up the 1500 Å contribution from each HDF-N galaxy and adopting the $V_{\max}$ formalism according to Lilly et al. (1996). A flat universe with $H_0 = 50$ km s^{-1} Mpc^{-1}, $q_0 = 0.5$, and $\Lambda = 0.0$ was assumed, throughout, in our calculations. Note that for this redshift range the 1500 Å rest-frame emission is sampled by the deep *HST* photometry, while the 4000 Å Balmer break is still within the infrared photometric bands of the IRIM observations.

The resulting apparent UV luminosity density at 1500 Å is shown in the second column of Table 1. A plot of its evolution with redshift is displayed in the upper panel of Figure 1. The nominal error bar on $\rho_{(1500)}$ in Table 1 has been estimated by means of a Monte Carlo simulation, taking into account photometric errors of each HDF-N galaxy as reported in the original catalog. This is certainly a lower limit to our uncertainty because we are not considering statistical scatter in the galaxy number counts and the sample incompleteness. In the following analysis we tried, however, to account for all these effects following the discussion in the current literature. Results obtained with L99 + BUZ and L99 + BC models are in agreement within the uncertainties due to photometric errors.

In Figure 1 our results are compared with the 1500 Å data of Madau et al. (1998) for $z > 2$ and with those of Connolly et al. (1997), obtained at 2800 Å, for $z < 2$. The Connolly et al. data suggest a slightly higher luminosity density at lower redshifts. One should consider, however, that dust reddening is milder at 2800 Å than at 1500 Å. By repeating our calculations for the HDF-N galaxies at 2800 Å, the resulting apparent UV density raises to $\log \rho_{(2800)} = 26.48$ (in log units of ergs s^{-1} Hz^{-1} Mpc^{-3}) at $z = 1.5$, thus better matching the Connolly et al. (1997) estimates, the observed discrepancy being due to the different wavelength range used.

Our values of $\rho_{(1500)}$ are larger than those of Madau et al. (1998) because of (1) the higher efficiency of the photometric redshift technique compared to the B drop-out galaxy selection

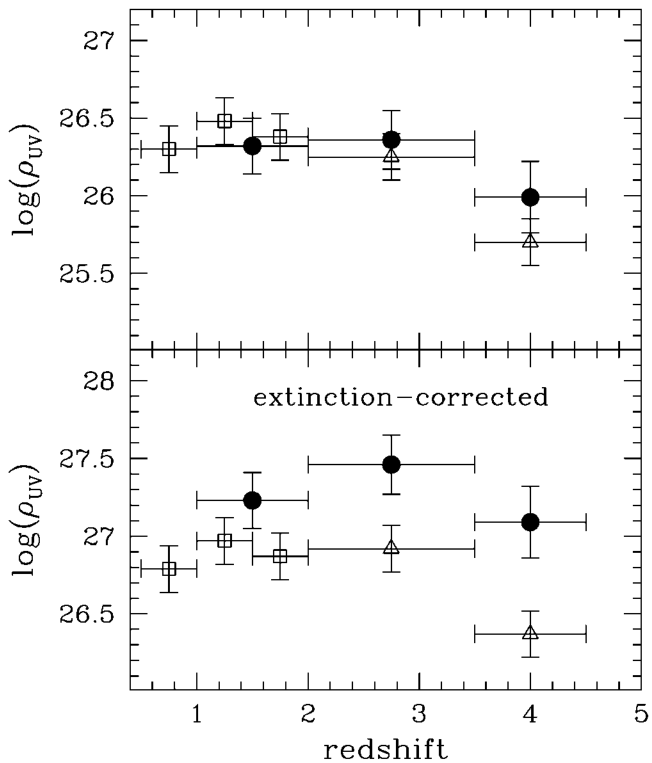

Fig. 1.—Redshift evolution of the comoving UV luminosity density (in log units of ergs s^{-1} Hz^{-1} Mpc^{-3}), as sampled by the HDF-N galaxies. The apparent value of $\rho_{(1500)}$ at 1500 Å, from the data in Table 1, is displayed in the upper panel, while its trend after correction for dust absorption is reported in the lower panel. Our results (*filled circles*) are compared with the Madau et al. (1998) 1500 Å data at $z > 2$ (*triangles*) and with the 2800 Å estimates of Connolly et al. (1997) at $z < 2$ (*squares*). Error bars on the points try to account for more realistic error estimates, including field-to-field variations (see Fontana et al. 1999) and errors induced by the unknown incompleteness of the sample studied.

(see Fontana et al. 2000) and (2) the deeper magnitude limit of the sample that we used.

It is important to stress that all data in our analysis are *not* corrected for the effect of the surface brightness dimming (Pascarelle, Lanzetta, & Fernández-Soto 1998) or for sample incompleteness in the galaxy number counts. As is widely recognized, the latter correction is still very poorly known for high-redshift data and probably exceeds a factor of 1.5–2 for faint galaxy counts beyond $z > 2$ (Buzzoni 2001; Madau et al. 1998). As our main concern is the effect of dust absorption at higher redshifts, a detailed analysis of incompleteness in the HDF-N data is beyond the scope of this letter.

4. THE EXTINCTION-CORRECTED LUMINOSITY DENSITY AT 1500 Å

The UV output changes significantly when HDF-N photometry is corrected for the galaxy color excess obtained from the SED fit. The extinction-corrected estimates of $\rho_{(1500)}$ in different redshift bins are shown in the third column of Table 1 and in the lower panel of Figure 1. Also plotted are values usually quoted in the literature, obtained by applying the Steidel et al. (1999) correction to the Connolly et al. (1997) and Madau et al. (1998) values.

The extinction-corrected values of $\rho_{(1500)}$ are noticeably larger, by a factor of about 8–14, than the apparent luminosity density we obtained by directly summing up galaxy fluxes. Quite interestingly, *the range of our 1500 Å correction factor*

TABLE 2
UV CORRECTING FACTOR FOR DUST ABSORPTION

Mean Redshift	$F(1500)$[a]	Reference
3.04	4.7	1
2.75	5.4 ± 0.9	2
2.75	12 ± 2	3

[a] The $\rho_{(1500)}$ (extinction corrected) = $\rho_{(1500)}$ (apparent) × $F(1500)$

REFERENCES.—(1) Steidel et al. 1999; (2) Meurer et al. 1999; (3) this work.

is much higher than previously assumed in the literature, as summarized in Table 2.

The reason for the striking difference from Steidel et al. (1999) does not reside in any substantial change of the input physics (Steidel et al. also used the Calzetti attenuation law to account for dust absorption) but rather in a different correction procedure, that relies on the *individual* value of $E(B-V)$ for each galaxy instead of the *mean* value over the whole sample.

To better understand this effect, consider for instance a toy sample of N galaxies, all with the same absolute luminosity but different amounts of reddening, distributed around a mean value $E(B-V)_{\rm ave} = \sum_j E(B-V)_j/N$. The mean absorption coefficient will be $A_{\rm ave} = k(\lambda)E(B-V)_{\rm ave}$, where $k(\lambda)$ is the adopted attenuation law. Following Steidel et al. (1999), the correction factor would be

$$F_{\rm ave} = 10^{0.4k\sum_j E(B-V)_j/N} = 10^{0.4kE(B-V)_{\rm ave}}, \quad (1)$$

equal for all galaxies. On the other hand, in our approach, the *individual* value of $E(B-V)$ is applied for each galaxy, and an effective correction factor can be defined for the whole sample as

$$F_{\rm eff} = \sum_j 10^{0.4kE(B-V)_j}/N = 10^{0.4kE(B-V)_{\rm eff}}. \quad (2)$$

It can be easily demonstrated that, in general, $F_{\rm eff} \geq F_{\rm ave}$ or, equivalently, that the *effective* color excess $E(B-V)_{\rm eff}$ systematically exceeds the value of $E(B-V)_{\rm ave}$.

Estimating the energy absorbed by dust using $E(B-V)_{\rm ave}$ over the whole sample instead of $E(B-V)_{\rm eff}$ can therefore result in a significant error. This point can also be verified in Figure 2, where we compute both the mean and the effective color excess for the full HDF-N sample according to the different sets of galaxy reference models. Using the L99 + BUZ template set, we obtain $E(B-V)_{\rm ave} = 0.132$, while $E(B-V)_{\rm eff} = 0.215$.

Moreover, our analysis shows that $E(B-V)$ correlates with absolute dust-corrected UV luminosity, up to the fainter magnitude levels observed (see also Meurer et al. 1999 and Adelberger & Steidel 2000 for a similar result on brighter spectroscopic samples). If high intrinsic UV luminosity starbursts have a higher dust content, the underestimate caused by using $E(B-V)_{\rm ave}$ is even larger, explaining the discrepancy with Steidel et al. (1999; see also Papovich et al. 2001).

The previous considerations suggest that while typical reddening in high-redshift objects could be low, the total amount of energy absorbed by dust can be considerable. This is because the total budget of absorbed energy is dominated by the amount of UV luminosity suppressed in highly and moderately reddened galaxies, and these are, in turn, the brightest UV galaxies of the sample.

When comparing our results with the Meurer et al. (1999) estimates of Table 2, one should keep in mind that their U drop-out selection technique is biased against heavily reddened galaxies. Choosing only those objects bluer than $(V_{606}-I_{814})_{\rm AB} = 0.5$, as in Meurer et al. (1999), will cause one to miss all the galaxies detected in I_{814} but with a color excess $E(B-V) \geq 0.32$–0.23 (at $z = 2$–3.5, respectively) and with an UV intrinsic spectral slope (i.e., in the absence of dust absorption; Meurer et al. 1999) of $\beta_0 > -2.23$. Moreover, and this is a crucial factor, since Meurer et al. 1999 assume for all starburst galaxies that $\beta_0 \sim -2.23$, the energy absorbed by dust is underestimated for objects that fit their selection criteria but possess UV intrinsic spectral slope $\beta_0 < -2.23$. Note that in the redshift range $z = 2.0$–3.5 we find for our chosen templates a median value of $\beta_0 = -2.6$.

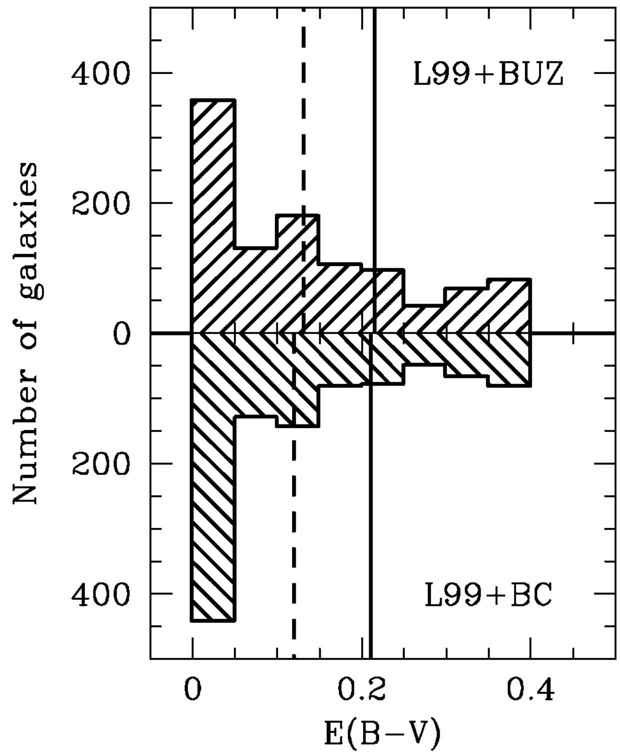

FIG. 2.—Color excess distribution of the HDF-N galaxies, according to our SED fitting comparing the output of the L99+BUZ and L99+BC reference sets of galaxy templates. The best-fit value of $E(B-V)$ for the 1067 galaxies in the sample is displayed together with the computed values of $E(B-V)_{\rm ave}$ (*dashed lines*) and $E(B-V)_{\rm eff}$ (*solid lines*), as discussed in the text.

A safe lower limit to the amount of dust absorption in the HDF-N galaxies can be computed by replacing the Calzetti attenuation law with the Small Magellanic Cloud (SMC) extinction curve (Prévot et al. 1984; Bouchet et al. 1985). This curve derives from observations of individual stars and therefore does not include the contribution of photon scatter along the line of sight. Consequently, a lower amount of dust is required to induce the same UV luminosity dimming. Repeating our calculations with the SMC extinction curve for galaxies at $\langle z\rangle = 2.75$, we obtain a value of $F_{(1500)} = 2.9$.

5. UV VERSUS FAR-IR INFERRED STAR FORMATION RATE DENSITY

A straightforward relationship exists between UV luminosity and SFR: UV-enhanced stars of high mass can be linked to the actual star formation in a galaxy once the initial mass function (IMF) for the stellar distribution is assumed. As far as the comoving luminosity density is concerned, we could therefore write

$$\rho_{\mathrm{UV}} = \alpha_{(\mathrm{IMF})} \frac{\mathrm{SFRD}}{M_{\odot}\ \mathrm{yr}^{-1}}\ \mathrm{ergs\ s^{-1}\ Hz^{-1}}, \qquad (3)$$

with α depending on the wavelength and the IMF details. Based on the BC models, at 1500 Å and for a Salpeter IMF, Madau et al. (1998) suggest $\alpha_{1500} = 8.0 \times 10^{27}$ ergs $\mathrm{s^{-1}\ Hz^{-1}}$. This is in good agreement with the corresponding calibration that depends on the Buzzoni (2001) models, which provide $\alpha_{1500} = 8.6 \times 10^{27}$ ergs $\mathrm{s^{-1}\ Hz^{-1}}$.

Optically selected galaxies in the redshift range $1 \lesssim z \lesssim 4.5$ probably give a marginal contribution to the bright source counts at far-IR/submillimeter wavelengths. Only two HDF-N galaxies from the Fernández-Soto, Lanzetta, & Yahil (1999) catalog within this redshift range might be tentatively associated to 850 μm SCUBA sources at a flux threshold of $S_{850} >$ 2 mJy (Hughes et al. 1998).

It is, however, relevant to compare the galaxy star formation history inferred from the observations in the two spectral windows in order to estimate the energy contribution of optically selected high-redshift starburst galaxies to the submillimeter background at faint flux levels $S_{850} < 2$ mJy, corresponding to ~75% of the total energy budget (Barger et al. 2000). This will give us further clues to assess, independently, the self-consistency of our galaxy evolutionary scenario.

The cosmic SFRD, as derived from the (extinction corrected) $\rho_{(1500)}$ estimates of Table 1, is displayed in Figure 3. Filled circles show our results while stars are the results of Barger et al. (2000) from SCUBA observations. The Barger et al. (2000) data have been transformed to our adopted cosmological model, and completeness corrections have been applied according to Fixsen et al. (1998).

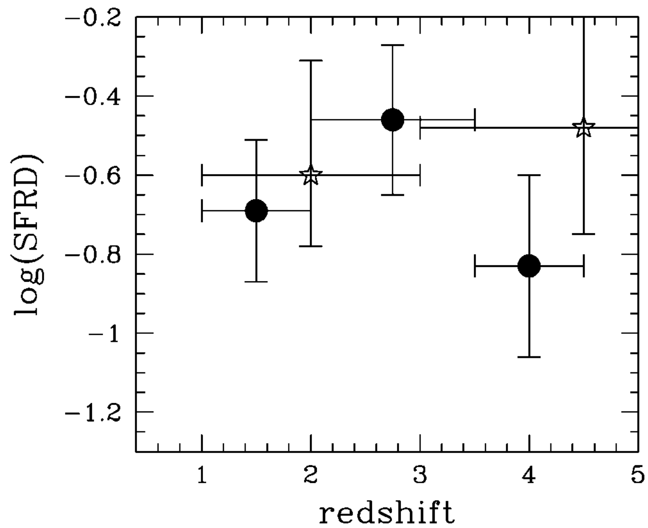

FIG. 3.—Inferred cosmic SFRD according to the evolution of the extinction-corrected comoving UV luminosity density, $\rho_{(1500)}$, from the data of Table 1 (*filled circles*). Our calibration is from eq. (3), with $\alpha_{1500} = 8.3 \times 10^{27}$ ergs $\mathrm{s^{-1}\ Hz^{-1}}$. Once accounting for dust absorption, our data from the HDF-N galaxies are consistent with the SCUBA far-IR background estimates from Barger et al. (2000) (*stars*) indicating a nondecreasing SFRD at least up to $z \sim 3$.

We stress again that owing to the HDF-N sample incompleteness, our results should certainly be taken as safe *lower* limits. Quite comfortingly, however, our new approach to dust correction of the UV data substantially improves the match with the far-IR observations, suggesting that the bulk of the far-IR energy budget at faint flux levels of $S_{850} < 2$ mJy is produced by galaxies detected in optical HST data.

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