# 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 $1 \leq z \leq 4.5$, 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 re–emitted 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 Bolometer Array (SCUBA) at faint sub–millimeter flux levels.

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

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## 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 galaxies 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, hereafter C97; Madau, Pozzetti, & Dickinson 1998, MPD98; Meurer, Heckman, & Calzetti 1999, MHC99; Steidel et al. 1999).

Even moderate amounts of dust may however 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 redshift.

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 $15 \div 20$ (see also Papovich, Dickinson, & Ferguson 2001). Pettini et al. (1998) obtained a factor about $2.5 \div 6.3$ from a sample of five Lyman-break galaxies. This is close to the value of about 5 recently proposed by MHC99 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 sub–millimeter background, as detected by Submillimeter Common-User Bolometer Array (SCUBA; see e.g., Adelberger & Steidel 2000, and Barger, Cowie, & Richards 2000, hereafter BCR00).

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 Sec. 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 (Sec. 3 and 4) and the inferred cosmic SFRD, compared with the corresponding estimates from the far–IR/submillimeter spectral window (Sec. 5).

## 2. The SED 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) WFPC2 at four photometric bands, $U_{300}$, $B_{450}$, $V_{606}$, $I_{814}$, and with the IRIM camera at KPNO 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, 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 use 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 $0.0 \div 0.4$ mag (we did not consider higher values of $E(B-V)$, in 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 $V_{\rm max}$ formalism according to Lilly et al. (1996). A flat Universe with $H_o = 50$ Km s$^{-1}$ Mpc$^{-1}$,

$q_o = 0.5$ 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 Fig. 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 Fig. 1 our results are compared with the 1500 Å data of MPD98 for $z > 2$, and with those of C97, obtained at 2800 Å for $z < 2$. The C97 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 C97 estimates, the observed discrepancy being due to the different wavelength range used.

Our values of $\rho_{(1500)}$ are larger than those of MPD98 because of: (1) the higher efficiency of the photometric-redshift technique compared to the $B$ drop-out galaxy selection (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 $1.5 \div 2$ for faint galaxy counts beyond $z > 2$ (Buzzoni 2001; MPD98). 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 Fig. 1. Also plotted are values usually quoted in the literature, obtained by applying the Steidel et al. (1999) correction to the C97 and MPD98 values.

The extinction–corrected values of $\rho_{(1500)}$ are noticeably larger, by a factor of about $8 \div 14$, than the apparent luminosity density we obtained by directly summing up galaxy fluxes. Quite interestingly *the range of our 1500 Å correction factor 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. 1999 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 $E(B-V)_{ave} = \sum_j E(B-V)_j/N$. The mean absorption coefficient will be $A_{ave} = k(\lambda)E(B-V)_{ave}$, where $k(\lambda)$ is the adopted attenuation law. Following Steidel et al. (1999), the correction factor would be:

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

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

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

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

Estimating the energy absorbed by dust using $E(B-V)_{ave}$ over the whole sample instead of $E(B-V)_{eff}$ can therefore result in a significant error.

This point can also be verified in Fig. 2, where we computed 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 $E(B-V)_{ave} = 0.132$, while $E(B-V)_{eff} = 0.215$.

Moreover, our analysis show that $E(B-V)$ correlates with absolute dust–corrected UV luminosity, up to the fainter magnitudes levels observed (see also MCH99, Adelberger & Steidel 2000 for a similar result on brighter spectroscopic samples). If high intrinsic UV luminosity starbursts have higher dust content, the underestimate caused by using $E(B-V)_{ave}$ 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 high- and moderately-reddened galaxies, and these are, in turn, the brightest UV galaxies of the sample.

When comparing our results with the MCH99 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 MCH99, will cause one to miss all the galaxies detected in $I_{814}$ but with a color excess $E(B-V)\geq 0.32 \div 0.23$ (at $z=2\div 3.5$ respectively), and with an UV intrinsic spectral slope (*i.e.* in the absence of dust absorption, MCH99) $\beta_0>-2.23$. Moreover, and this is a crucial factor, since MCH99 assume for all starburst galaxies $\beta_0\sim -2.23$, 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 $\beta_0=-2.6$.

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, and 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 $<z>=2.75$ we obtain a value of $F_{(1500)}=2.9$.

## 5. UV vs. FAR–IR inferred SFRD

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

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

with $\alpha$ depending on the wavelength and the IMF details. Based on the BC models, at 1500 Å and for a Salpeter IMF, MPD98 suggest $\alpha_{1500} = 8.0\ 10^{27}$ ergs s$^{-1}$ Hz$^{-1}$. This is in good agreement with the corresponding calibration that depends on the Buzzoni (2001) models which provide $\alpha_{1500} = 8.6\ 10^{27}$ ergs s$^{-1}$ Hz$^{-1}$.

Optically–selected galaxies in the redshift range between $1 \lesssim z \lesssim 4.5$ 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 $\mu m$ 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 sub–millimeter background at faint flux levels $S_{850} < 2$ mJy, corresponding to $\sim 75\%$ of the total energy budget (BCR00). 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 Fig. 3. Solid dots show our results while stars are BCR00 results from SCUBA observations. The BCR00 data have been transformed to our adopted cosmological model, and completeness corrections have been applied according to Fixsen et al. (1998).

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 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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Table 1. Comoving UV luminosity density

| Redshift z | $\rho_{1500}$ $^{(a)}$ apparent | extinction corrected |
|---|---|---|
| 1.0-2.0 | $2.1 \pm 0.1$ | $17 \pm 1$ |
| 2.0-3.5 | $2.3 \pm 0.1$ | $28 \pm 3$ |
| 3.5-4.5 | $1.0 \pm 0.1$ | $12 \pm 2$ |

$^{(a)}$Flux density at 1500 Å is given in unit of $10^{26}$ ergs $s^{-1}$ $Hz^{-1} Mpc^{-3}$.

Table 2. UV correcting factor for dust absorption

| Mean redshift | $F(1500)^{(a)}$ | Reference |
|---|---|---|
| 3.04 | 4.7 | Steidel et al |
| 2.75 | $5.4 \pm 0.9$ | MHC99 |
| 2.75 | $12 \pm 2$ | This work |

$^{(a)}\rho_{(1500)}$ (extinction–corrected) $=$ $\rho_{(1500)}$ (apparent) $\times F(1500)$

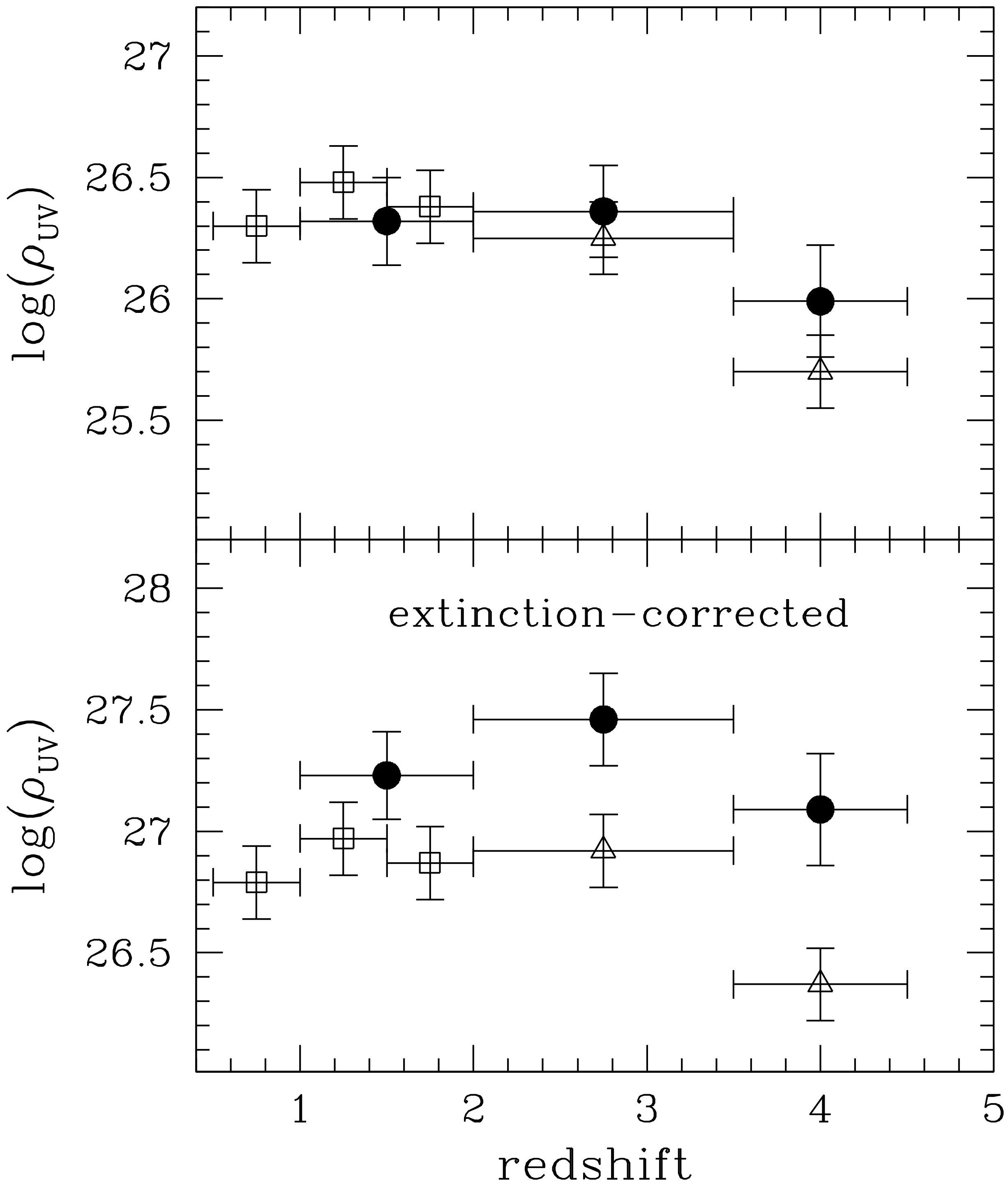


Fig. 1.— Redshift evolution of the comoving UV luminosity density (in log unit of ergs $s^{-1}$ $Hz^{-1}Mpc^{-3}$), as sampled by the HDF–N galaxies. The apparent value of $\rho_{(1500)}$ at 1500 Å, from the data in Table 1, is displayed in the upper panel, while its trend after correction for dust absorption is reported in the lower panel. Our results (solid dots) are compared with the MPD98 1500Å data at $z > 2$ (triangles), and with the 2800 Å estimates of C97 at $z < 2$ (squares). Error bars on the points try to account for a more realistic error estimates including field–to–field variations (see Fontana et al. 1999) and the errors induced by the unknown incompleteness of the sample studied.

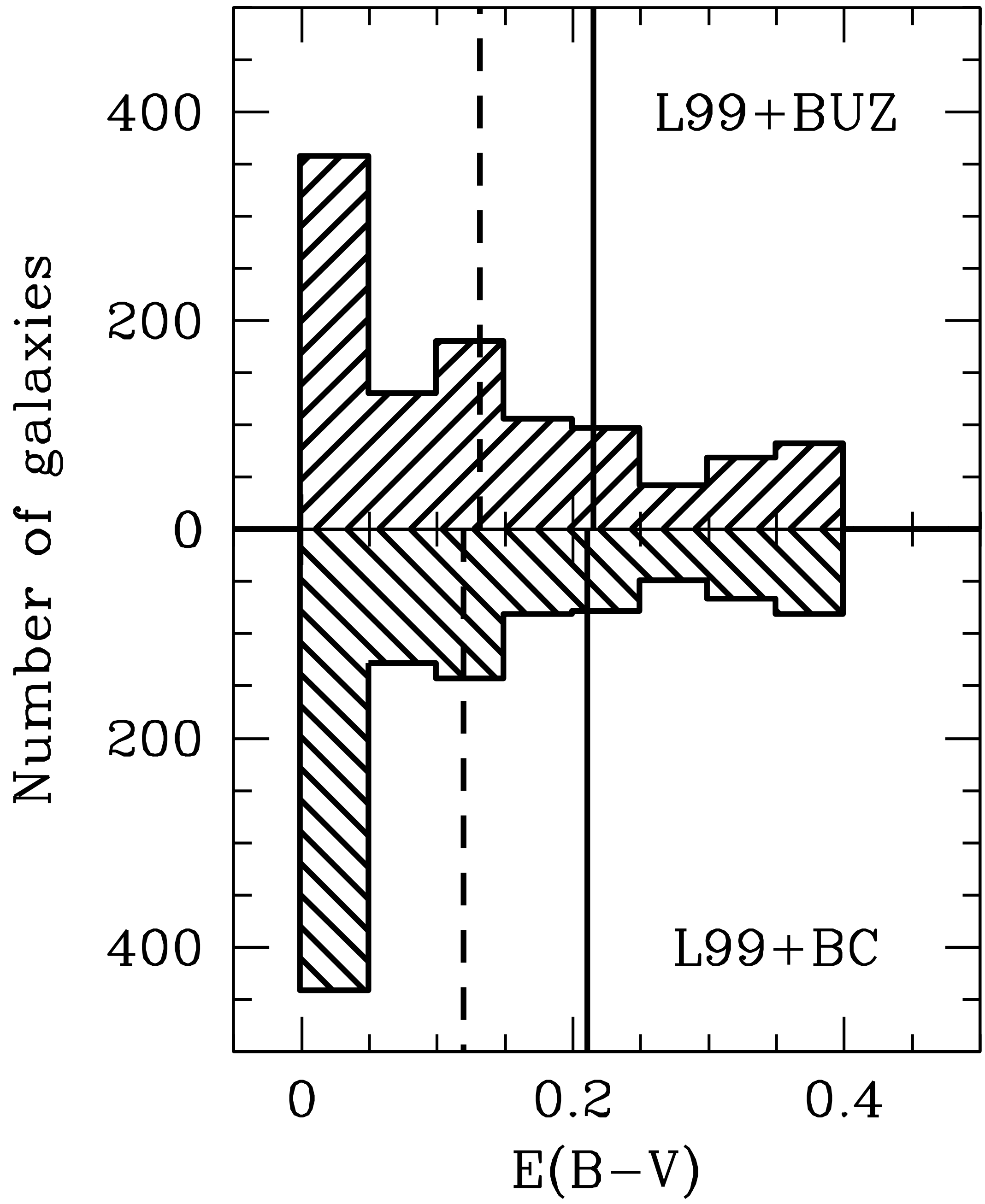


Fig. 2.— Color excess distribution of the HDF–N galaxies, according to our SED fitting comparing the output of the L99+BUZ and L99+BC reference sets of galaxy templates. The best-fit value of $E(B-V)$ for the 1067 galaxies in the sample is displayed together with the computed values of $E(B-V)_{ave}$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

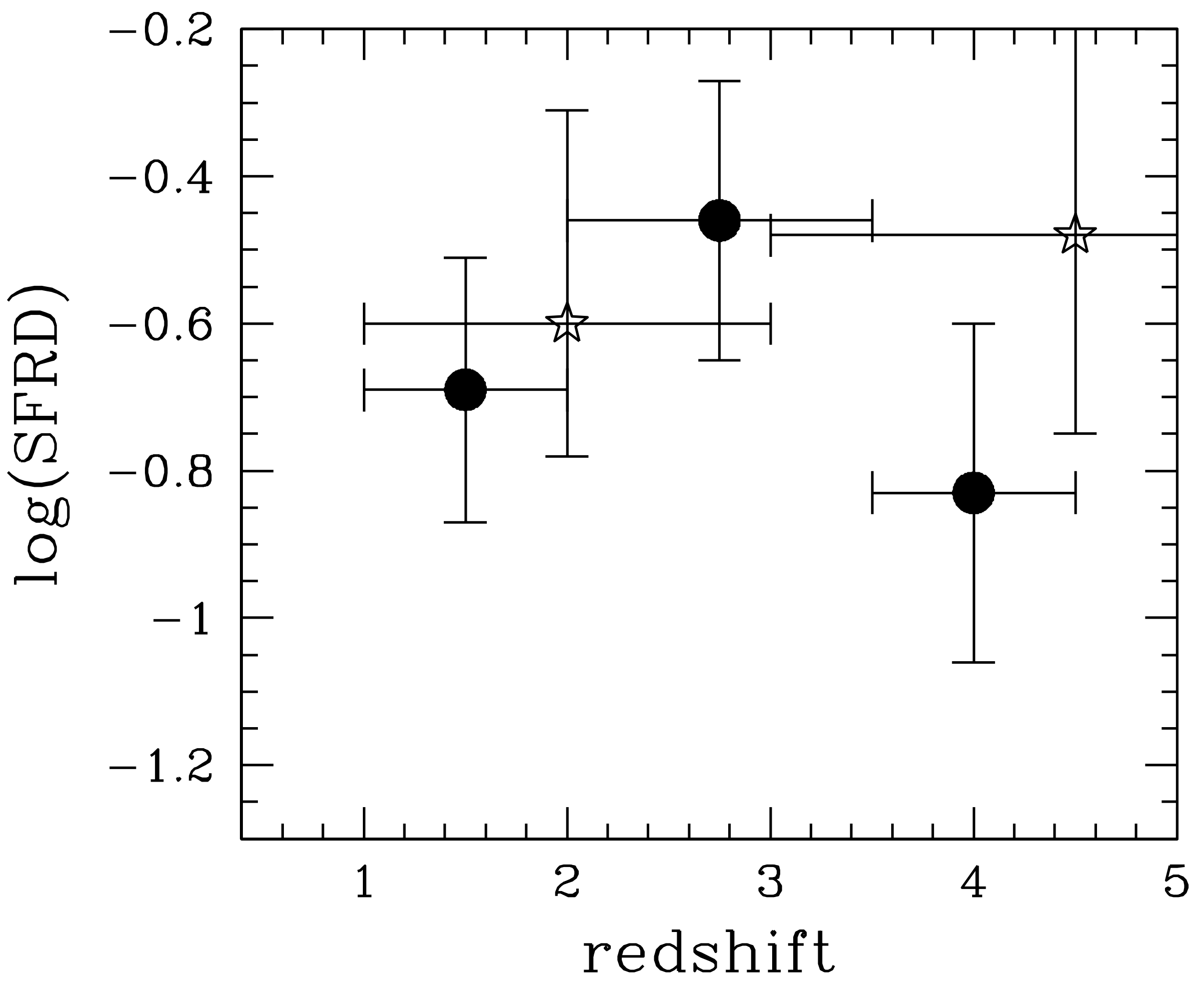


Fig. 3.— Inferred cosmic SFRD according to the evolution of the extinction–corrected comoving UV luminosity density, $\rho_{(1500)}$, from the data of Table 1 (solid dots). Our calibration is from eq. (3), with $\alpha_{1500} = 8.3\ 10^{27}$ ergs s$^{-1}$ Hz$^{-1}$. Once accounting for dust absorption, our data from the HDF–N galaxies are consistent with the SCUBA far–IR background estimates from BCR00 (stars) indicating a non-decreasing SFRD at least up to $z \sim 3$.