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THE STAR FORMATION RATE HISTORY IN THE FORS DEEP AND GOODS-SOUTH FIELDS[1]

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ABSTRACT

We measure the star formation rate (SFR) as a function of redshift z up to $z \approx 4.5$, based on B-, I-, and $(I+B)$-selected galaxy catalogs from the FORS Deep Field (FDF) and the K-selected catalog from the GOODS-South field. Distances are computed from spectroscopically calibrated photometric redshifts accurate to $\Delta z/(z_{\rm spec}+1) \leq 0.03$ for the FDF and ≤ 0.056 for the GOODS-South field. The SFRs are derived from the luminosities at 1500 Å. We find that the total SFR estimates derived from B, I, and $I+B$ catalogs agree very well ($\lesssim 0.1$ dex), while the SFR from the K catalog is lower by ≈ 0.2 dex. We show that the latter is due solely to the lower star-forming activity of K-selected intermediate- and low-luminosity ($L < L_*$) galaxies. The SFR of bright ($L > L_*$) galaxies is independent of the selection band, i.e., the same for B-, I-, $(I+B)$-, and K-selected galaxy samples. At all redshifts, luminous galaxies ($L > L_*$) contribute only approximately one-third to the total SFR. There is no evidence for significant cosmic variance between the SFRs in the FDF and in the GOODS-South field, $\lesssim 0.1$ dex, consistent with theoretical expectations. The SFRs derived here are in excellent agreement with previous measurements, provided that we assume the same faint-end slope of the luminosity function as previous works ($\alpha \sim -1.6$). However, our deep FDF data indicate a shallower slope of $\alpha = -1.07$, implying a SFR lower by ≈ 0.3 dex. We find the SFR to be roughly constant up to $z \approx 4$ and then to decline slowly beyond, if dust extinctions are assumed to be constant with redshift.

Subject headings: galaxies: evolution — galaxies: formation — galaxies: high-redshift

1. INTRODUCTION

The determination of the star formation rate (SFR) history of the universe is one of the most interesting results extracted from the deep photometric and spectroscopic surveys of the last decade. A large number of measurements have been collected, at low (the Canada-France redshift survey at $z < 1$; Lilly et al. 1996) and high redshift from the Hubble Deep Field–North (Madau et al. 1996) and from the large samples of U- and B-dropout galaxies (Steidel et al. 1999) up to the most recent determinations based on I-dropouts at redshift ≈ 6 from the Great Observatories Origins Deep Survey (GOODS), Ultra Deep Field (UDF), and UDF-Parallel Advanced Camera for Surveys (ACS) fields (Giavalisco et al. 2004a; Bunker et al. 2004; Bouwens et al. 2004). These studies show that the SFR (uncorrected for dust) increases from $z = 0$ to 1, stays approximately constant in the redshift range 1–4, and starts to decline at larger redshifts. In all the cases quoted above, the determination is based on the estimate of the total UV galaxy luminosity density, which for a given initial mass function (IMF) is proportional to the instantaneous SFR (Madau et al. 1996, 1998). As discussed by many authors (e.g., Hopkins et al. 2001), this approach is affected by the uncertainties of dust correction but roughly agrees with other estimators at low to intermediate redshifts ($z \lesssim 1$). Theoretical models of galaxy formation and evolution can be tested against the measured SFR history (Somerville et al. 2001; Hernquist & Springel 2003).

So far, all determinations of the SFR history have suffered from some major limitations. High-redshift samples have been small in number because of the limited field of view of deep pencil-beam surveys, resulting in large Poissonian fluctuations and large field-to-field variations (cosmic variance). The faint end of the luminosity function (LF) is thus far only poorly constrained at high redshifts, implying large completeness correction factors. Finally, the technique used to generate the high-redshift galaxy catalogs (dropout selection, optical magnitude–limited survey) might have introduced biases by selecting only specific types of galaxies and possibly missing relevant fractions of UV light (Ilbert et al. 2004).

Here we try to minimize these uncertainties and determine the SFR history of the universe with improved accuracy up to $z \approx 4.5$. Our sample of high-redshift galaxies is based on two deep fields, the (I- and B-selected) FORS Deep Field (FDF; Heidt et al. 2003) and the (K-selected) GOODS-South field (Giavalisco et al. 2004b). Both cover a relatively large sky area, reducing the problem of cosmic variance. Both are deep enough to allow the detection of several times 10^3 galaxies, thus minimizing the effect of shot noise.

Accurate photometric redshifts [$\Delta z/(z_{\rm spec}+1) \leq 0.03$ for the FDF and ≤ 0.056 for the GOODS-South field] with only $\approx 1\%$ catastrophic failures allow us to measure the UV LF down to fainter limits than spectroscopic samples. A detailed comparison of the UV luminosity functions of the FDF with the LF derived in large surveys was presented in Gabasch et al. (2004) and shows good agreement in the overlapping magnitude range at all redshifts. Finally and most importantly, the two fields provide us with B-, I-, and K-band–selected catalogs, making

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it possible to assess the dependence of the SFR on the detection band and galaxy colors and the associated selection biases.

The Letter is organized as follows. In § 2 we discuss the photometry and the photometric redshifts of the two fields, in § 3 we present our results on the SFR history, and in § 4 we draw our conclusions. Throughout this Letter we use AB magnitudes and adopt a concordance cosmology with $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = 70$ km s^{-1} Mpc^{-1}.

2. DATA SETS

The present results are based on photometric catalogs derived for the FDF (Heidt et al. 2003; Gabasch et al. 2004; *UBgRI*, 834 nm, zJK_s bands) and the GOODS-South fields (M. Salvato et al. 2004, in preparation; *UBVRIJHKs* bands). The two fields cover approximately the same area (39.81 arcmin^2 for FDF and 50 arcmin^2 for GOODS); the FDF reaches effective absolute magnitude limits ≈1 mag deeper than GOODS-South (see below). We use the *I*- and *B*-band selected FDF catalogs as derived in Heidt et al. (2003) and Gabasch et al. (2004). The *B*- and *I*-band selected catalogs list 5488 and 5557 bona fide galaxies (having excluded the one known bright quasar in the field) down to $B_{\rm lim} = 27.6$ and $I_{\rm lim} = 26.8$, respectively. The $I+B$ catalog obtained by merging these two contains 6756 entries. Photometric redshifts for the FDF galaxies have an accuracy of $\Delta z/(z_{\rm spec} + 1) \leq 0.03$ with only ~1% catastrophic outliers (Gabasch et al. 2004).

Our *K*-band selected catalog for the GOODS-South field is based on the eight 2.5 × 2.5 arcmin^2 *J*, *H*, K_s Very Large Telescope ISAAC images publicly available, taken with seeing in the range 0."4–0."5. The *U* and *I* images are from the GOODS/ESO Imaging Survey public survey, while *BVR* are taken from the Garching-Bonn Deep Survey. Data reduction is described in Arnouts et al. (2001) and Schirmer et al. (2003), respectively.

The data for the GOODS field were analyzed in a very similar way to the data of the FDF. The objects were detected in the *K*-band images closely following the procedure used for the FDF *I*- and *B*-band detection (Heidt et al. 2003), using both SExtractor (Bertin & Arnouts 1996) and the YODA package (Drory 2003). A detailed description of the procedure can be found in M. Salvato et al. (2004, in preparation). We detected 3367 objects in the *K* band for which we derived magnitudes (fixed aperture and total) in all bands. Number counts match the literature values down to $K \approx 25.4$, which is the completeness limit of the catalog, in agreement with the number obtained following Snigula et al. (2002). Note that much deeper ACS-based catalogs are available (Giavalisco et al. 2004b), but as we are focusing on the *K*-selection they are not relevant in this context. We computed photometric redshifts following Bender et al. (2001; R. Bender et al. 2004, in preparation) and using the same spectral energy distribution (SED) template spectra as for the FDF. The comparison with the spectroscopic redshifts of the Visible Multiobject Spectrograph team (Le Fèvre et al. 2004) and the FORS2 spectra[2] shows that the photometric redshifts have an accuracy $\Delta z/(z_{\rm spec} + 1) \leq 0.056$. Similar results are obtained when comparing with the COMBO-17 (Wolf et al. 2004) data. This is nearly a factor of 2 better than Mobasher et al. (2004) obtained using ground-based plus *Hubble Space Telescope* ACS data. Stars are identified and excluded as in Gabasch et al. (2004), as are known active galactic nuclei (Szokoly et al. 2004), leaving 3297 bona fide galaxies used in the further analysis.

Figure 1 shows the distribution of galaxies (slightly smoothed with a Gaussian kernel) in the rest frame 1500 Å absolute magnitude M_{1500} versus redshift plane, computed by integrating the best-fitting SED over the band definition (1500 ± 100 Å). The contours agree remarkably well at the bright end, showing that the number density of bright galaxies does not significantly depend on the wavelength at which they were selected (for the *B* band, this is of course only true up to $z \approx 3$). For better comparability of the FDF and GOODS-South samples at the faint end, we chose a consistent magnitude cutoff for all samples in Figure 1. This magnitude cutoff corresponds to the completeness limit of the GOODS-South sample and is about 1 mag brighter than the completeness limits of the FDF *B* and *I* samples. For the redshift bins defined by the limits 0.45, 0.81, 1.21, 1.61, 2.43, 3.01, 4.01, and 5.01, the cutoffs in M_{1500} are at −15, −16, −17, −18, −19, −20, and −20.

The M_{1500} LFs and the related parameters M_*, Φ_*, and α of the *B*-, *I*-, and $(I+B)$-selected FDF samples are almost identical. We derived consistent values for α (−1.07 ± 0.04) for all three samples considered here, similar to that described in Gabasch et al. 2004. Consistent faint-end slopes ($\alpha = -1.01 \pm 0.08$) were obtained using a brighter subset of the data set (i.e., 1 mag brighter than the 50% completeness limit). Objects that were detected in only one band and not in both are all faint and do not contribute significantly to the SFR determined from the integral over the LF. Gabasch et al. (2004) show that the steeper slope of other surveys is due largely to shallower limiting magnitudes. This is supported by an analysis of $z \sim 6$ dropouts from GOODS and the Hubble Ultra Deep Parallel Fields (Bouwens et al. 2004), where an α of −1.15 was derived. Compared to LF parameters of the optically selected samples, the M_{1500} LF of the *K*-selected sample has slightly brighter values of M_*, significantly lower values in Φ_*, and, within the

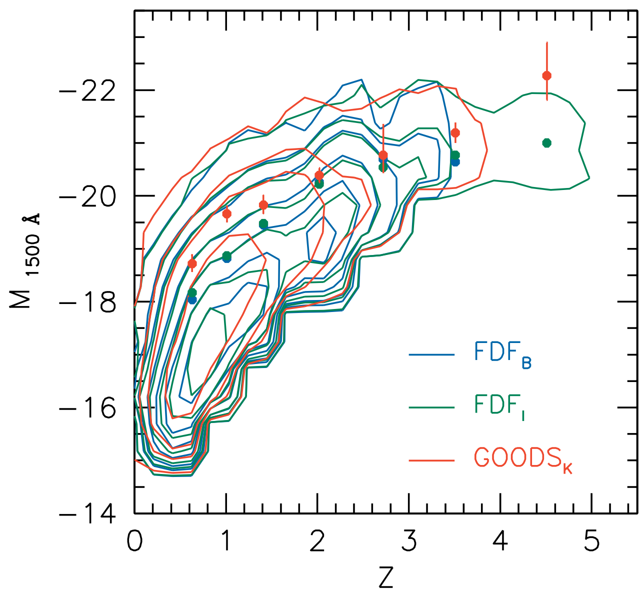

FIG. 1.—Distribution of galaxies in the rest frame, 1500 Å absolute magnitude vs. redshift space, slightly smoothed with a Gaussian kernel. The red colors refer to the *K*-selected galaxies of the GOODS-South field, and the blue and green colors refer to *B*- and *I*-selected galaxies of the FDF. The lowest contour corresponds to 0.75 galaxies arcmin^{-2} mag^{-1} per unit redshift bin; the others give the 2.5, 3.75, 6.25, 8.75, 11.25, and 13.75 galaxies arcmin^{-2} mag^{-1} per unit redshift bin density levels. For a better comparison of the FDF and GOODS-South samples at the faint end, we chose the completeness limit of the GOODS-South as the magnitude cutoff for all samples. The filled circles show the best-fit values of M_*, with the error bars of the *K* determinations (similar or smaller errors are derived in *I* and *B*).

[2] Released at http://www.eso.org/science/goods.

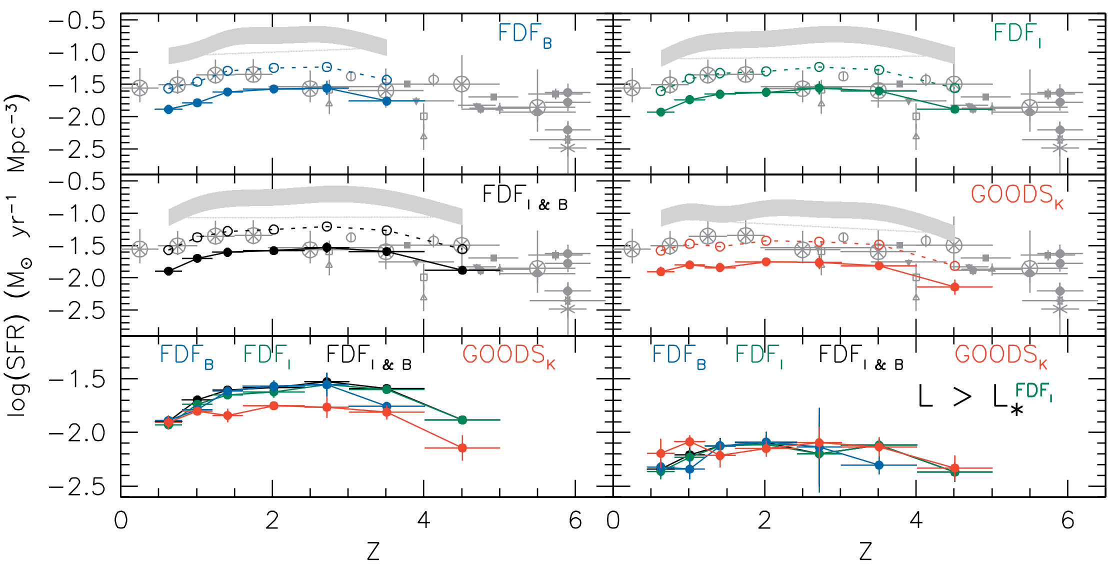

Fig. 2.—Four plots at the top show the SFR as a function of redshift derived from the 1500 Å luminosity densities computed from the *B*- (*blue*), *I*- (*green*), and (I+B)-selected (*black*) FDF and the *K*-selected (*red*) GOODS-South field. The points are connected by the thick lines for clarity. These SFRs are based on a faint-end slope of the LF of −1.07 as derived from the FDF and GOODS data. The dotted lines show the effect of assuming a slope of −1.6. The gray-shaded region shows the effect of dust corrections with correction factors between 5 and 9, following Adelberger & Steidel (2000). The gray symbols show the results (taken from the table of Somerville et al. 2001) of Pascarelle et al. (1998, *circled crosses*), Steidel et al. (1999, *open circles*), Madau et al. (1996, *open triangles*), Madau et al. (1998, *open squares*), and (taken from Bunker et al. 2004) Iwata et al. (2003, *filled triangles*), Giavalisco et al. (2004a, *filled squares*), Bouwens et al. (2003b, *filled circles*), Bouwens et al. (2004, *hexagonal crosses*), Fontana et al. (2003, *filled pentagons*), Bunker et al. (2004, *open star*), and Bouwens et al. (2003a, *inverted filled triangles*). The plots at the bottom show the SFRs of the four catalogs together (*left*) and the SFRs derived considering the contributions of the galaxies brighter than L_*^I only (*right*).

large errors, a similar faint-end slope α. Since the slightly shallower *K*-selected sample does not allow us to constrain the faint-end slope to the same level as our FDF sample (but is consistent with the faint-end slope $\alpha = -1.07$ determined for that field), we adopt this value for our *K*-selected sample. We examine the consequences of these findings for the SFR in the next section.

3. THE STAR FORMATION RATE

We compute the SFR for all four catalogs from the total luminosity densities l_{1500} in the 1500 Å band. First, we derive l_{1500} at a given redshift by summing the completeness-corrected (using a $V/V_{\max}$ correction; see Gabasch et al. 2004) LFs up to the 1500 Å absolute magnitude limits. Second, we apply a further correction (to zero galaxy luminosity [ZGL]) to take into account the missing contribution to the luminosity density of the fainter galaxies. To this end we use the best-fitting Schechter function. For the FDF catalogs, the ZGL corrections are only 2%–20% in size. The small ZGL correction employed here owes itself to the faint magnitude limits probed by our deep FDF data set and the relatively flat slopes ($\alpha \approx -1.07$) of the Schechter function. Because of the brighter magnitude limit, the ZGL corrections for the GOODS catalog can be as high as 50%. Note that if we follow, i.e., Steidel et al. (1999), who find $\alpha = -1.6$ (excluded at 2 σ with our fits; see Gabasch et al. 2004), we would get much larger ZGL corrections for the same M_*, Φ_* (see the dotted line in Fig. 2 and the discussion below).

Finally, following Madau et al. (1998) we derive the SFR by scaling the UV luminosity densities, $\mathrm{SFR}_{1500} = 1.25 \times 10^{-28} \times l_{1500}$ in units of $M_\odot$ yr^{-1} Mpc^{-3}, where the constant is computed for a Salpeter IMF. The resulting values of SFR_{1500} are shown in Figure 2 as a function of redshift. Errors are computed from Monte Carlo simulations that take into account the probability distributions of photometric redshifts and the Poissonian error (Gabasch et al. 2004). Following Adelberger & Steidel (2000), we assume that dust extinction does not evolve with redshift and is about a factor of ~5–9 in the rest-frame UV. A more detailed discussion of the role of dust will be given in a future paper, such as an analysis based on the SFR derived at 2800 Å. Thanks to the large area covered and the faint limiting magnitudes probed, our determination of the SFR is the most precise to date, with statistical errors less than 0.1 dex for the single redshift bins spanning the range $0.5 < z < 5$.

The considerations of § 2 translate to the following conclusions about the SFR. Out to redshift $z \approx 3$, the SFRs derived from the *I*- and *B*-band selected FDF, or the merged I+B catalog, are identical within the errors ($\lesssim$0.1 dex; see plot at the bottom left of Fig. 2). At larger redshifts the *B*-band selected SFRs underestimate the true values, since *B*-dropouts are not taken into account. The strong evolution in both the M_* and the ϕ_* parameters of the Schechter LF measured as a function of redshift by Gabasch et al. (2004) results in a nearly constant SFR, because the strong brightening of M_* is compensated by the dramatic decrease of ϕ_* with z. Comparing the two bottom panels of Figure 2 shows that luminous galaxies ($L > L_*$) contribute only a third of the total SFR at all observed z, independent of the selection band.

The K-selected SFRs are similar in shape but systematically lower by ≈0.2 dex at $z > 1$. This result holds independently of our completeness correction. If we consider only the contributions to the SFR down to the limiting magnitude set by the *K* band, we find the same 0.2 dex difference for $1 < z \leq 3$ and 0.15 dex at $z > 3$. Figure 1 shows that this result originates from the lower density of $M_{1500} > -19$ galaxies in the *K*-selected catalog, as intermediate- and low-luminosity blue galaxies contributing to the SFR budget are more easily detected in the bluer bands than in *K*. In fact, the contributions to the SFR coming from the galaxies brighter than L_*^I are identical within the errors for the *I*- and *K*-selected catalogs (see Fig. 2, *bottom right panel*). Therefore, cosmic variance does not play a role, as we also verified by comparing the *B*-band number counts in the two fields. They agree within 0.1 dex, which is the expected variation derived by Somerville et al. (2004) scaled to the area of the GOODS-South field. On the other hand, Gabasch et al. (2004) show that the *I*-band FDF catalog might be missing only about 10% of the galaxies that would be detected in a deep *K*-band selected survey with magnitude limit $K_{AB} \approx 26$ (as in Labbé et al. 2003). The missing galaxies would be faint and likely not contributing significantly to the SFR, provided that their dust extinction is not exceedingly large. Independent of the selection band, the SFR declines beyond $z \sim 4.5$. Our results confirm the conjecture of Kashikawa et al. (2003) that the *K*-selected UV LFs match the optically selected LFs at high luminosities.

The comparison with the literature shows that our results are ∼0.3 dex lower, independent of the selection band. This difference stems from the large completeness corrections applied by, e.g., Steidel et al. (1999), derived from the steep slopes fitted to the LF (see § 2). Our results scale to the literature values if similar slopes are used for the same M_* and ϕ_*. This is shown by the dotted lines of Figure 2, where we have assumed a slope of -1.6 for our data set while keeping M_* and ϕ_* the same as in our fit.

The overall agreement between the SFRs derived over a wide wavelength range (within 0.2 dex), from the optical *B* and *I* to the NIR *K*, sampling at $z \approx 4$ the rest-frame UV and *B*, shows that we are approaching (in the optical) the complete census of the galaxies contributing to the stellar production of the universe up to this redshift. Therefore, we can expect possible biases induced by missing stellar energy distributions with redshift (Ilbert et al. 2004) to be small, when deep enough optical or NIR catalogs are available. However, we might still not take into account the possible contribution to the SFR coming from faint, highly dust-absorbed red star-forming galaxies (Hughes et al. 1998; Genzel et al. 2001), which are likely missing from optically or NIR-selected samples. Nevertheless, it is encouraging to find that recent *Spitzer* results (e.g., Egami et al. 2004) indicate that the majority of the star formation has already been accounted for using the dust-corrected SFR derived from optical studies.

4. CONCLUSIONS

We have measured the SFR of the universe out to $z \approx 4.5$ with unprecedented accuracy from the FDF and the GOODS-South Field (90 arcmin^2 in total). Our main conclusions are as follows:

1. The cosmic variance in the SFR history between the FDF and GOODS-South field is negligibly small. The difference between these fields is ≲0.1 dex, consistent with theoretical expectations.
2. The SFR of galaxies brighter than L^I_* is the same (≲0.1 dex) in *B*-, *I*-, (*I*+*B*)-, and *K*-selected catalogs. This indicates that present optical and NIR surveys are unlikely to have missed a substantial fraction population of massive star-forming objects (with the possible exception of heavily dust-enshrouded starbursts).
3. The total SFR integrated over all galaxy luminosities is the same in the *B*-, *I*-, and (*I*+*B*)-selected catalogs and is lower in the *K*-selected catalog by 0.2 dex. This difference originates at luminosities lower than L_*, which implies that *K*-selected surveys miss a significant fraction of star-forming lower luminosity galaxies.
4. At all redshifts, luminous galaxies ($L > L_*$) contribute only approximately one-third to the total SFR; i.e., the integrated SFR of $L < L_*$ galaxies is a factor of ∼2 higher than the one of $L > L_*$ galaxies.
5. Our fits to the FDF luminosity functions suggest a flat faint-end slope of $\alpha = -1.07 \pm 0.04$ in contrast to the assumed slope of $\alpha \sim -1.6$ in the literature. This implies that past determinations have overestimated the SFR by a factor of 2.
6. The SFR is approximately constant over the redshift range $1 \leq z \leq 4$ and drops by about 50% around $z = 4.5$, if dust corrections constant with redshift are assumed.

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