

Stars, dust, and the growth of ultraviolet-selected sub- L^* galaxies at redshift $z \sim 2$

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ABSTRACT

This work concerns the physical properties of very faint ($\mathcal{R}_{\text{lim}} = 28$ AB mag; $M_{\text{stars,lim}} \sim 10^8 M_{\odot}$), ultraviolet-selected (UV-selected) sub- L^* BX galaxies at $z \sim 2.3$. Stellar masses, dust content and dust-corrected star formation rates are constrained using broad-band spectral energy distribution fitting, resulting in a number of insights into the nature of these low-mass systems. First, a correlation between rest-frame UV luminosity and galaxy stellar mass appears to exist in BX galaxies and its presence suggests that many sub- L^* galaxies at this redshift may have approximately constant, rather than highly variable, star formation histories. A nearly-linear relation between stellar mass and star formation rate is also found, hinting that the rate at which a sub- L^* BX galaxy forms its stars is directly related to the mass of stars that it has already formed. A possible explanation for this phenomenon lies in a scenario in which new gas that falls on to the galaxy's host halo along with accreting dark matter is the main source of fuel for ongoing star formation. The instantaneous efficiency of star formation is low in this scenario, of the order of 1 per cent. Turning to bulk quantities, it is found that the low-mass end of the stellar mass function at $z \sim 2.3$ is steeper than expected from extrapolations of shallower surveys, resulting in a stellar mass density at $z \sim 2.3$ that is ~ 25 per cent of the present-day value; this value is ~ 1.5 – 2 times higher than that given by extrapolations of most of the shallower surveys, suggesting that the build-up of stellar mass in the Universe has proceeded somewhat more rapidly than previously thought. With spectral energy distribution fitting results in hand, an update to the Keck Deep Fields $z \sim 2$ UV luminosity function finds a steeper faint-end slope than previously reported, $\alpha = -1.47$, though this is not as steep as that found by Reddy & Steidel. Finally, it is also found that sub- L^* galaxies at $z \sim 2$ carry very small amounts of dust compared to their more luminous cousins, so that while only ~ 20 per cent of 1700-\AA photons escape from a typical M^* galaxy, more than half make it out of an M^*+3 one. This paucity of dust highlights the fact that sub- L^* galaxies are not simple scaled copies of their more luminous cousins. Assuming that absorption by neutral hydrogen is not stronger in sub- L^* galaxies than in their more luminous counterparts, it also means that sub- L^* galaxies are important contributors to keeping the Universe ionized at $z \sim 2$.

Key words: galaxies: evolution – galaxies: formation – galaxies: high-redshift – galaxies: star formation – galaxies: stellar content.

1 INTRODUCTION

The epoch around $z \sim 2$ is particularly important for our understanding of galaxy formation and evolution: it was at this time, when the Universe was only about a quarter of its present age, that the rates of star formation and active galactic nucleus (AGN) activity were at their peak, and when many key processes, such as downsizing and the formation of the red sequence of massive galaxies, were

likely getting underway. However, to date, studies of $z \sim 2$ galaxies have focused largely on luminous members of the population. This focus has in part been motivated by theoretical interests in massive systems as a means to test hierarchical galaxy formation models, but part of the problem is also practical: because high- z galaxies are faint and thus challenging to observe, most follow-up studies to date have focused on relatively luminous objects around the L^* knee in the luminosity function (LF). While economical, this approach has limited us to studying what are, in fact, quite rare objects.

Only recently has the importance of sub- L^* galaxies started to be appreciated. It is now becoming apparent that sub- L^* galaxies

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at high redshift are important contributors to the star formation and metal production budgets in the cosmos and contain a significant fraction of its assembled stellar mass (e.g. Sawicki & Thompson 2006b; Reddy & Steidel 2009). Given the paucity of quasars and luminous galaxies, sub- L^* galaxies are also postulated as the dominant sources of cosmic reionization at very high redshifts, $z > 5$ (e.g. Bouwens et al. 2009). Meanwhile, it is unwise to assume that sub- L^* galaxies are simple scaled-down copies of their super- L^* cousins – instead, they may differ from them in key properties such as star formation histories, metallicities, dust content, and so forth. Indeed, the shape of the galaxy LF and the presence of phenomena such as downsizing (e.g. Cowie, Songaila & Hu 1996) point to different evolutionary mechanisms in sub- L^* and super- L^* populations. Theory also posits that star production is limited by different mechanisms across the halo mass spectrum: at the high-mass end growth may be limited by, for example, AGN feedback (e.g. Best et al. 2005; Croton et al. 2006), while at the low-mass end stellar feedback by supernovae (e.g. Dekel & Silk 1986), radiation pressure (e.g. Thompson, Quataert & Murray 2005) or metallicity effects (Krumholz & Dekel 2012) may play a role. Given the differences with galaxy mass, it is thus vital that we understand the nature of sub- L^* galaxies at high redshift, how they differ from the better studied $\sim L^*$ objects, and what they tell us about how galaxies form and evolve.

Several techniques for selecting galaxies at $z \sim 2$ are now available (e.g. Franx et al. 2003; Daddi et al. 2004). Galaxies selected using the LBG/BM/BX selection techniques (Steidel et al. 1999, 2003, 2004), which are based on rest-frame ultraviolet (UV) broadband photometry and thus sensitive to star-forming populations that are at most only weakly obscured by interstellar dust, are among the best studied and understood. In order to leverage on this knowledge, this work pushes the BX selection to much fainter objects than those that are usually studied.

As is the case with more luminous galaxies, once a sample of galaxies is in hand, several lines of attack are available. The LF (e.g. Gabasch 2004; Sawicki & Thompson 2006a; Reddy & Steidel 2009) provides a useful but crude descriptor of the galaxy population, and although it is important to measure the LF's faint end accurately, the shape of the LF and its evolution has only limited interpretive value. Spectroscopic observations would be desirable, but for sub- L^* galaxies at $z \sim 2$ they are extremely challenging in terms of telescope time and consequently little is known about the spectral properties of these important objects. Galaxy–galaxy clustering can tell us about the dark matter haloes that host high-redshift galaxies (e.g. Adelberger et al. 1998, 2005; Ouchi et al. 2001), but such work is only now being done for sub- L^* galaxies at $z \sim 2$ (Savoy et al. 2011, hereafter KDF IV, where KDF stands for Keck Deep Fields). Finally, much can be learned from broad-band spectral energy distributions (SEDs) of high- z galaxies (e.g. Sawicki & Yee 1998; Papovich, Dickinson & Ferguson 2001; Shapley et al. 2001); this paper presents the results of such a study of the stellar populations of UV-selected faint ($\mathcal{R}_{\text{lim}} = 28$ AB mag) galaxies at $z \sim 2$.

This paper is organized as follows. Section 2 describes the source data, photometry and sample selection of the sub- L^* $z \sim 2$ sample. Section 3 deals with estimation of stellar masses, dust-corrected star formation rates (SFRs) and other parameters using SED fitting. Results of the SED fitting are presented in Section 4. Section 5 contains a discussion of the broader implications of the results on our understanding of galaxy formation and evolution. Finally, Section 6 summarizes the key results. Throughout this work, it is assumed that $(\Omega_M, \Omega_\Lambda, H_0) = (0.3, 0.7, 70 \text{ km s}^{-1} \text{ Mpc}^{-1})$. At $z =$

2.3, this cosmology gives the age of the Universe to be 2.8 Gyr. Unless otherwise noted, all magnitudes are on the AB system (Oke 1974).

2 DATA

2.1 The Hubble Deep Field: oldie but goodie

This study uses the publicly available WFPC2 and NICMOS data from the original *Hubble Deep Field* (HDF; Williams et al. 1996; Dickinson 1999). While several excellent multiwavelength *HST* data sets, such as the GOODS fields or the *Hubble Ultra Deep Field*, surpass the original HDF in both depth and/or area, the depth of U_{300} imaging in the original HDF maintains its position as an excellent data set for studying star-forming galaxies at $z \sim 2$. This is because selection of UV-bright galaxies at $z \sim 2$ can be done efficiently using a combination of observed-frame UV/optical filters that span $\sim 3000\text{--}6000 \text{ \AA}$, with deep U -band imaging being critical (e.g. Steidel et al. 1996, 2004; Adelberger et al. 2004). As Steidel et al. (2004) have shown, colour–colour selection that includes the U band identifies $z \sim 2$ galaxies while rejecting most foreground ($z \lesssim 1.5$) interlopers. The very deep U_{300} data of the HDF allow such $z \sim 2$ selection, making it excellent for studying sub- L^* galaxies at this epoch.

The HDF has an area of only $\sim 5.3 \text{ arcmin}^2$, but this relatively small size is not a serious limitation in this work. While studies of the LF and of the clustering properties of galaxies need large samples drawn from large volumes as they need to combat simple Poisson noise in the counts as well as clustering-induced field-to-field variance ('cosmic variance'), these are not the dominant sources of noise in SED studies. Instead, what is critically important in SED-fitting work are data with very deep and well-calibrated photometry, while the number of galaxies in the sample needs only to be large enough to allow the identification of major trends in their physical parameters. With several dozen $z \sim 2$ galaxies (see Section 2.3) and very deep multicolour data, from U_{300} to H_{160} , the HDF is well suited for such work.

2.2 Object detection and photometry

Object detection and photometry were done using `SEXTRACTOR` version 2.3.2 (Bertin & Arnouts 1996) on the publicly available WFPC ($U_{300} B_{450} V_{606} I_{814}$) and NICMOS ($J_{110} H_{160}$) image mosaics of the HDF. The V_{606} image is the deepest among the six bands, and so object detection was carried out on the unsmoothed V_{606} -band images, requiring for detection that an object has a minimum of 10 pixels brighter than the 3σ sky level. The HDF images are extremely deep, and faint high- z UV-selected galaxies are compact (e.g. Giavalisco, Steidel & Macchetto 1996), so it is possible to reach faint levels in the population. Simulations that use compact but not point-like sources show that the present catalogue is ~ 50 per cent complete at $V_{606} = 29.1$ and >90 per cent complete at $V_{606} = 28.8$.

Accurate colours are critical for SED studies and great care was taken to measure them reliably. First, the unsmoothed V_{606} image was used to measure the `SEXTRACTOR` total V_{606} -band magnitudes. This step needs only to be accurate to ~ 10 per cent and so `SEXTRACTOR` `MAG_AUTO` magnitudes were sufficient here. In contrast, the measurement of flux ratios (i.e. colours) between bands for a given object is much more critical for estimating accurate stellar masses, ages, dust corrections and dust-corrected SFRs. To ensure accurate colour measurements, photometry in the other bands

was done on smoothed $U_{300}B_{450}V_{606}I_{814}J_{110}H_{160}$ images as follows. First, the $U_{300}B_{450}V_{606}I_{814}J_{110}H_{160}$ images were smoothed using Gaussian kernels to give common full width at half-maximum (FWHM) of ~ 0.17 arcsec, which matches the FWHM in the lowest resolution image, namely the H_{160} image. Next, `SEXTRACTOR` was run in its dual-image mode, in which it detected objects in the *unsmoothed* V_{606} image, but carried out photometry at the corresponding location in the smoothed $U_{300}B_{450}V_{606}I_{814}J_{110}H_{160}$ images. Here, fluxes were measured using positionally matched, fixed circular apertures of 12 pixel (~ 0.5 arcsec) diameter. These aperture magnitudes were then transformed into ‘total’ magnitudes by applying the offsets found between the V_{606} -band total and aperture magnitudes: $m_{\text{tot}} = m_{\text{ap}} + (V_{606,\text{tot}} - V_{606,\text{ap}})$, where m_i refer to the total and aperture magnitudes in the various bands $U_{300} B_{450} I_{814} J_{110} H_{160}$. Using images smoothed to a common resolution ensures that the 12-pixel ‘colour apertures’ capture the same fraction of a galaxy’s flux in each waveband, and results in accurate galaxy colours that are essential for SED fitting. Measurements on compact objects in the smoothed data show that colours measured within the 12-pixel apertures in the smoothed images are typically accurate to ~ 1 per cent or better, without incurring large sky noise that would result from using larger apertures. Overall, the above procedure results in a catalogue of V_{606} -selected objects with ‘total’ magnitudes that accurately represent object colours.

The Steidel et al. (1996, 2004) selection of $z \sim 2$ galaxies relies on R -band data, and so it was necessary to construct a synthetic R -band magnitude for each object. Following Steidel et al. (1996), this was done by averaging the V_{606} and I_{814} fluxes:

$$\mathcal{R}_{VI} = -2.5 \log \left(\frac{10^{-0.4V_{606}} + 10^{-0.4I_{814}}}{2} \right). \quad (1)$$

The sample retained for further analysis was then defined on the basis of this synthetic \mathcal{R}_{VI} magnitude and consists of 1498 objects with $\mathcal{R}_{VI} < 28.0$. At this relatively bright (for the HDF) magnitude cut-off, the sample is close to complete and photometric errors for the majority of objects are still only a few per cent in most bands.

2.3 The $z \sim 2.3$ sample

The $z \sim 2.3$ sample is magnitude limited and is selected using colour–colour LBG selection followed by a photometric redshift cut, as defined below. These steps mimic the selection procedures used to select $z \sim 2.3$ ‘BX’ galaxy samples (e.g. Steidel et al. 2004; Shapley et al. 2005; Erb et al. 2006; Reddy et al. 2007). The main differences between the Steidel group’s samples and the one used here are the slightly different filter systems, and the use of photometric redshifts – instead of spectroscopic ones – in the present, much fainter sample. These differences are small and the present HDF sample selects a population very similar to the Steidel et al. $z \sim 2.3$ ‘BX’ galaxies, while pushing to much fainter depths, with a catalogue limit at $\mathcal{R} = 28$ instead of $\mathcal{R} = 25.5$ as typically used by the Steidel et al. team for SED-fitting work (Shapley et al. 2005; Erb et al. 2006).

The sample is based on HDF *HST* data, and consequently it seemed reasonable to use the colour–colour selection criteria defined by Steidel et al. (1996) for their HDF high- z galaxy selection. These criteria are as follows:

$$\begin{aligned} U_{300} - B_{450} &> 1.2 + (B_{450} - \mathcal{R}_{VI}), \\ -0.5 &< (B_{450} - \mathcal{R}_{VI}) < 1.2. \end{aligned} \quad (2)$$

In addition to the colour–colour criteria, the sample is restricted to the magnitude cut defined by

$$23 < \mathcal{R}_{VI} < 28. \quad (3)$$

This magnitude cut is designed to guard against potential rare, anomalous objects at the bright end, and, at the faint end, to exclude objects with large photometric errors that propagate to large errors on the SED-fitting output parameters. Note that the sample is nearly complete at these relatively bright magnitudes.

The left-hand panel of Fig. 1 shows the colours of all the $23 \leq \mathcal{R}_{VI} \leq 28$ HDF objects in the $U_{300}B_{450}\mathcal{R}_{VI}$ colour–colour plane, together with the selection region defined by equation (2). There are 284 objects that meet the criteria defined by equations (2) and (3). All 284 objects are detected at high confidence in the B_{450} , V_{606} and I_{814} bands. All but nine are detected in J_{110} and all but two in H_{160} , with all 284 being detected in either J_{110} or H_{160} .

Next, the pure colour–colour selection is followed by a photometric redshift cut based on photometric redshifts calculated from U_{300} to H_{160} SEDs as described in Section 3. This photometric redshift cut requires that

$$1.8 \leq z_{\text{phot}} \leq 2.6, \quad (4)$$

where z_{phot} is the redshift of the most likely model (i.e. the model with the lowest χ^2). The lower photo- z cut in equation (4) is applied to eliminate potential low- z interlopers, and is similar to the spectroscopic rejection of low- z galaxies from samples such as those used by Shapley et al. (2005) or Steidel et al. (2004). This $1.8 \leq z_{\text{phot}}$ cut eliminates 87 objects out of the original 284, or ~ 30 per cent of the total. As the photometric redshift distribution suggests (inset diagram in the right-hand panel of Fig. 1), some 30 of these objects are likely to be at $z > 1$, but they nevertheless are eliminated from further analysis to avoid complications that could be introduced by a wide sample Δz that spans a very wide range of cosmic time. The upper- z cut, $z_{\text{phot}} \leq 2.6$, is applied to avoid objects that are at too high a redshift to have enough rest-frame spectral coverage for accurate SED fitting. This upper cut is particularly important since it is impossible to estimate stellar population ages and galaxy stellar masses without a filter redwards of the 4000 Å break, as would be the case at $z \gtrsim 2.6$ for the $U_{300}B_{450}V_{606}I_{814}J_{110}H_{160}$ filter set. This $z_{\text{phot}} \leq 2.6$ cut eliminates 106 higher- z objects, giving a final sample of 91 objects whose mean redshift is $\langle z_{\text{phot}} \rangle = 2.3$.

It should be noted that the $z_{\text{phot}} \leq 2.6$ photometric redshift cut could potentially introduce a systematic bias since, in the absence of a visible Balmer/4000 Å break, extremely young $z_{\text{phot}} \leq 2.6$ galaxies could be confused for $z_{\text{phot}} > 2.6$ objects and thus eliminated from the sample; however, for a $z_{\text{phot}} \leq 2.6$ galaxy to lack a detectable break it would have to be extremely young and so only a small number of objects are likely to be missed in this way. The reverse process – that of higher- z objects masquerading as extremely young $z \sim 2$ stellar populations – is unlikely to be important in practice, given the very small number of $z \sim 2$ objects with very young stellar populations that are observed in the sample in practice (Section 4.4).

In summary, the final sample of 91 objects resembles the selection and other properties (other than the luminosities) of the brighter Steidel et al. BX samples and thus henceforth will be referred to as the ‘HDF-BX sample’. While the focus of this study is on the z_{phot} -restricted HDF-BX sample of 91 objects, the analysis of the full, unrestricted sample of 284 objects shows that the conclusions reached with the HDF-BX sample are not significantly altered when using the full, unrestricted sample.

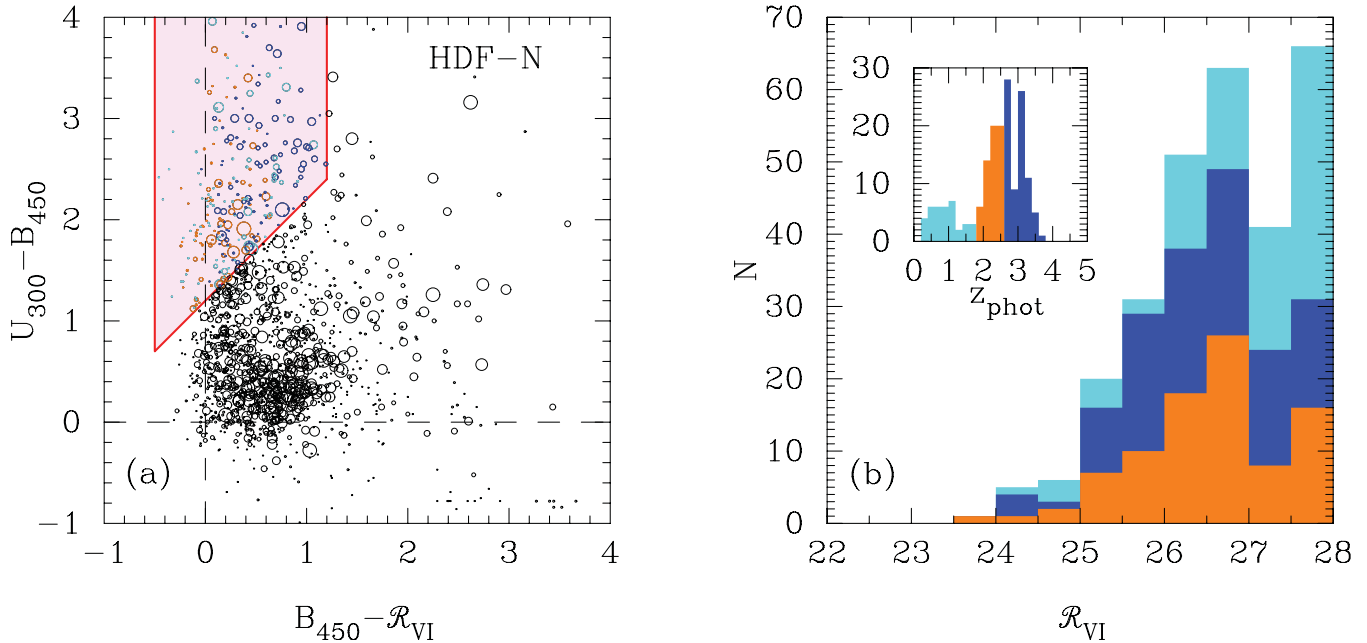


Figure 1. Sample selection. The left-hand panel shows the colour–colour diagram for all the HDF objects with $23 < \mathcal{R}_{VI} < 28$. The larger symbols correspond to brighter objects. The colour–colour selection region (equation 2 and Steidel et al. 1996) is highlighted and the objects within this region are colour-coded according to their photometric redshifts, as given in the right-hand panel. The photometric redshift distribution is shown in the inset plot in the right-hand panel, with the three colours corresponding to the three ranges defined by equation (4). The right-hand panel also shows the number counts of the colour–colour–selected objects: the lowest, orange histogram shows the numbers for the final sample of 91 objects, blue denotes the objects with $z_{\text{phot}} > 2.6$, and cyan those with $z_{\text{phot}} < 1.8$. Note that the histograms are stacked on top of each other, rather than overlapping.

2.4 Absolute rest-frame UV magnitudes

The absolute rest-frame UV magnitude, M_{1700} , is calculated at the rest-frame wavelength of ~ 1700 , which matches the rest-frame wavelength of a number of LBG LF studies (e.g. Steidel et al. 1999; Sawicki & Thompson 2006a, hereafter KDF II; Reddy & Steidel 2009) and also approximately corresponds to the central wavelength of the B_{450} bandpass at $z = 2.3$. It is derived using the usual cosmological distance modulus, DM, and k -correction, K ,

$$M_{1700} = m_{\lambda_{\text{obs}}} - \text{DM} - K, \quad (5)$$

which can be rewritten as

$$M_{1700} = m_{\lambda_{\text{obs}}} - 5 \log(D_L/10\text{pc}) + 2.5 \log(1+z) + [m_{1700} - m_{\lambda_{\text{obs}}/(1+z)}]. \quad (6)$$

Here, D_L is the luminosity distance and $m_{\lambda_{\text{obs}}}$ is the observed V_{606} magnitude. The last term of equation (6), $[m_{1700} - m_{\lambda_{\text{obs}}/(1+z)}]$, is the k -correction colour between rest-frame 1700 \AA and the V_{606} filter in the *rest frame* (e.g. Lilly et al. 1995; KDF II).

The k -correction colour is expected to be very small because at $z \sim 2.3$ the V_{606} filter probes close to rest-frame 1700 \AA , as is illustrated in Fig. 2. Because the change in DM + K (equation 6) is small over the redshift range of the selection window (Fig. 2), rather than computing a separate correction for each galaxy based on its photometric redshift, a common value of DM + $K = 44.9$ is assumed for all objects in the sample. This approach introduces only small errors ($\sim \pm 0.4$ mag) in the derived absolute magnitudes, errors that are of the same order as those that would have been introduced by propagating the photometric-redshift uncertainties ($\Delta z_{\text{phot}} \sim 0.3$ at these redshifts: Sawicki, Lin & Yee 1997; Hogg et al. 1998) through equation (6).

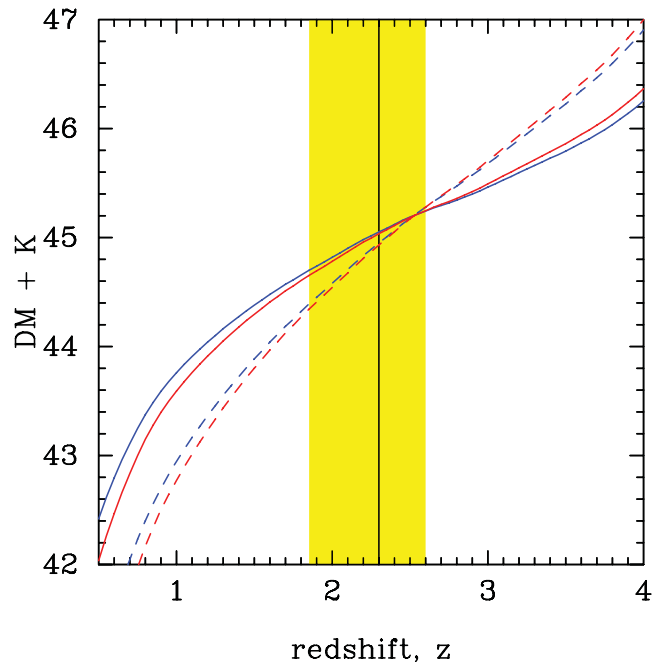


Figure 2. The cosmological corrections to calculating the absolute rest-frame 1700 \AA magnitudes from apparent V_{606} magnitudes. Several different assumed SEDs are shown: blue curves identify 10-Myr-old constant-SFR models, while red curves indicate 100-Myr constant-SFR models; dashed curves show SEDs with no dust, while continuous curves show SEDs with $E(B - V) = 0.3$. The redshift range of the present sample is shown as a shaded region, with the vertical line indicating the median photometric redshift. In this work, a uniform correction is adopted for all objects, DM + $K = 44.9$.

2.5 Comparison with other samples at $z \sim 2$

The HDF-BX sample selection procedure described in Section 2.3 mimics the procedure used for selecting the $z \sim 2$ BX sample of Shapley et al. (2005). In both samples, objects are rest-frame UV selected and then $z \sim 2$ subsamples are identified on the basis of very similar colour–colour cuts. The photometric redshift cuts imposed here on the HDF-BX sample ($1.8 \leq z_{\text{phot}} \leq 2.6$) mimic the spectroscopic cuts ($1.7 < z_{\text{spec}} < 2.8$) applied by Shapley et al. to their sample: in both samples the upper redshift cut eliminates $z \sim 3$ LBGs, and the lower one rejects foreground interlopers. The resultant mean redshifts are also similar: $\langle z_{\text{phot}} \rangle = 2.3 \pm 0.2$ for the HDF-BX sample closely matches $\langle z_{\text{spec}} \rangle = 2.26 \pm 0.3$ of the BX sample of Shapley et al. (2005). As is illustrated in the left-hand panel of Fig. 3, the key difference between the samples lies in the fact that the HDF-BX sample consists of galaxies that are significantly fainter than those in the BX samples of Shapley et al. (2005), Steidel et al. (2004) and Erb et al. (2006): while their samples have a limiting magnitude of $\mathcal{R} = 25.5$, the HDF-BX sample reaches to $\mathcal{R}_{VI} = 28.0$, and while typical galaxies in the Shapley et al. (2005) BX sample have luminosities around L^* , those in the HDF-BX sample are a factor of ~ 10 fainter.

The right-hand panel of Fig. 3 compares the stellar masses of the present HDF-BX sample (obtained through SED fitting described in Section 3) with the similarly selected but brighter BX sample of Shapley et al. (2005) and with the BzK galaxies of Daddi et al. (2007). The stellar masses of the HDF galaxies are significantly lower than those in the other two samples: the median stellar mass in the HDF-BX sample is, at $\sim 2.5 \times 10^9 M_{\odot}$, ~ 10 times smaller than that in the BX sample of Shapley et al. (2005) and in the BzK

sample of Daddi et al. (2007). The HDF sample is thus probing a similar but significantly fainter and apparently less massive UV-selected, star-forming population.

3 SPECTRAL ENERGY DISTRIBUTION FITTING

3.1 The technique

Broad-band SED fitting has in recent years become a popular tool for studying the properties of high-redshift galaxies. It was first used for that purpose by Sawicki & Yee (1998) who used it to study the properties of the first samples of spectroscopically confirmed high- z galaxies in the HDF and was subsequently employed in numerous other studies of distant galaxies (e.g. Hall et al. 2001; Papovich et al. 2001; Sawicki 2001; Shapley et al. 2001, 2005; Förster Schreiber et al. 2004; Yabe et al. 2009; Yuma et al. 2010, 2011; and many others); it now forms a part of the standard toolkit for high- z galaxy research. In this work, the technique is applied to the HDF sample of very faint, sub- L^* LBGs in order to explore the dependence of galaxy properties on UV luminosity.

The SED-fitting approach quantitatively compares the photometry of a galaxy to a grid of models that span a range of parameters of interest. The comparison is done by means of a maximum likelihood test (χ^2 fitting) and returns the best-fitting model parameters along with their uncertainties. The technique is now past its infancy so only a brief description is provided here; for more details, the reader is referred to papers by, for example, Sawicki & Yee (1998),

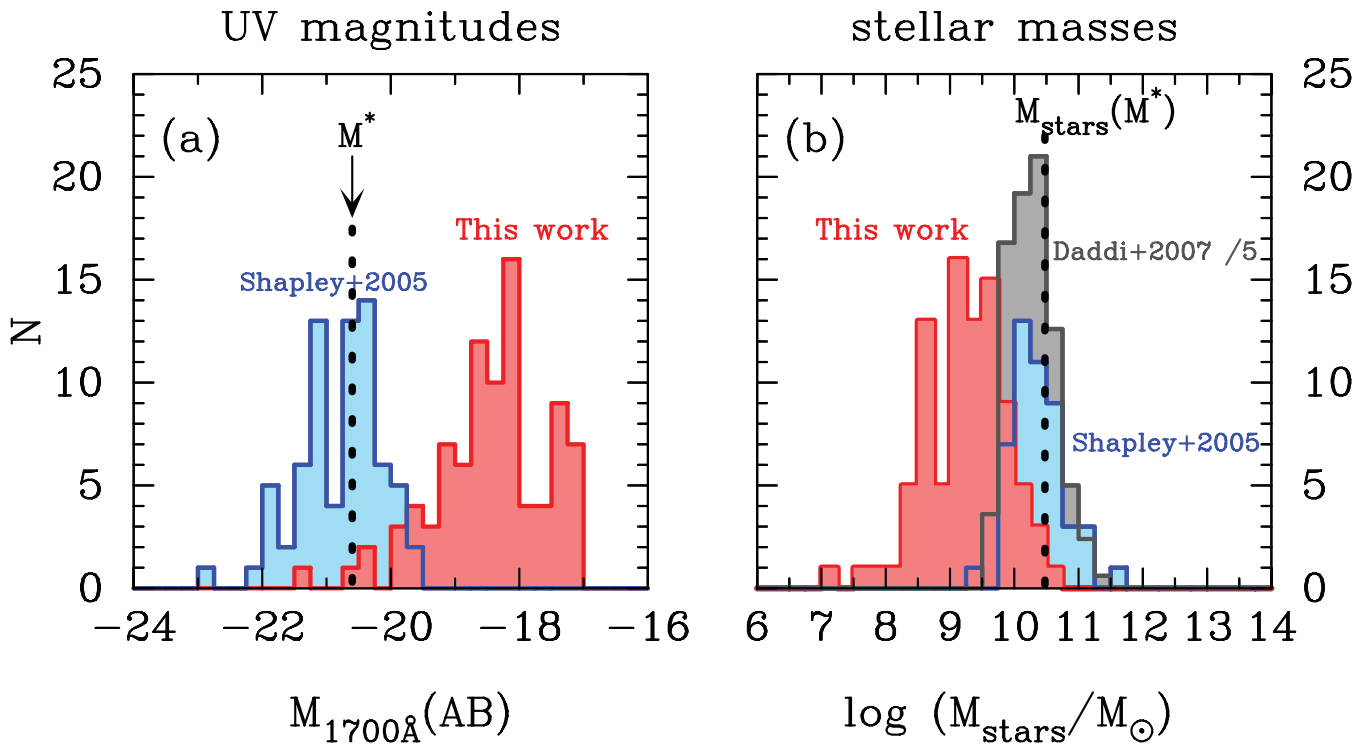


Figure 3. Comparison of the present HDF-BX sample with the BX sample of Shapley et al. (2005) and the sample of Daddi et al. (2007). Left-hand panel: the Shapley et al. sample focuses on galaxies around the characteristic magnitude M^* , while the HDF-BX sample probes significantly fainter galaxies. Right-hand panel: stellar masses of galaxies in the present sample are typically an order of magnitude smaller than those in the Shapley et al. and Daddi et al. samples. Note that the Daddi et al. numbers have been scaled down by a factor of 5 to allow them to be displayed in this plot.

Table 1. Model parameters. The first four are free parameters of the fit and the last four are fixed.

Parameter	Value(s)	Step size	Remarks
Redshift	0–5	0.05	
$\log(\text{age}/\text{Gyr})$	5.1–10.3	0.1	
$E(B - V)$	0–0.6	0.02	Calzetti et al. (2000)
Flux normalization	Any	Exact	See equation (3) of Sawicki (2002)
Star formation history	Constant SFR	–	Bruzual & Charlot (2003)
IMF	Salpeter (1955)	–	$0.1 < M/M_{\odot} < 100$
Metallicity	$1 Z_{\odot}$	–	
Intergalactic attenuation	1	–	Madau (1995)

Papovich et al. (2001), Shapley et al. (2001), and to the paper on SEDFIT (Sawicki 2012), which is the publicly-available SED-fitting software tool used in the work presented here.

The generation of the model broad-band SED grid begins with model galaxy spectra. In this work, the underlying spectra are drawn from spectral synthesis models of Bruzual & Charlot (2003) with solar metallicity, the Salpeter (1955) stellar initial mass function (IMF) and a constant SFR. These spectra are first reddened using the starburst extinction curve of Calzetti et al. (2000), with the amount of reddening parametrized by the colour excess $E(B - V)$. Next, to simulate galaxies at high redshift, the reddened spectra are shifted in both wavelength and intensity as dictated by the adopted cosmology of $(\Omega_M, \Omega_{\Lambda}, H_0) = (0.3, 0.7, 70 \text{ km s}^{-1} \text{ Mpc}^{-1})$. Then, to include the effects of the absorption of UV photons by intergalactic neutral hydrogen along the line of sight, the spectra are attenuated below the Lyman limit using the prescription of Madau (1995). Finally, the spectra are integrated through WFPC2 and NICMOS filter profiles to produce a grid of model fluxes to be compared against the data. This grid is in effect four dimensional as it contains the following parameters: redshift, time since the onset of the dominant star formation episode ('age'), colour excess $E(B - V)$, along with normalization of the model fluxes with respect to the data. Table 1 lists the model grid parameters and their ranges. Note that the input stellar evolutionary models, dust law, etc., used here to fit the HDF-BX objects are identical to those used by Shapley et al. (2005) for their BX sample. This commonality allows the two samples to be combined in order to cover a large luminosity baseline.

For each of the 284 objects in the colour-selected catalogue, the photometry data are compared against the model grid and the best-fitting model is determined by a maximum likelihood (minimum χ^2) search. In addition to the best-fitting parameters, the SEDFIT software also provides estimates of their associated uncertainties by propagating the photometric uncertainties through the fitting procedure and deriving associated error volumes in the model grids. The parameters derived from the fitting are: age (i.e. time since the onset of the present episode of star formation), accumulated stellar mass, amount of reddening by dust, intrinsic (dust-corrected) SFR, and redshift. Not all of these parameters are independent (e.g. accumulated stellar mass and SFR are both linked to the overall flux normalization of the model to the data), but all have their best-fitting values reported by SEDFIT along with their associated uncertainties.

SEDFIT is capable of generating and fitting model SEDs based on a far wider range of star formation histories, stellar IMFs, dust attenuation laws, etc., than used in the present project, but the restricted set of free parameters was a deliberate choice made to allow the comparison of the present sample with the luminous BX sample of

Shapley et al. (2005). The dependence of fit results on the assumed metallicity, star formation history, and the like have been explored previously by Sawicki & Yee (1998), Papovich et al. (2001), and many others, and are reasonably well understood. For example, it is known that SED fitting cannot usefully constrain metallicity or star formation history – but, by the same token, metallicity differences in the models do not impact the resulting fit parameters for other quantities such as stellar mass and SFR. Galaxy stellar masses derived via SED fitting are reasonably robust to the various model assumptions with typical systematic uncertainties of factors of 2–3. SFRs, on the other hand, are highly sensitive to the unknown star formation histories. This paper proceeds on the assumption that SFRs are constant for galaxies of all UV luminosities. This seems a reasonable assumption in light of the tightness of the SFR– M_{stars} relation (Section 4.5); potential systematic uncertainties are further mitigated by the approach of relative – rather than absolute – comparisons between galaxies of different luminosities.

3.2 SED-fitting results and examples

Representative examples of the fits are shown in Fig. 4. The left-hand panels of Fig. 4 compare the photometric data (points) with the Bruzual & Charlot (2003) spectra that give the best-fitting model SEDs. The FWHM of the filter transmission curves is shown as a horizontal error bar, but it should be kept in mind that these are not actual error bars in the normal understanding of that term, but rather are meant to give an indication of the wavelength range over which the observed and model spectra are integrated when producing broad-band magnitudes.

The contour plot panels of Fig. 4 show the values of the best-fitting redshift, age and colour excess $E(B - V)$, together with the permissible ranges of these parameters. The inner contours (in some cases largely hidden under the best-fitting point) correspond to a probability of 68.3 per cent that the observed data were drawn from the enclosed models; the outer contours show 95 per cent probability. The error contours were calculated for each object by perturbing the observed photometry assuming Gaussian uncertainties and then refitting the perturbed data. 200 such Monte Carlo re-fits were performed for each object and on the basis of these $91 \times 200 = 18\,200$ realizations, the values of χ^2 that enclose the desired percentage probabilities were estimated for plotting.

The redshift error contours in Fig. 4 are remarkably tight and not particularly degenerate with the other parameters. This fact gives confidence that the lack of spectroscopic redshifts for the very faint

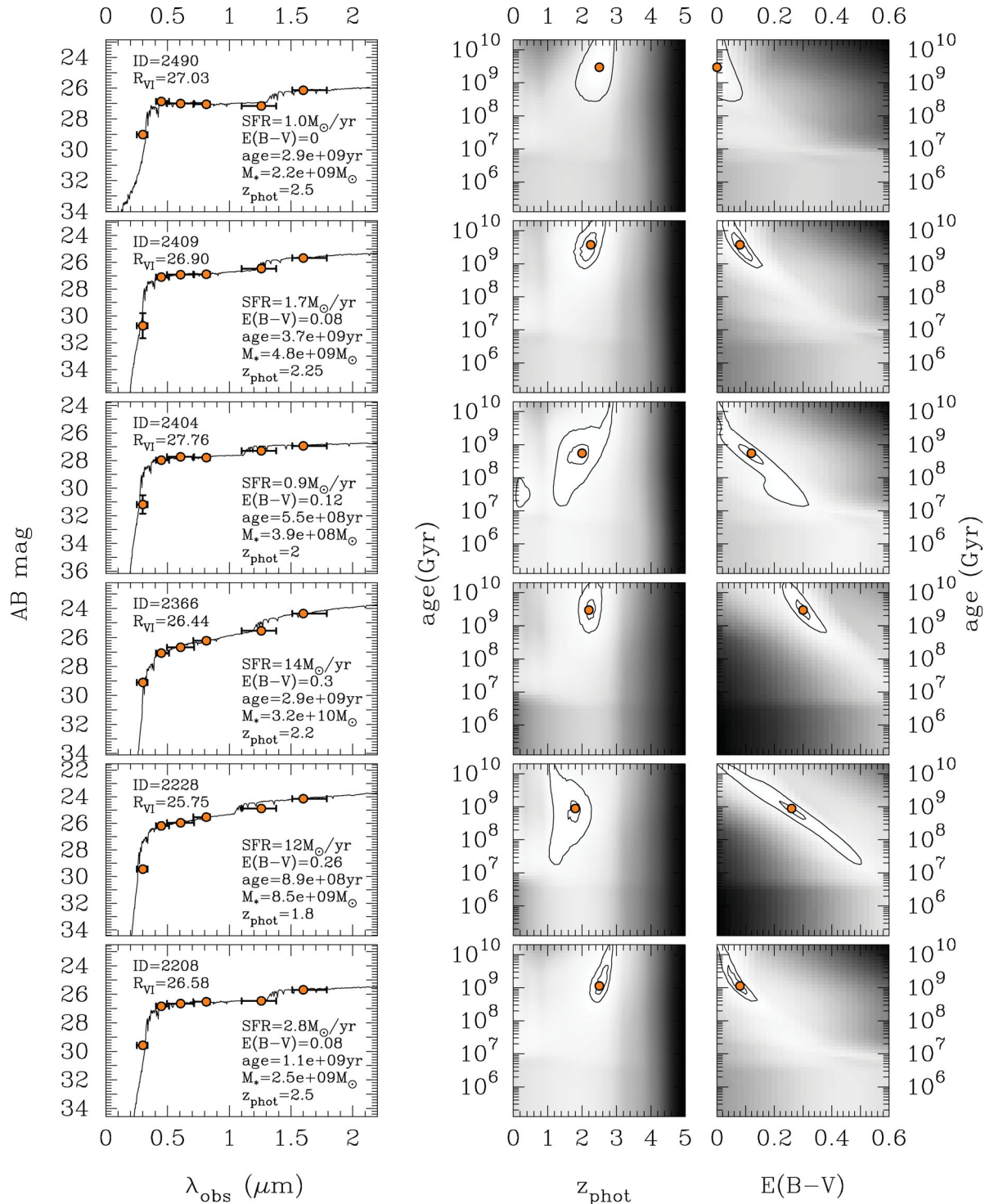


Figure 4. Examples of SED fits. In the left-hand panels, the horizontal error bars are not uncertainties but rather denote the FWHM range of the filter transmission curves. Note that the U_{300} -band (shortest λ) photometric points were not used in the SED fitting and are shown here for completeness only. In the middle and right-hand panels, the inner contours are drawn at surfaces of constant χ^2 that correspond to 68 per cent statistical significance, while the outer contours correspond to 95 per cent confidence.

objects studied here is not a serious impediment. The error contours on the other parameters are also well behaved and although some degeneracies exist between age and extinction, characterizing the sizes of the error bars through this Monte Carlo based procedure makes it possible to proceed with the fit results to help us understand the nature of this sample of very faint galaxies.

4 RESULTS

4.1 Preliminaries

This section discusses some interesting trends found in the properties of UV-selected galaxies at $z \sim 2$. In several instances, the

sample of 91 very faint HDF objects is compared against similarly selected and similarly fitted but more luminous galaxies from the BX sample of Shapley et al. (2005). In other instances, the Shapley et al. (2005) sample is used to augment the HDF sample in order to extend or highlight important trends present in the data as a function of galaxy luminosity.

The exact values of the best-fitting parameters can depend sensitively on the details of the assumed dust extinction law, star formation history, stellar IMF, etc. (see e.g. Sawicki & Yee 1998; Papovich et al. 2001), so it is vital to use models with exactly the same parameters when comparing different samples. With that thought in mind, the SED fits to the present HDF-BX sample use exactly the same underlying models as those for the brighter BX sample of Shapley et al. (2005): solar metallicity, constant-SFR Bruzual & Charlot (2003) models with the Salpeter (1955) IMF and Calzetti et al. (2000) dust. Consequently, the two samples can be regarded as directly comparable.

Notwithstanding the commonality of models, one of the strongest limitations of broad-band SED fitting is the need to assume a star formation history, which cannot be reliably constrained for a galaxy from the small number of photometric points available. Whereas many parameters of interest – such as reddening or stellar masses – are relatively insensitive to the assumed star formation history (e.g. Sawicki & Yee 1998; Papovich et al. 2001), stellar population ages and SFRs are highly dependent on the assumed star formation history. Additionally, prior star-forming episodes may well have occurred but their existence in a galaxy can be masked by the glare of the newly born massive stars belonging to the most recent star-forming episode; furthermore, star formation in high-redshift galaxies may in fact be increasing with time (e.g. Lee et al. 2010; see also Section 5.4.4), thereby effectively masking the presence of older stars. For these two reasons – the challenge of constraining the history of even the most recent episode of star formation along with difficulty of detecting possible earlier star-forming episodes – interpreting the ages derived from SED fitting can be problematic.

Neglecting possible prior star-forming episodes and considering only a single episode of star formation, constant star formation models give older ages than do models in which star formation declines with time. For this reason, constant-SFR fits that yield ages older than that of the Universe can be regarded as likely having declining star formation histories as opposed to the constant-SFR ones that were assumed in the fitting. A number of such objects are present in both the HDF-BX and the Shapley et al. (2005) samples and these objects – while plotted (in red) in the figures that follow – are excluded from the main part of the analysis. On the other extreme, objects with extremely young best-fitting ages are also problematic: such an object is unlikely to have formed immediately prior to the epoch of observation and is, instead, probably a normal galaxy whose light is dominated by a very recent burst of star formation that masks an older, underlying stellar population. Only a very small handful of such objects exist in the HDF-BX sample, with a somewhat larger fraction present in the Shapley et al. (2005) sample. Since the goal of this work is to establish longer term behaviour of galaxies, such ‘young’ galaxies (defined here as best-fitting age < 30 Myr) are thus also treated with suspicion. While they are shown (in blue) in the figures that follow they are excluded from the main part of the analysis.

Because of these issues, stellar population ages determined from the SED fitting are not analysed in detail in what follows. With these preliminaries out of the way, let us turn to some of the interesting trends found in the data.

4.2 Dust

It has now been known for some time that UV-selected high- z galaxies possess significant amounts of interstellar dust (e.g. Meurer et al. 1997; Sawicki & Yee 1998; Papovich et al. 2001; Vihj, Witt & Gordon 2003; Reddy et al. 2006). However, the effect of dust remains unknown in very faint and/or low-mass galaxies at high redshift. This section examines the dependence of dust attenuation on UV luminosity, reaching very deep into the galaxy population, by pushing to $\mathcal{R}_{VI} = 28$, or 3.5 mag below M^* at $z \sim 2$.

Fig. 5(a) shows the dependence of colour excess, $E(B - V)$, on galaxy UV luminosity. The data suggest that fainter BX galaxies suffer less extinction than the more luminous ones, a trend that extends to the very faint limit of the HDF data. This finding is in agreement with the conclusion of Adelberger & Steidel (2000), but here, for the first time, the trend is extended to high- z galaxies ~ 3.5 mag fainter than M^* . The reality of this trend is verified by Monte Carlo simulations that suggest that moderately dusty galaxies [$E(B - V) \sim 0.15$] are unlikely to be scattered by photometric errors to look like the nearly-dust-free objects seen at the faint end of Fig. 5. Naively, Fig. 5(a) could be interpreted to show a preference for galaxies dominated by very young stellar populations (blue squares) to be more dusty than the mean, especially so at the bright end of the population where the Shapley et al. (2005) data dominate. However, at least within the HDF-BX sample, Monte Carlo simulations suggest that this effect is an artefact of correlated extinction-age errors, and this may also be the case for the Shapley et al. data, given their large photometric uncertainties. In summary, the tendency for low-luminosity BX galaxies to have little dust is likely real but any apparent trends of dust with age are not.

Fig. 5(b) quantifies the dependence of extinction on UV brightness by showing the distribution of $E(B - V)$ values in bins of galaxy UV magnitude. As in the left-hand panel of Fig. 5, there is a trend for fainter galaxies to have lower $E(B - V)$ values, and both the median (solid vertical lines) and mean (dashed lines) $E(B - V)$ values decrease for the fainter-magnitude bins. These results are summarized in Table 2. Inspecting the A_{1700} values in Table 2, it is interesting to note that while only about one out of five UV photons escapes from an L^* BX galaxy, sub- L^* galaxies are far more ‘naked’: in the mean we are able to see more than half of the UV photons produced by $M^* + 3$ BX objects. One useful consequence of this low dust attenuation is that sub- L^* galaxies may be simpler to study than their L^* counterparts.

As is discussed in Section 4.3, there is a correlation between the stellar mass and luminosity of BX galaxies, with more luminous objects being more massive. Given the luminosity–extinction relation discussed above, it is thus clear that the low-mass BX galaxies contain smaller amounts of dust than their higher mass $\sim L^*$ cousins. It is plausible that the low-mass galaxies have lower baryon densities than the more massive objects, or, alternatively, that they are physically smaller. Either of these two possibilities is consistent with the luminosity/mass versus reddening trend. Whatever the reason, the UV photons produced by their stars have smaller dust column densities to risk on their way into the intergalactic medium. Some of the issues related to the dust–stellar mass correlation will be explored further in Section 5.3.

4.3 Stellar mass–UV luminosity relation

Given that the UV light from faint BX galaxies appears to be fairly unobscured (Section 4.2), it is interesting to ask how stellar

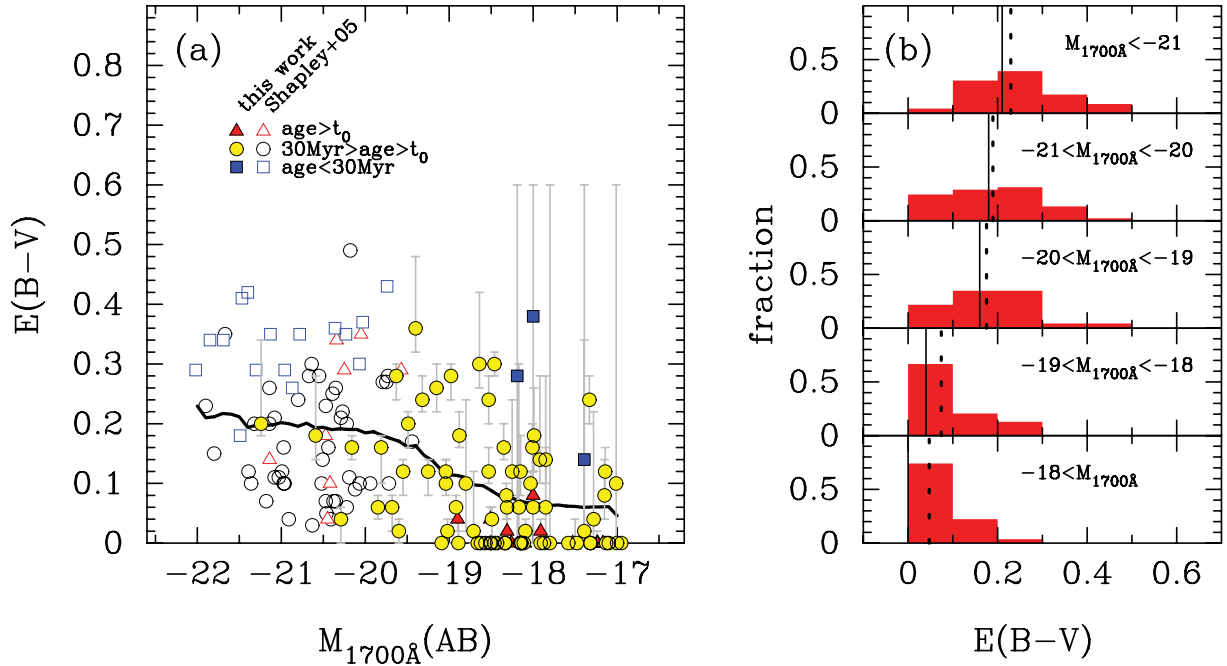


Figure 5. Dependence of extinction on UV luminosity. The left-hand panel shows colour excess values as a function of absolute UV magnitude (not corrected for extinction) with objects in different best-fitting ages indicated by different symbols. The black line shows the running mean $E(B - V)$ value, taken with a 2-mag-wide box. A systematic reduction in extinction towards fainter rest-frame UV luminosities can be seen. Note that no uncertainties are shown for the Shapley et al. (2005) data because these authors do not report them; however, their uncertainties are likely significantly larger than those at similar luminosities in the HDF. The right-hand panel shows the distributions of colour excess values for objects grouped by different UV magnitudes, with both the present HDF and the Shapley et al. (2005) samples treated jointly. The solid and dashed vertical lines in each plot mark the median and mean colour excess values, respectively. Again, a decrease in the amount of extinction can be seen with decreasing UV luminosity.

Table 2. Extinction as a function of UV magnitude. The uncertainties given are simple rms measurements. The stellar masses are estimated using the $M_{1700} - M_{\text{stars}}$ relation given by equation (7).

UV magnitude	$\log(M_{\text{stars}}/M_{\odot})$	Median $E(B - V)$	Mean $E(B - V)$	Mean A_{1700}
$M_{1700} < -21$	>10.60	0.21	0.23 ± 0.10	2.24 ± 0.98
$-21 < M_{1700} < -20$	10.35	0.18	0.19 ± 0.11	1.84 ± 1.07
$-20 < M_{1700} < -19$	9.84	0.16	0.18 ± 0.11	1.75 ± 1.07
$-19 < M_{1700} < -18$	9.33	0.04	0.07 ± 0.09	0.68 ± 0.88
$-18 < M_{1700}$	<9.07	0	0.04 ± 0.07	0.39 ± 0.68

mass correlates with the emergent UV luminosity in these objects. With this in mind, Fig. 6 examines the dependence of stellar mass on UV magnitude (not corrected for dust) and shows that there is a strong correlation between stellar mass and UV luminosity. This correlation is unlikely to be an artefact of an observational bias: concentrating on the HDF-BX sample, where the data cover a relative large luminosity baseline, one does not see any luminous ($M_{1700} \sim -20$) undermassive ($10^8 - 10^9 M_{\odot}$) galaxies, although the data are deep enough to identify such objects were they present in significant numbers; similarly, not many overmassive galaxies are found at the faint end of the population, though such galaxies, too, would be easily detected if present in significant numbers. The $M_{1700} - M_{\text{stars}}$ relation in Fig. 6 thus appears to be real.

The relation in Fig. 6 can be fitted as

$$\log\left(\frac{M_{\text{stars}}}{M_{\odot}}\right) = (0.68 \pm 0.49) - (0.46 \pm 0.03)M_{1700} \quad (7)$$

(black line in Fig. 6).¹ One important application of this relation is that it can be used to estimate BX galaxy stellar masses from optical (rest-frame UV) data alone without the need to resort to infrared (IR) observations. The uncertainties in the slope and intercept values given in equation (7) are strongly correlated (see the inset panel in Fig. 6), which means that the conversion between rest-frame UV magnitude and stellar mass is actually quite tight – much tighter than the one-dimensional uncertainties might imply at first glance.

Fig. 6 suggests that the $M_{1700} - M_{\text{stars}}$ relation is valid from M^* to $M^* + 4$, or over $M_{1700} = -21$ to -17 . It is not clear whether at brighter magnitudes, $M_{1700} < M^*$, the relation holds, given the apparent flattening of the data at $M_{1700} < M^*$, the lack of data

¹ Note that the values in equation (7) here are slightly different from those reported earlier in Sawicki et al. (2007) and subsequently used by others (e.g. Reddy & Steidel 2009) – these differences are due to the updated, deeper sample that is used in this work.

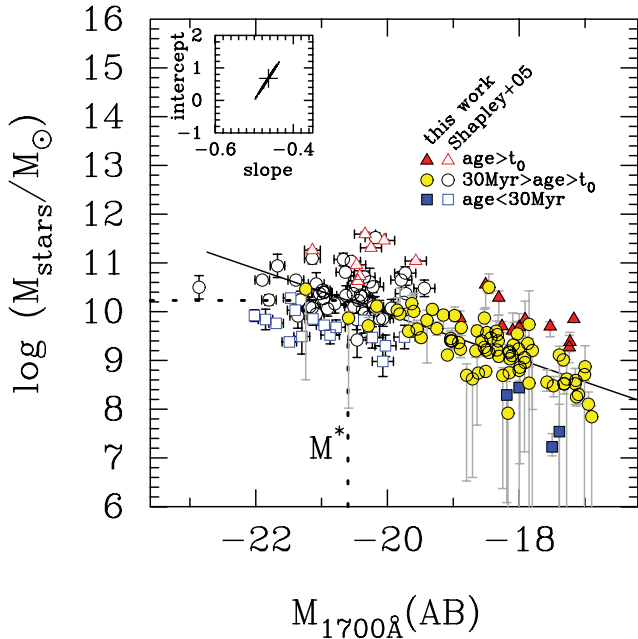


Figure 6. Stellar mass as a function of UV magnitude. The best fitting line is described by equation (7) and UV magnitudes are *not* corrected for dust. The different symbol shapes show objects in different age ranges (constant SFR histories have been assumed for all objects). The objects marked with triangles are older than the approximate age of the Universe at $z = 2.3$. The 1σ error contour for the best-fitting line is shown in the inset.

beyond $M_{1700} = -22$, and the expectation that different physics play a role above the knee of the LF. Although no data exist at $M_{1700} > -17$, it is plausible that the relation extrapolates well to fainter galaxies.

The results of Fig. 6 and equation (7) are robust in that they do not change dramatically if HDF-BX objects outside the $1.8 \leq z_{\text{phot}} \leq 2.6$ range are included: the scatter in the relation increases and the slope of the relation steepens somewhat, but these changes are not unexpected since the stellar masses are then poorly constrained, particularly at $z_{\text{phot}} > 2.6$. It is therefore preferable to use only the restricted $1.8 \leq z_{\text{phot}} \leq 2.6$ HDF-BX sample, as is done through the rest of this paper.

It should be kept in mind that the galaxies here are UV selected, so the data in Fig. 6 are certainly not representative of the entire $z \sim 2$ galaxy population as they could miss, for example, quiescent galaxies, or very heavily dust obscured ones. However, when applied to UV-selected samples, the observed mass–luminosity correlation gives an interesting tool for studying galaxy evolution: for example, it can link UV-selected samples from different studies (e.g. KDF IV), or provide a way to convert deep LFs into MFs (Section 5.1; also Reddy & Steidel 2009). It also hints at an underlying correlation between SFR and stellar mass (Section 4.5). It is thus worth examining in more detail.

The rms scatter in the $M_{1700}-M_{\text{stars}}$ relation for the combined, Shapley + HDF-BX, sample is ~ 0.4 in $\log M_{\text{stars}}$. Within the HDF-BX sample the scatter goes down from high values at the faint/low-mass end as one moves to the more luminous/massive galaxies. Monte Carlo simulations that perturb the photometry of the HDF-BX galaxies indicate that the observed scatter is entirely consistent with random photometric scatter from an intrinsically perfectly tight relation described by equation (7).

The $M_{1700}-M_{\text{stars}}$ trend becomes clear only when the data are extended below L^* and may well be absent in the more luminous BX galaxies alone. One explanation for the absence of correlation in the Shapley et al. (2005) sample is that large photometric scatter in their relatively shallow ground-based data is propagated into their stellar mass estimates. An alternative explanation stems from the fact that Shapley et al.’s galaxies, which have higher masses and larger SFRs, have a much larger intrinsic range of dust extinctions than do the fainter HDF objects (Section 4.2). If this is the case, then at the brighter magnitudes studied by Shapley et al. (2005) the stellar mass–UV luminosity correlation may be naturally broad, making in-the-mean trends difficult to discern. In contrast, the fainter HDF-BX galaxies, which suffer less extinction, are less affected and so hold truer to the underlying correlation. In either case, the deep HDF data allow the luminosity–mass trend among sub- L^* BX galaxies to stand out.

In Fig. 6, the blue squares mark objects whose best-fitting ages are extremely young (younger than 30 Myr), while the red triangles flag objects whose best-fitting ages are older than the age of the Universe. Note that at a given UV magnitude, these seemingly very young objects tend to have stellar masses that are low relative to the norm, while the objects with very old age fits have masses that are high. This trend would at first glance appear consistent with the build-up of stellar mass with time in galaxies. However, as tempting as this conclusion may appear, it may not be warranted, given the random uncertainties due to photometric errors and the systematic ones due to assumptions about star formation histories that were discussed in Section 4.1.

Next, it is interesting to consider what is the stellar mass of a ‘typical’ (i.e. L^*) BX galaxy at $z \sim 2.3$. To this end, the vertical dashed line in Fig. 6 indicates the location of the L^* ‘knee’ of the BX galaxy LF ($M_{1700}^* = -21.0^{+0.5}_{-0.6}$ at $z \sim 2.3$ –Section 5.1; see also KDF II; Reddy & Steidel 2009); the corresponding characteristic stellar mass at the knee is $M_{\text{stars}}(L_{1700}^*) = (2.60^{+2.33}_{-1.08}) \times 10^{10} M_{\odot}$. This characteristic stellar mass is a factor of several lower than the bimodality transition mass that separates low- z galaxies into two distinct families [$\sim 6 \times 10^{10} M^*$; Kauffmann et al. 2003 after adjusting from their Kroupa (2001) IMF to the Salpeter IMF used here] or the characteristic mass in the local IR-selected galaxy LF (Cole et al. 2001).

4.4 Ages and star formation histories

What can we learn about the ages and star formation histories of sub- L^* galaxies from the results of SED fitting? As was pointed out in Section 4.1, best-fitting ages are highly dependent on the assumed star formation history and consequently it is impossible to say anything absolute about the ages of the star-forming episodes that we observe in the individual BX galaxies. Moreover, correlated uncertainties in the best-fitting parameters can make even relative age trends uncertain: for example, Monte Carlo simulations that perturb the photometry of the HDF-BX galaxies confirm this view, showing that the apparent age trends seen in Fig. 6 are likely simply a result of photometric scatter. Naively, one might be tempted to conclude that the objects fitted with very old ages have declining star formation histories and are thus overmassive for their SFRs, and the objects fitted with very young ages are experiencing transient bursts of star formation. However, Monte Carlo simulations show that the distribution seen in Fig. 6 can be produced by random photometric scatter of a uniform population in which all objects have identical, moderate ages and are forming stars at a fixed (though

object-dependent) rate. The apparent age trends in Fig. 6 are simply a result of correlated errors in best-fitting parameters.

On the positive side, the existence of the luminosity–stellar mass and SFR–stellar mass correlations (Fig. 6) suggests that star formation histories in $z \sim 2$ BX galaxies may be relatively smooth rather than rapidly fluctuating. Turning to the HDF-BX sample, where the photometric uncertainties are smaller and consequently so is random scatter in the best-fitting parameters, the tightness of the correlation and the relative small number of outliers are impressive. Were the majority of the galaxies in the sample undergoing significant recent bursts of star formation, one would expect to see many more outliers than are observed. This fact has three important consequences: first, it validates the assumption of constant star formation histories, which was made in the SED fitting (Section 3); secondly, it suggests that by $z \sim 2$ many star-forming galaxies have been forming stars in a relatively steady mode for significant periods of time, rather than being dominated by frequent bursts or other fluctuations to their star formation history; and, thirdly, it suggests that there is not a large population of galaxies with very large stellar masses hidden by small amounts of new star formation.

In summary, while any age trends seen in the best-fitting results are unlikely to be real, the existence of the M_{1700} – M_{stars} correlation suggests that star formation in sub- L^* UV-selected galaxies at $z \sim 2$ may be approximately constant rather than highly variable.

4.5 Relation between SFR and stellar mass

The correlation between rest-frame UV magnitude and mass (Section 4.3; Fig. 6) may seem unexpected at first, but it is not surprising given that – for sub- L^* galaxies – dust corrections are rather small: unlike for the more massive objects, emergent UV luminosity is a reasonably good indicator of the SFR in a sub- L^* BX galaxy. Nevertheless, it is important and interesting to correct for dust attenuation, and such dust-corrected quantities are examined in this section.

Fig. 7 shows the dependence of the intrinsic (dust-corrected) SFRs on the galaxies’ stellar masses. The present BX galaxy results improve on a similar relation reported in Sawicki et al. (2007) by extending it to lower still stellar masses. It is remarkable that a SFR–stellar mass correlation can be seen at $z \sim 2.3$ over as much as three orders of magnitude in stellar mass.

Also shown in Fig. 7 is the location of the 24- μm -detected star-forming BzK (i.e. sBzK) galaxies studied by Daddi et al. (2007; beige oval), along with their best-fitting line to those data (pink line). Both the Daddi et al. sBzK sample and the Shapley et al. (2005) BX galaxies can be viewed as a high-mass extension of the HDF-BX galaxies studied in this work.

The Shapley et al. sample has two sizeable outlier populations that are puzzling and likely unphysical artefacts: the small red triangles are objects that were fitted with ages older than the age of the Universe (~ 2.8 Gyr at $z \sim 2.3$), while the small blue squares mark objects with very young ages (< 30 Myr). Each population lies on a distinct locus from the moderately aged objects in their sample – possibly an artefact of their fitting procedure. In light of this, it might be preferable to use the Daddi et al. zBzK objects as a high-mass complement of the faint HDF-BX sample, but for the sake of commonality of selection techniques it was decided to use the Shapley et al. BX galaxies after rejecting their two outlier populations.

Ignoring the two extreme-age outlier populations in both the Shapley et al. data and the present HDF-BX sample, the BX galaxy

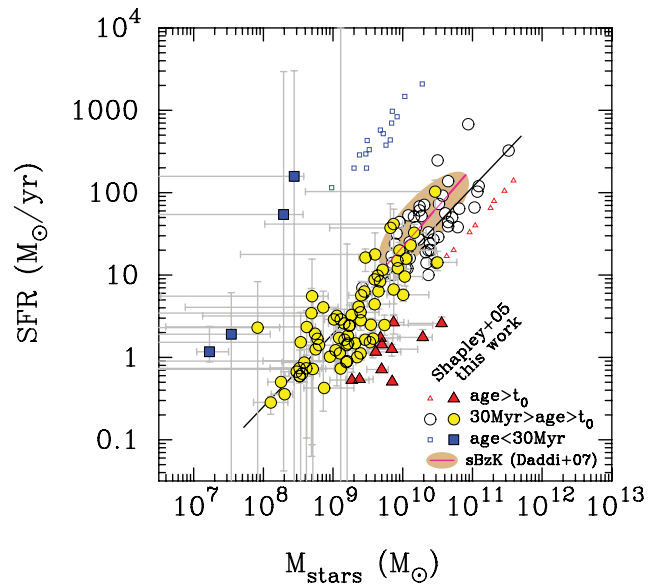


Figure 7. The dependence of SFR on stellar mass. No error bars are shown for the Shapley et al. (2005) data as these authors do not provide uncertainties on their SFR measurements. The black line shows the fit to the combined HDF-BX and Shapley et al. BX populations, after the extreme-age outlier objects have been removed (see Section 4.5). The beige region and pink line show the locus of the 24- μm -detected sBzK galaxies of Daddi et al. (2007) and their fit to those data.

SFR–stellar mass relationship is fitted by

$$\log \left(\frac{\text{SFR}}{M_{\odot} \text{ yr}^{-1}} \right) = (0.89 \pm 0.03) \log \left(\frac{M_{\text{stars}}}{M_{\odot}} \right) - (7.69 \pm 0.27), \quad (8)$$

which is shown as the black line in Fig. 7. Note that using the sBzK galaxies instead of the BX galaxies of Shapley et al. would produce a similar fit to the overall population, with perhaps just a slightly steeper slope.

Taken at face value, the correlation between stellar mass and SFR (equation 8) suggests that the rate at which a galaxy converts gas into stars (i.e. its SFR) is dictated by the mass in stars that the galaxy has already assembled. This seems surprising at first since one might expect that, for a constant SFR, stellar mass should increase with time, and such an increase should make galaxies drift off the relationship found above. Although evidence for such a drift may be sought in the presence of the massive, old galaxies in Fig. 7, the fairly small number of such galaxies in the HDF-BX sample suggests that the constant-SFR scenario is unlikely. Moreover, Monte Carlo simulations suggest that this massive old HDF-BX population can be produced by simple photometric scatter of a moderately aged population of galaxies that lie on the relation given by equation (8), thus further hinting that a different scenario may be at play. One such scenario, which posits that the galaxy’s SFR is proportional to the dark matter accretion rate of its growing dark matter halo, is examined in Section 5.4.

5 IMPLICATIONS

5.1 Updated LF and cosmic SFR density

One of the most basic yet important descriptors of a galaxy population is its LF and much effort has gone into characterizing the shape and evolution of the LF of high-redshift star-forming galaxies (e.g. Sawicki et al. 1997; Steidel et al. 1999; KDF II; Iwata et al.

2007; Reddy & Steidel 2009). This section revisits the faint end of the BX galaxy LF examined by KDF II, in order to update their result in light of the effects that luminosity-dependent extinction can play on the estimation of effective survey volume and, hence, on the number density of galaxies. It is important to be clear that this does not represent an attempt to correct the UV luminosities of galaxies for dust obscuration, but, rather, to better include the effect that dust has on the model galaxy colours needed to estimate the effective survey volume in the V_{eff} method of LF estimation.

Estimation of the LF is complicated by issues such as incompleteness corrections and proper determination of the survey volume. When dealing with colour-selected samples such as BX or LBGs, the survey volume can depend on assumptions made about the intrinsic colour distribution of high-redshift galaxies, which in turn can depend on the amounts of dust assumed to be present in these galaxies. In this respect, KDF II found that while LBG LFs at $z \sim 3$ and 4 are not strongly sensitive to such underlying assumptions about galaxy SEDs, the $z \sim 2.3$ BX galaxy LF can be. In particular, they pointed out that the assumed amount of reddening will affect the normalization of the BX galaxy LF (see their figs 7 and 8) and examined the impact of different amounts of assumed reddening on their LF results. However, lacking concrete knowledge of extinction in sub- L^* BX galaxies, the scenarios they examined assumed luminosity-invariant $E(B - V) = 0.15$. With the finding of luminosity-dependent extinction discussed in Section 4.2, it is now possible to revisit the previous analysis and to better constrain the shape of the BX galaxy LF.

The LF analysis of KDF II used the effective volume (V_{eff}) method and their data are re-analysed here using the same approach but using magnitude-dependent $E(B - V)$ values when constructing the mock galaxies used in gauging the redshift selection function and the effective volume of the survey, V_{eff} . To this end the KDF fiducial dust-corrected 100-Myr starburst model is modified to accommodate magnitude-dependent dust following the prescription given by interpolating the values in Table 2; the resulting adjusted LF is shown as points in Fig. 8. The Schechter

function (Schechter 1976) fitted to these data is shown with the thick solid line; the Schechter function parameters are $M^* = -21.0_{-0.6}^{+0.5}$, $\phi^* = (-2.74_{-0.35}^{+0.28}) \times 10^{-3} \text{ Mpc}^{-3}$ and $\alpha = -1.47_{-0.21}^{+0.24}$. Using the observed distribution of $E(B - V)$ values (as did Steidel & Reddy 2009) rather than medians (as was done above) produces almost identical results. Some differences with the original $z \sim 2.3$ KDF LF are apparent.

Fig. 8 compares the updated, variable dust LF with the original constant-dust KDF fiducial result shown as the continuous light-blue line. The most dramatic change from the original result lies in the slope of the faint end of the LF: there are more faint BX galaxies than in the original LF, and the faint-end slope of the Schechter function has steepened from $\alpha = -1.20_{-0.22}^{+0.24}$ to $-1.47_{-0.21}^{+0.24}$. These changes are to be expected, given that for low dust values the original KDF work predicted smaller V_{eff} end hence higher LF normalizations. Given the evidence for luminosity-dependent extinction (Section 4.2), the updated $z \sim 2.3$ LF presented here should be regarded as more accurate than the original KDF one.

Fig. 8 also shows the $z \sim 2$ LF determined by Gabasch et al. (2004) from their FORS Deep Field, and that determined by Reddy & Steidel (2009) from their large, deep BX samples. All the LFs agree reasonably well at the bright end, but differ at the faint end. The faint end of the original KDF LF was already steeper than the Gabasch et al. (2004) FORS LF, and the improved, dust-corrected KDF result is steeper still. However, the adjusted KDF faint-end slope is not as steep as that of Reddy & Steidel (2009), even if the more extreme models are used (grey lines) instead of the fiducial one. At $M_{1700} = -18$ the Reddy & Steidel (2009) LF contains two to three times more BX galaxies than does the adjusted KDF one. There are several possible reasons for this difference: although Reddy & Steidel (2009) used the same BX sample selection technique as did KDF II, they (1) had more area, (2) used a different LF estimator, and (3) used magnitude-dependent extinction corrections to model galaxy SEDs in estimating survey volumes. Reddy & Steidel (2009) suggest that the discrepancy is due to the difference in LF estimators; this suggestion remains to be tested by analysing a common data set using the two different techniques.

In the original KDF work, KDF II discussed the evolution of the UV LF, and KDF III examined the contributions of different luminosity galaxies to the UV luminosity density of the Universe. Both these papers acknowledged the possibility of a dust-dependent systematic uncertainty at $z \sim 2.3$ in these measurements. Now both the LF evolution plot and the UV luminosity density plot can be updated at $z \sim 2.3$ and these updated measurements are shown in Fig. 9. Overall, the luminosity-downsizing picture presented in the KDF papers remains unchanged: the most luminous galaxies disappear most quickly, and the least luminous ones persist the longest. Sub- L^* galaxies (where $L^* = -21.0$ as at $z \sim 3$) dominate the luminosity density at all redshifts.

As Fig. 9(b) shows, galaxies fainter than the $z \sim 2.3 L^*$ dominate the UV luminosity density of the Universe at all epochs. At the $z \sim 2.3$ epoch that is the focus of this paper, sub- L^* galaxies contribute 84 per cent of the rest-frame 1700 Å luminosity density that escapes from galaxies into intergalactic space, a result that is consistent with the earlier findings of KDF III and Reddy & Steidel (2009). Assuming that absorption by neutral hydrogen gas is not stronger in sub- L^* galaxies than in more luminous objects, it is then reasonable to conclude that sub- L^* galaxies are responsible for the bulk of the ionizing photons escaping into the intergalactic medium at these epochs. Sub- L^* galaxies thus may make a key contribution to keeping the Universe ionized at $z \sim 2$.

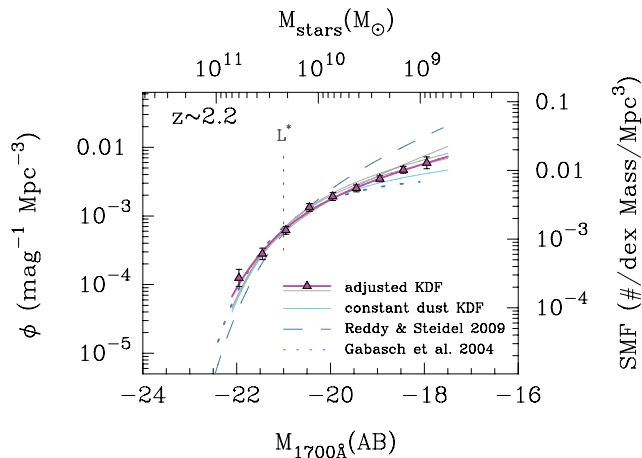


Figure 8. The UV-selected galaxy LF at $z \sim 2.3$. The data points show the Sawicki & Thompson (2006) result updated for the effects of magnitude-dependent attenuation. The heavy solid curve shows the Schechter fit to the data, while the light-coloured curves are fits to other implementations of the V_{eff} correction (see KDF II for details). The Reddy & Steidel (2009) and Gabasch et al. (2004) LFs are shown for comparison. Because of the tight correlation between UV luminosity and stellar mass (see Section 4.3), the LF can be readily used to estimate the stellar MF, shown here with the other top/right-hand axes.

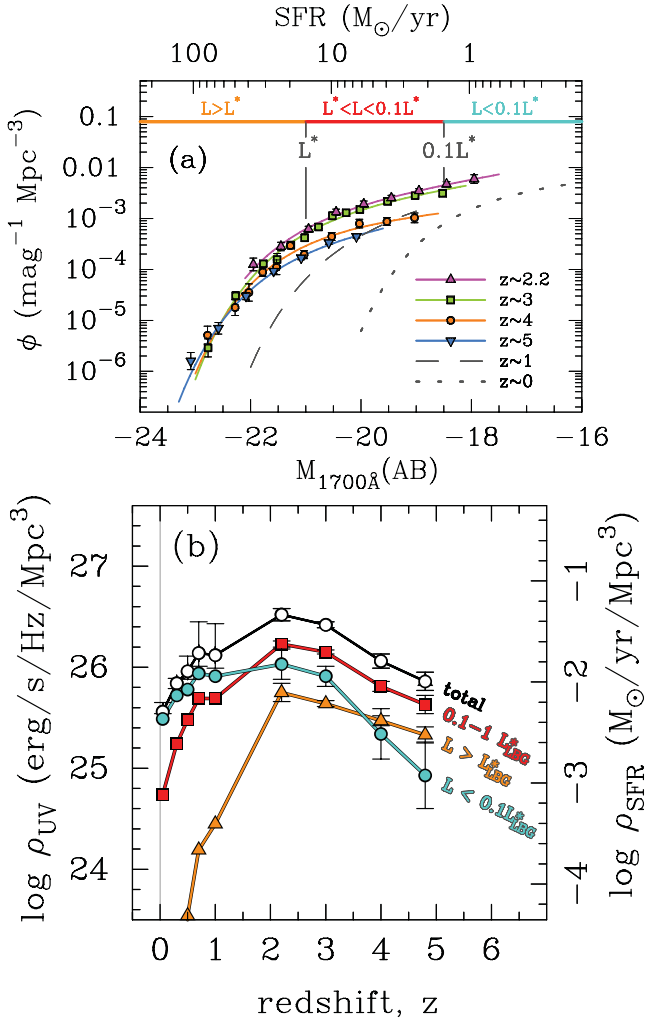


Figure 9. The LF (top panel) and luminosity density (bottom panel) updated from the original KDF II and Sawicki & Thompson (2006b, hereafter KDF III) analyses at $z \sim 2.3$ to account for the magnitude-dependent dust corrections on V_{eff} . The $z \sim 3$ and 4 values are unchanged from the original KDF, where magnitude-dependent dust does not affect V_{eff} estimates significantly. The $z \sim 5$ LF is from the Subaru/Suprime-Cam study by Iwata et al. (2007) and the $z \sim 1$ and 0 LFs are from the *GALEX* results of Wyder et al. (2005) and Arnouts et al. (2005). In the bottom panel, the comoving UV luminosity densities are calculated from the LFs of the top panel. The total luminosity density is shown along with its contributions due to galaxies in different luminosity bins.

5.2 Stellar mass function and the stellar mass density of the Universe

The correlation between UV luminosity and stellar mass seen in Fig. 6 (and equation 7) invites a straightforward conversion from the UV LF to a stellar MF. This conversion can be accomplished by using equation (8) to recalibrate the axes on a UV LF plot, as is done in Fig. 8 where the top and right-hand axes recast the observations in terms of a stellar MF. After this conversion, it is clear that at $z \sim 2$ the number of low-mass BX galaxies is significantly higher than that of high-mass ones: by number, low-mass galaxies are a very important population at $z \sim 2$.

The MF thus obtained is also plotted with symbols and the thick solid line in Fig. 10(a). Several other $z \sim 2.2$ stellar MFs are also shown, namely those of Reddy & Steidel (2009; $z \sim 2.3$), Fontana

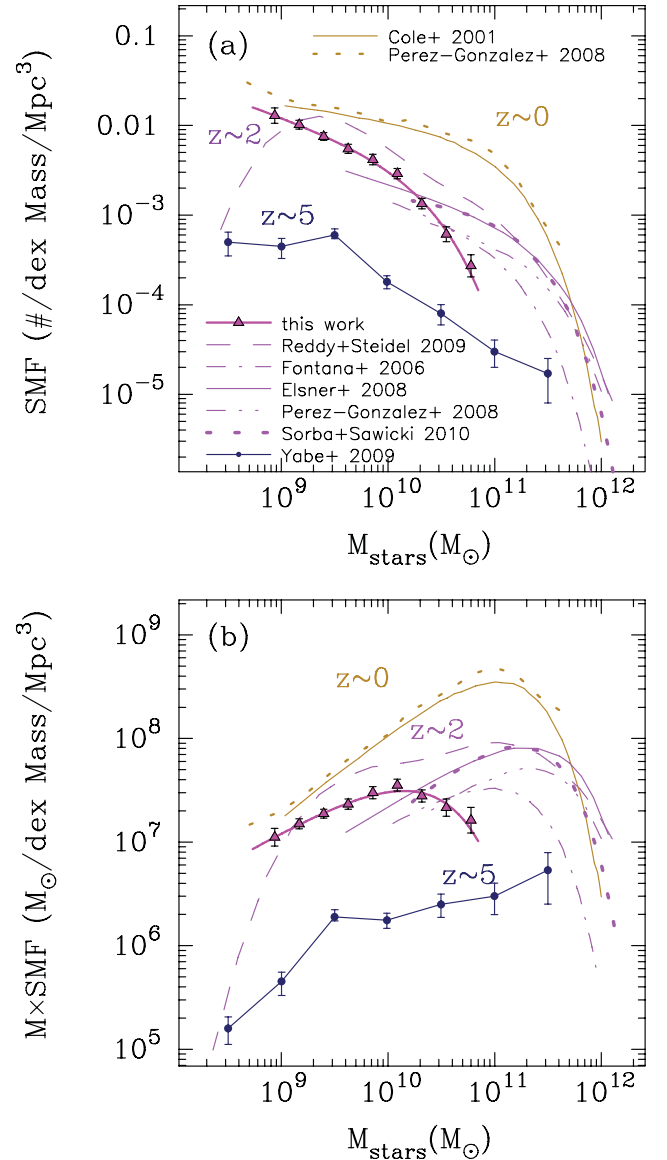


Figure 10. The stellar MF. The top panel shows measurements of the stellar MF at different redshifts. At $z \sim 2$ several determinations are shown, including that by Reddy & Steidel (2009), which, at the low-mass end, uses an earlier version of the HDF-BX UV luminosity to stellar mass conversion presented in this work (Sawicki et al. 2007). Where needed, all the results have been converted to the Salpeter (1955) IMF. The bottom panel shows the mass-weighted stellar MFs. A clear picture of the buildup of stellar mass over cosmic time can be seen.

et al. (2006; $z \sim 2.5$), Elsner, Feulner & Hopp (2008; $z \sim 2.0$), Pérez-González et al. (2008; $z \sim 2.25$) and Sorba & Sawicki (2010; $z \sim 2$). With the exception of the Reddy & Steidel (2009) MF, all these MFs are based on mass-selected samples; the Reddy & Steidel (2009) MF uses BX selection, with direct stellar mass measurements from SED fitting of bright galaxies and an earlier version of the HDF-BX SFR to mass conversion (Sawicki et al. 2007) to estimate the contribution of faint galaxies. Consequently, their results are not entirely independent of the present ones, but share a degree of commonality at the low-mass end. Crucially for probing low-mass galaxies, the present HDF work (and the related results of Reddy & Steidel 2009) reaches an order of magnitude in mass deeper into the low-mass end of the $z \sim 2$ population than do the other studies. This

is important, given the large number of low-mass galaxies present at $z \sim 2$. It is interesting to note that the deeper studies (Reddy & Steidel 2009; present work) yield a larger number density of low-mass galaxies than would be inferred from extrapolations of the shallower surveys.

At the low-mass end of the MF, differences between the present MF result and that of Reddy & Steidel (2009) are due to a combination of differences at the faint end of the input LFs (as shown in Fig. 8) and differences in the luminosity to mass conversion procedures. For the latter, Reddy & Steidel (2009) used an earlier version of equation (8) that was presented in Sawicki et al. (2007) along with their own model of magnitude-dependent dust. Consequently, their results include the potentially non-cancelling effect of two different dust corrections: one, from the SED fitting of Sawicki et al. (2007), to get from observed M_{UV} to SFR, while the other, based purely on UV slope, to get back from SFR to M_{UV} . In contrast, the procedure used in this work is more direct as it bypasses any assumptions about dust corrections on UV luminosity by simply using the empirical relationship between directly observed UV luminosity and stellar mass (equation 7). For more massive galaxies, the difference in the stellar MFs arises because Reddy & Steidel used direct SED fits that their large sample of $\sim L^*$ BX galaxies afforded them – an approach that is preferable to using a luminosity to mass conversion which necessarily breaks down for these more dusty, luminous objects. Overall, however, the two MF determinations are in reasonable agreement and both emphasize that there is a large number of low-mass galaxies at $z \sim 2$.

At the high-mass end, the differences between the various $z \sim 2$ studies are quite pronounced, with differences of an order of magnitude or more in the number density of 10^{12} - M_{\odot} galaxies between the various surveys. However, regardless of which of the high-mass end results prove closer to the truth, it is clear that both high-mass and low-mass galaxies contribute significantly to the stellar mass density of the Universe at $z \sim 2$. This fact is illustrated further in Fig. 10(b) which shows the mass-weighted stellar MF.

Fig. 10 also shows examples of stellar MFs in the local Universe (Cole et al. 2001; Pérez-González et al. 2008). It has been known that the high-mass end of the stellar MF was largely in place by $z \sim 2$ (e.g. Pérez-González et al. 2008). However, the present data (and those of Reddy & Steidel 2009) on the low-mass end suggest that the number density of low-mass galaxies at $z \sim 2$ was also quite high, within a factor of ~ 2 or so of the local number density for $M_{\text{stars}} \sim 10^9 M_{\odot}$ galaxies. If true, it would appear that the bulk of the growth since $z \sim 2$ has been in the number of mid-weight galaxies ($M_{\text{stars}} \sim 10^{11} M_{\odot}$).

Fig. 10 also shows the $z \sim 5$ stellar MF of Yabe et al. (2009). Overall, there is clear growth in the stellar MF across the redshift range covered, which is also reflected in the growth of the total mass density of the Universe – a quantity that has been extensively studied over the past few years. Fig. 11 presents a compilation of stellar mass density results from several studies. In all the data shown, the stellar mass density has been integrated down to $1 \times 10^8 M_{\odot}$, although in all cases this involved an extrapolation from higher mass data since no study at high redshift has yet reached such low-mass galaxies directly. Integrating further, to $M = 0$, would not add appreciably to the stellar mass densities because the contribution of galaxies with $M < 10^8 M_{\odot}$ is small, as can be seen in Fig. 10(b). The open symbols at high redshift show the results of various shallower studies, while the orange point shows the mass density in low-mass galaxies (integrated down to $10^8 M_{\odot}$) as inferred from this work.

As Fig. 11 illustrates (open symbols), the accepted view is that stellar mass density builds up over cosmic time with perhaps ~ 1

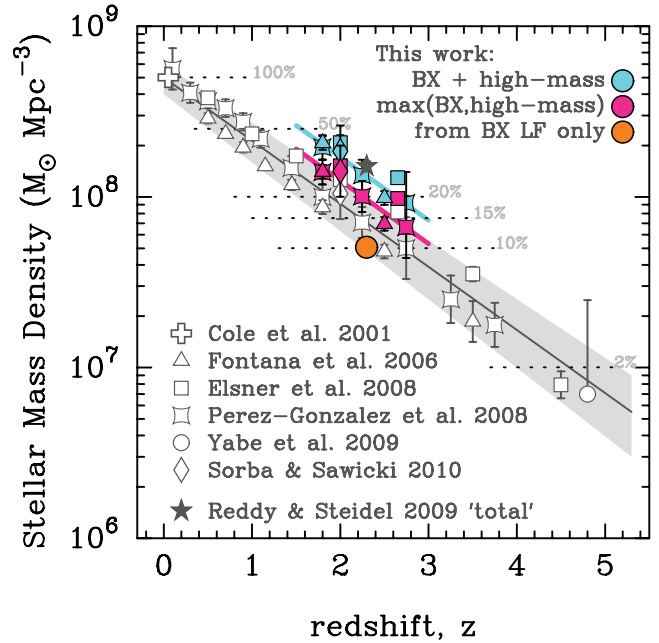


Figure 11. Evolution of the comoving stellar mass density. All measurements are adjusted to the $0.1 > M/M_{\odot} > 100$ Salpeter IMF and integrated down to $1 \times 10^8 M_{\odot}$. The orange ‘from BX LF only’ point is derived by converting the UV LF to a MF using the light to mass conversion of equation (7). The blue and magenta points result from combining the shallower measurements with the deeper results of this study. See text for more details (Section 5.2). The horizontal dashed lines indicate the fraction of the assembled present-day stellar mass, as labelled. The grey region and line are an approximate representation of the growth of the $M_{\text{stars}} > 10^8 M_{\odot}$ stellar mass density as inferred by shallower surveys (unfilled symbols).

percent of the present stellar mass density being in place at $z \sim 5$, ~ 15 percent by $z \sim 2.3$, and ~ 50 percent by $z \sim 1$. The present BX-based measurement matches that picture (orange point in Fig. 11). However, neither the shallower studies nor the present, deeper, HDF study accounts fully for the total mass, even with extrapolations to low or high masses.

To account for both low-mass and high-mass galaxies properly, one should combine the results of the two types of studies. The blue and magenta points show the consequence of doing this combination in two different ways. The magenta points were obtained by taking the maximum of the low-mass² and high-mass stellar MFs in each mass bin and then integrating to $M = 10^8 M_{\odot}$; they likely underestimate the mass density at intermediate masses ($\sim 3 \times 10^{10} M_{\odot}$) where both the high-mass and low-mass measurements are likely deficient. The magenta points are thus conservative estimates of the total stellar mass densities. The blue points were obtained by summing, in each mass bin, the low-mass and high-mass measurements and then integrating over the mass range down to $10^8 M_{\odot}$; because summing the MFs effectively double-counts galaxies where the two MFs are approximately equal ($\sim 3 \times 10^{10} M_{\odot}$), the blue points are a plausible upper limit to the stellar mass density.

The resulting ‘total’ stellar mass densities (blue and magenta points in Fig. 11) are higher than the extrapolations of either the

² Before combining it with each of the high-mass results at $2.6 < z < 3$, the $z \sim 2.3$ low-mass stellar MF of this study was shifted in number density following the solid black line in Fig. 10 to reflect its likely evolution with redshift.

shallower survey results or the present results alone. Specifically, after correcting for the steep low-mass end of the stellar MF, the total stellar mass densities are ~ 1.5 – 2 times higher than those obtained from extrapolations of the shallower surveys. These higher stellar mass densities are in agreement with the ‘total’ stellar mass density found by Reddy & Steidel (2009; star symbol) using their directly determined stellar masses at the bright end in combination with a LF-derived contribution for the low-mass end, which they obtained using their UV LF and UV to SFR conversion, and the SFR to mass conversion of Sawicki et al. (2007).

Altogether, it thus seems that while the broad picture of a gradual build-up of stellar mass over time remains correct, the actual stellar mass density at $z \sim 2$ is higher, by a factor of ~ 1.5 – 2 , than those extrapolated from observations of the more massive galaxies alone. Apparently, by $z \sim 2.3$ the Universe had already made ~ 25 per cent of its present-day stellar mass instead of the ~ 15 per cent that most of the shallower measurements suggest. In other words, the build-up of stars in the high-redshift Universe has proceeded more quickly than was previously thought.

5.3 Dust content as a function of galaxy stellar mass

The dependence of extinction [parametrized as colour excess, $E(B - V)$] on galaxy stellar mass is shown in Fig. 12. Overall, it appears that galaxies with higher stellar masses are also more heavily extinguished. A similar trend is seen in the local Universe, where several potential explanations for this phenomenon are usually offered: (1) more massive galaxies may have built up

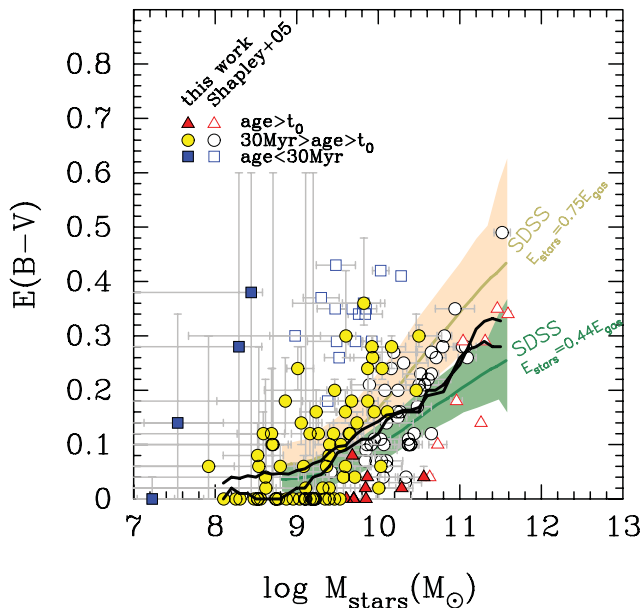


Figure 12. The dependence of colour excess $E(B - V)$ on stellar mass. Shapley et al. (2005) do not provide uncertainty estimates on their $E(B - V)$ measurements, so only stellar mass uncertainties are plotted for their sample. The black curves show the running mean and median $E(B - V)$ values (upper and lower curves, respectively) taken with a box of width $\log M_{\text{stars}} = 1$, after excluding galaxies with age $> t_0$ and age < 30 Myr. The coloured solid lines and shaded regions show two implementations of the local reddening–stellar mass correlation found in SDSS galaxies by Garn & Best (2010): green marks the fiducial relation, while tan shows what might happen if, for example, star formation were more globally distributed within high- z galaxies than is the case in local starbursts.

larger dust reservoirs than have the less massive ones; (2) more actively star forming galaxies may have larger and more dusty star-forming regions; and (3) more metal rich galaxies may have higher dust-to-gas ratios and, consequently, higher extinctions. Based on a large SDSS sample of local galaxies, Garn & Best (2010) argue that stellar mass is the underlying cause of the variation in extinction between galaxies, with the SFR and metallicity correlations resulting as a byproduct of the underlying dust–stellar mass correlation. It is plausible that this is also the case at $z \sim 2$, although the data at high redshift are not yet adequate to perform an analysis similar to that of Garn & Best (2010) beyond the local Universe.

It is interesting to compare the $z \sim 2$ results of this study with those for the local Universe (Garn & Best 2010). To do so, it is necessary to account for the methodical differences between the studies, since in the present $z \sim 2$ SED-fitting study extinction results are based on stellar continua, while Garn & Best (2010) used the Balmer decrement between nebular emission lines. This methodological difference is significant because nebular line measurements probe sightlines to the excited gas that surrounds short-lived, intensely radiating massive stars, that is, to environments that are hostile to dust, while continuum measurements probe those to regions dominated by older, lower mass stars that are more benign. Calzetti et al. (2000) found that $E(B - V)_{\text{stars}} = 0.44E(B - V)_{\text{gas}}$ in local starburst galaxies, likely reflecting such geometrical differences. Using this relation along with the Calzetti et al. (2000) starburst extinction curve, and adjusting for differences between IMFs in the present (Salpeter IMF) and the Garn & Best (2010; Kroupa IMF) studies, it is then possible to plot the Garn & Best (2010) SDSS results in Fig. 12. For the canonical $E(B - V)_{\text{stars}} = 0.44E(B - V)_{\text{gas}}$ of Calzetti et al. (2000), these are shown using the green line and shaded region. In the mean, there is reasonable agreement between the $z \sim 2$ population and the local result.

While in the mean the local and $z \sim 2$ relations are in reasonable agreement, the large amount of scatter seen at $z \sim 2$ implies that there are many high- z galaxies that are significantly above the local relation, as well as others that are below it. Garn & Best (2010) suggested that the local extinction–stellar mass relation can be used to predict the extinctions of high- z galaxies of known stellar mass, but doing so can be problematic for individual objects, given the large scatter seen in the $E(B - V) - M_{\text{stars}}$ plot at $z \sim 2$.

Nevertheless, the fact remains that at $z \sim 2$ there appears to exist a correlation between dust and galaxy stellar mass. It is then interesting to consider what may be its root cause. One possible explanation may lie in the correlation between stellar mass and metallicity (Pettini et al. 2001; Erb et al. 2006). These authors found that more massive high- z galaxies are also more metal rich, and one could speculate that the more massive objects contain more dust because they contain larger fractions of the elements required to produce dust grains. However, this is not the only possible explanation: for example, it is also possible that lower mass galaxies are also physically smaller and thus – for a fixed physical gas and dust density – they present lower column densities of both gas and dust. A similar trend would also result if galaxy sizes were constant as a function of stellar mass, but with more massive galaxies having higher densities of both stars and dust-bearing gas. An examination of physical sizes of $z \sim 2$ galaxies as a function of their stellar mass may shed light on this issue, although such analysis is beyond the scope of this paper. Finally, it is worth pointing out again that in the local Universe Garn & Best (2010) found that the primary driver of extinction is not metallicity but rather galaxy stellar mass, with metallicity (and SFR) being indirectly linked to extinction by virtue of all of them being

correlated with the more fundamental quantity, that is, galaxy stellar mass. Although $z \sim 2$ samples are not yet suitable for a similarly detailed analysis, it is reasonable to suppose that at high redshift it is also stellar mass, rather than metallicity, that governs the amount of extinction.

5.4 A simple model for the growth of galaxy masses

The nearly-linear relationship between ongoing SFR and the accrued stellar mass that is evident in Fig. 7 (also equation 8) may, at first glance, appear puzzling. Simply put, if a galaxy is forming stars at a given rate, should it not, in short order, grow its stellar population so that it no longer lies on the observed SFR– M_{stars} relation? How does such a growing galaxy ‘know’ how to adjust its SFR as its stellar mass increases with time? This section develops a simple model that can account for this phenomenon.

5.4.1 How do BX galaxies choose their SFRs?

Let us assume that the SFR in a BX galaxy is simply related to the rate at which it is accreting new gas, modulated by the instantaneous, or nearly-instantaneous, star formation efficiency, f_* . The f_* here is more strictly defined as the fraction of the accreting gas that gets converted into stars, so that

$$\text{SFR} = \dot{M}_{\text{stars}} = f_* \dot{M}_{\text{gas}}. \quad (9)$$

This assumption is similar to that made by Tilvi et al. (2009) for Lyman α emitters (see also Bouché et al. 2010), but while Tilvi et al. included an on/off duty cycle of star formation in their objects, the correlation between SFR and stellar mass in BX galaxies (Fig. 7 and Section 4.4) suggests that steady-state star formation is appropriate here, making such a duty cycle unnecessary. Note that in this model the fraction of the accreting gas that fails to be converted into stars right away, namely $(1 - f_*)$, does not participate in star formation but remains in gaseous form indefinitely and even possibly leaves the dark matter halo: it can be thought of as having been shock heated, ejected or made otherwise unavailable for star formation on time-scales of relevance.

If gas and dark matter accrete out of the background on to a galaxy together, and some fraction of the gas gets converted into stars on a reasonably short time-scale, as explained above, then

$$\text{SFR} = f_* (\Omega_b / \Omega_{\text{dm}}) \dot{M}_{\text{dm}}, \quad (10)$$

where \dot{M}_{dm} is the host halo’s dark matter accretion rate and $\Omega_b / \Omega_{\text{dm}}$ is the cosmic baryon-to-dark matter ratio. Note that f_* and $\Omega_b / \Omega_{\text{dm}}$ in the above equation are degenerate and their values may vary somewhat from galaxy to galaxy, possibly in a systematic way, so long as their product remains fixed. Indeed, in practice, f_* is unlikely to be constant with galaxy mass due to various physical feedback effects at play.

With the help of equation (10), equation (8) can then be recast as

$$\log \left(\frac{\dot{M}_{\text{dm}}}{M_{\odot} \text{ yr}^{-1}} \right) = 0.89 \log \left(\frac{M_{\text{stars}}}{M_{\odot}} \right) - 7.69 - \log \left(\frac{f_* \Omega_b}{\Omega_{\text{dm}}} \right), \quad (11)$$

which implies that the stellar mass of a BX galaxy is nearly proportional to the dark matter accretion rate of its halo: $\dot{M}_{\text{dm}} \propto (M_{\text{stars}})^{0.89}$. Note that in this model more massive haloes accrete matter – both dark and baryonic – at a faster rate than do lower mass haloes. A galaxy’s SFR is proportional to the present baryonic mass accretion rate and the stellar mass is proportional to the integral of the past baryonic mass accretion rate, so it follows that

galaxies with high stellar masses also have high SFRs. This argument accounts for the observed correlation between SFR and stellar mass.

5.4.2 Dependence on dark matter halo mass

In Λ cold dark matter (Λ CDM) cosmologies, dark matter haloes accrete matter more quickly than do low-mass ones. One can then ask how will a galaxy’s properties depend on its dark matter halo mass in the model above. Using Λ CDM dark matter simulations, Tilvi et al. (2009; see their fig. 3) find that the growth rate of haloes can be approximated as

$$\log \left(\frac{\dot{M}_{\text{dm}}}{M_{\odot} \text{ yr}^{-1}} \right) = m \log \left(\frac{M_{\text{dm}}}{M_{\odot}} \right) + b, \quad (12)$$

with slope m and intercept b are nearly invariant over the redshift range $z = 6.6$ – 3.1 discussed in their work. Their $z = 3.1$ values (the lowest redshift they show) are $m = 0.85$ and $b = -6.35$ and $m = 0.8$ – 0.9 at higher redshifts. Although they do not show the accretion relation at lower redshifts, given its invariance at higher redshifts, it seems reasonable to adopt their higher redshift slope values, $m = 0.8$ – 0.9 , for $z \sim 2.2$ as well. The similarity in slopes with equation (11) then suggests that the observed SFR– M_{stars} correlation may be simply related to the halo mass accretion rate. Following this line of reasoning and combining equations (11) and (12), while taking $m = 0.9$ and $b = -6.4$ for simplicity and consistency with the lowest z simulation results, yields

$$0.9 \log \left(\frac{M_{\text{stars}}}{M_{\text{dm}}} \right) = \log(f_*) + \log \left(\frac{\Omega_b}{\Omega_{\text{dm}}} \right) + 1.3. \quad (13)$$

This equation simply states that the stellar-to-dark matter mass ratio in galaxies is related to the cosmic baryon-to-dark matter ratio via the instantaneous efficiency at which gas is converted into stars (f_*). The equation also provides an empirical calibration of this conversion rate, f_* , by allowed it to be determined from the BX stellar mass and SFR measurements combined with theoretical dark halo growth rates. Moreover, the fact that the slopes of the empirical relation for stellar mass growth (equation 11) and the Λ CDM model derived one for halo growth (equation 13) are similar suggests that the star formation efficiency may be constant over the mass range considered here.

5.4.3 Star formation efficiency in BX galaxies

With equation (13) in hand and a knowledge of stellar-to-dark matter ratio in $z \sim 2$ galaxies, it should then be possible to estimate the star formation efficiency. Deriving the $M_{\text{stars}}/M_{\text{dm}}$ ratio requires a combination of stellar mass and clustering measurements for $z \sim 2$ BX galaxies, and such measurements have not yet been done concurrently. However, the ratio can be estimated by combining separate measurements of luminosity dependence of stellar mass (such as in this work) with measurements of the luminosity dependence of halo mass (e.g. KDF IV). Simply put, one ties the two measurements, performed on similar but separate samples, by means of a common UV luminosity scale. The situation is complicated by the fact that while at higher redshifts, $z \gtrsim 3$, there appears to exist a well-established correlation between UV luminosity and halo mass (e.g. Giavalisco & Dickinson 1998; Ouchi et al. 2001; Adelberger et al. 2005), the results for UV-selected galaxies at $z \sim 2$ are still sparse and contradictory: Adelberger et al. (2005) find a correlation between UV luminosity and clustering strength among BX galaxies, while KDF IV, using an identically selected deeper

sample of BX galaxies in the KDF (Sawicki & Thompson 2005, hereafter KDF I), find a more complex relation that they interpret as due to confusion of the clustering signal by very massive haloes ($M_{\text{dm}} > 10^{12} M_{\odot}$) whose resident galaxies are in the process of shutting down their star formation (i.e. a manifestation of downsizing).

Despite this confused $z \sim 2$ clustering picture, it is nevertheless possible to put constraints on the $M_{\text{stars}}/M_{\text{dm}}$ ratio and hence on the star formation efficiency. Combining the stellar masses from this study with the deep BX clustering measurements from KDF IV gives $M_{\text{stars}}/M_{\text{dm}} \sim 0.01\text{--}0.005$ (see KDF IV for more details). Combining them instead with the clustering results of Adelberger et al. (2005) leads to $M_{\text{stars}}/M_{\text{dm}} \sim 0.06$. With these two results in hand, and assuming the cosmic baryon-to-dark matter mass ratio of $\Omega_{\text{b}}/\Omega_{\text{dm}} = 0.2$ (e.g. Komatsu et al. 2009), equation (13) then tells us that the star formation efficiency of $z \sim 2$ BX galaxies is $f_* \sim 0.2\text{--}2$ per cent, which is similar to the ~ 2.5 per cent derived for Lyman α emitters by Tilvi et al. (2009). Strictly speaking, because f_* and $\Omega_{\text{b}}/\Omega_{\text{dm}}$ are degenerate and their values may vary for individual galaxies, the value of f_* derived above is not expected to be constant from galaxy to galaxy. Systematic differences of factors of a few are likely over the range in mass spanned by the data (e.g. Behroozi, Conroy & Wechsler 2010), but these are smaller than the range of f_* values permitted by the range of plausible $M_{\text{stars}}/M_{\text{dm}}$ values adopted above. Overall, then, the model suggests that only a small fraction of the gas that falls into a BX galaxy's halo ends up condensing into stars, with the bulk of the accreted gas remaining unconsumed.

5.4.4 Limitations and implications for star formation histories

The simple model described above is remarkably successful at accounting for the observed correlation between SFR and accrued stellar mass in $z \sim 2$ UV-selected star-forming galaxies. The model would, clearly, fail were it to be applied to 'red and dead' galaxies at these redshifts such as passive BzK galaxies (Daddi et al. 2004) or distant red galaxies (DRGs; Franx et al. 2003). In such galaxies, star formation has largely shut down already and even though material is likely still being accreted on to them, some mechanism prevents it from being formed into stars. In the simple picture suggested in the model, this would be equivalent to a star formation efficiency that is much lower than that in the present sample.

The simple model likely also fails in UV-selected galaxies at higher redshifts, $z \sim 5$. While a SFR–stellar mass relation is observed there (Yabe et al. 2009), the assumption of constant SFR – as required by the dependence of SFR on halo mass accretion rate – would overproduce the masses observed in $z \sim 2$ star-forming galaxies of similar SFR (Ohta et al. 2008). This overshoot could potentially be resolved by invoking SFRs that decline with time, but this approach would require either an equally declining mass accretion rate (an unlikely proposition) or a time-variable star formation efficiency. Attractively, the $z \sim 5 \rightarrow 2$ mass overshoot could possibly also be resolved by an *increasing* SFR rate that would make galaxies more massive *and* more star forming over time and would be naturally consistent with the idea of increasing mass accretion rates that follows from the growing halo paradigm. Such increasing star formation histories have recently been discussed (e.g. Lee et al. 2010, 2011; Maraston et al. 2010; Papovich et al. 2011) and thus appear attractive on other grounds as well. In this respect, low-mass galaxies may be able to provide a clearer picture than that afforded by their more massive counterparts which likely suffer

more strongly from a variety of effects that act to complicate their star formation histories, thereby making the link to hierarchical models less direct.

In conclusion, despite its limitations, the simple model is nevertheless remarkable in that it successfully explains the observed correlation between SFR and accrued stellar mass in an important class of galaxies at $z \sim 2$ and it does so by invoking a simple and quite plausible mechanism whereby SFR is related directly to the growth rate of dark matter haloes, which is a fundamental feature of Λ CDM cosmologies.

6 SUMMARY AND CONCLUSIONS

This paper presents the results of an SED-fitting study of the stellar populations of sub- L^* UV-selected galaxies at $z \sim 2$. The main results of this study can be summarized as follows:

(i) *$L_{\text{UV}}\text{--}M_{\text{stars}}$ correlation.* Deep optical–IR observations show that there is a correlation between UV luminosity and stellar mass in sub- L^* BX galaxies (equation 7). The existence of this correlation suggests that star formation histories in many sub- L^* BX galaxies may be approximately constant with time, rather than dramatically variable. In addition to revealing such physical insights, the $M_{1700}\text{--}M_{\text{stars}}$ correlation allows a useful approximate conversion between rest-frame UV (observed optical) luminosities and stellar masses of BX galaxies, which can be used to estimate stellar masses when IR observations are unavailable.

(ii) *Stellar MF and stellar mass density of the Universe.* The low-mass end of the stellar MF at $z \sim 2.3$ is estimated from the UV LF function by means of the empirical $M_{1700}\text{--}M_{\text{stars}}$ relation. It is found that there are many low-mass galaxies at this epoch – the low-mass end of the BX stellar MF is steeper than predicted by extrapolations of shallower surveys at $z \sim 2$, with more low-mass galaxies present at this epoch than such extrapolations predict. These numerous low-mass galaxies contribute significantly to the stellar mass density at $z \sim 2.3$, increasing its values by a factor of ~ 1.5 compared to extrapolations from higher mass data alone. This upward revision means that by $z \sim 2.3$ the Universe has already made ~ 22 per cent of its present-day stellar mass, as compared to only ~ 15 per cent that the extrapolations of the shallower surveys would suggest. Apparently, the build-up of stellar mass in the Universe has proceeded somewhat more quickly than previously thought.

(iii) *Correlation between UV luminosity and interstellar extinction.* Sub- L^* BX galaxies appear to have less dust than their $\sim L^*$ counterparts. For example, more than half the UV photons produced by a typical $M^* + 3$ ($M_{\text{stars}} \sim 10^9 M_{\odot}$) galaxy escape into intergalactic space, in contrast to $L \sim L^*$ BX galaxies from which only about one in five UV photons escape absorption by dust. Sub- L^* BX galaxies are thus very important contributors to the UV luminosity density budget at $z \sim 2$.

(iv) *Correlation between interstellar extinction and stellar mass.* The data show that more massive $z \sim 2$ galaxies tend to be more dusty than lower mass galaxies. This trend is similar to that found in the local Universe, albeit with significantly larger scatter.

(v) *Updated UV LF and luminosity density of the Universe.* The dependence of reddening on UV luminosity results in a revision of the effective survey volume, V_{eff} , of the KDF survey at $z \sim 2.3$ (KDF II) and hence a revised $z \sim 2.3$ UV LF. The updated LF has a steeper faint-end slope, with $\alpha = -1.47^{+0.24}_{-0.21}$ (compared to the previous $\alpha = -1.20^{+0.24}_{-0.22}$), although this revised slope is not as steep as $\alpha = -1.73 \pm 0.13$ reported by Reddy & Steidel (2009).

Nevertheless, it is clear that sub- L^* galaxies at $z \sim 2$ are very numerous and contribute significantly to the UV luminosity density at this epoch, producing ~ 84 percent of the emergent 1700 Å luminosity density. If absorption by neutral hydrogen in sub- L^* galaxies is not stronger than in brighter objects, then sub- L^* galaxies make a key contribution to keeping the Universe ionized at these redshifts.

(vi) *SFR– M_{stars} correlation.* A correlation between SFR and stellar mass exists in $z \sim 2.3$ galaxies, and this correlation extends over three orders of magnitude in stellar mass. This nearly one-to-one (in log–log space) correlation suggests that the rate at which a sub- L^* galaxy forms new stars is related to its past star formation history, and – more precisely – to the amount of stars that the galaxy has already formed.

(vii) *A scenario for the growth of galaxy stellar masses.* The existence of a SFR– M_{stars} relation over a wide range of stellar masses among $z \sim 2$ star-forming galaxies poses the challenge: how do star-forming galaxies ‘know’ that they should have $\text{SFR} \propto \int \text{SFR}(t) dt$? A simple model successfully explains this phenomenon: the model simply assumes that SFRs are proportional to baryon accretion rates, which in turn are proportional to dark matter accretion rates. Since in the Λ CDM paradigm dark matter accretion rates scale with halo mass, it naturally follows that both SFRs and stellar masses will correlate via the masses of the underlying dark matter haloes. Based on the scaling of halo accretion rates with mass, the model successfully accounts for the slope of the observed BX galaxy SFR– M_{stars} correlation, and finds that the instantaneous star formation efficiency (i.e. the fraction of accreting baryons that condense into stars) is only about 1 per cent or so. The key ingredient of this model – that SFRs are governed by the (continually growing) dark matter masses of galaxies – has the potential to naturally account for the increasing star formation histories that have recently been suggested for high- z galaxies.

Sub- L^* galaxies at high redshift account for significant amounts of star formation in the Universe and contain significant amounts of its stellar mass. At the same time, they are not simply scaled-down copies of their more luminous L^* cousins, as is evidenced, for example, by the presence of differential, luminosity-dependent extinction. While high- z sub- L^* galaxies are challenging to study because of their faintness, understanding their physical nature holds the potential to understand a different physical regime in galaxy formation from that probed by L^* and super- L^* objects. Moreover, as was illustrated in this paper, the ability to span several orders of magnitude in stellar mass gives the ability to tease out important hidden trends; it also enables differential, comparative measurements of galaxy properties, whose results are more trustworthy than those of absolute measurements. Sub- L^* galaxies are thus both important and useful denizens of the Universe, and we need to continue to strive to better understand what they tell us about the history of structure formation in the Universe.

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