My Thesis Title

My Name

The University of Nottingham

Thesis submitted to the University of Nottingham
for the degree of Doctor of Philosophy, October 2006

“My amusing/profound quotation”

– Author

Supervisor:	Prof. ?? ??
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Abstract

Text of abstract.

Acknowledgements

Text of acknowledgements.

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Chapter 2

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2.1 Section

The photometry used throughout this work is taken from the catalog of Guo *et al.* (2013), a UV to mid-infrared multi-wavelength catalog in the CANDELS GOODS South field based on the CANDELS WFC3/IR observations combined with existing public data.

2.1.1 Imaging Data

The near-infrared WFC3/IR data combines observations from the CANDELS survey (Grogin *et al.*, 2011; Koekemoer *et al.*, 2011) with the WFC3 Early Release Science (ERS; Windhorst *et al.* 2011) and Hubble Ultra Deep Field (HUDF; PI Illingworth; Bouwens *et al.* 2010) surveys. The southern two thirds of the field (incorporating the CANDELS 'DEEP' and 'WIDE' regions and the UDF) were observed in the F105W, F125W and F160W bands. The northern-most third, comprising the ERS region, was observed in F098M, F125W and F160W. In addition to the initial CANDELS observations, the GOODS South field was also observed in the alternative J band filter, F140W, as part of the 3D-HST survey (Brammer et al. 2012).

The optical HST images from the Advanced Camera for Surveys (ACS) images are version v3.0 of the mosaicked images from the GOODS HST/ACS Treasury Program, combining the data of Giavalisco *et al.* (2004) with the subsequent observations obtained by Beckwith *et al.* (2006) and (Koekemoer *et al.*, 2011). The field was observed in the F435W, F606W, F775W, F814W and F850LP bands. Throughout the paper, we will refer to the HST filters F435W, F606W, F775W, F814W, F850LP, F098M, F105W, F125W, F160W as B_{435}, V_{606}, i_{775}, I_{814}, z_{850}, Y_{098}, Y_{105}, J_{125}, H_{160} respectively.

The *Spitzer*/IRAC (Fazio *et al.*, 2004) 3.6 and 4.5μm images were taken from the Spitzer Extended Deep Survey (PI: G. Fazio, Ashby *et al.* 2013) incorporating the pre-existing cryogenic observations from the GOODS Spitzer Legacy project (PI: M. Dickinson). Complementary to the space based imaging of HST and Spitzer is the ground-based imaging of the CTIO U band, VLT/VIMOS U band (Nonino *et al.*, 2009), VLT/ISAAC K_s (Retzlaff *et al.*, 2010) and VLT/HAWK-I K_s (Fontana et al. *in prep.*) bands.

2.1.2 Source photometry and deconfusion

The full details on how the source photometry was obtained are outlined in Guo *et al.* (2013), however we provide a brief summary of the method used for reference here. Photometry for the HST bands was done using SExtractor's dual image mode, using the WFC3 H band mosaic as the detection image and the respective ACS/WFC3 mosaics as the measurement image after matching of the point-spread function (PSF).

For the ground-based (VIMOS and CTIO U band and ISAAC and Hawk-I Ks) and Spitzer IRAC bands, deconvolution and photometry was done using template fitting photometry (TFIT). We refer the reader to Laidler *et al.* (2007),Lee *et al.* (2012) and the citations within for further details of the TFIT process and the improvements gained on mixed wavelength photometry.

2.1.3 Subsection

Chapter 3

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3.1 Section

3.2 Photometric Redshifts and Sample Selection

Photometric redshifts for the entire source catalog were calculated using the EAZY photometric redshift software (Brammer, vanDokkum & Coppi, 2008). The fitting was done to all available bands using the default reduced template set based on the PEGASE spectral models of Fioc & Rocca-Volmerange (1997) with an additional template based on the spectrum of Erb *et al.* (2010). The additional template exhibits features expected in young galaxy populations such as strong optical emission lines and a high Lyman-α equivalent width.

For each galaxy we construct the full redshift probability distribution function (PDF), $P(z) \propto exp(-\chi_z^2/2)$, using the χ^2-distribution returned by EAZY. Although EAZY allows the inclusion of a magnitude based prior when calculating redshifts, none was included in the fitting due to the large uncertainties still present in the H-band (our photometry selection band) luminosity function at high-redshifts (Henriques, 2012).

3.2.1 Selection Criteria

To investigate how the SMF evolves from $z =$ 4-7, we constructed a sample of galaxies in the redshift range $3.5 < z < 7.5$. To select a robust sample suitable for SED fitting, we apply a set of additional criteria based on the full redshift probability distribution for each galaxy to construct the different redshift samples, similar to those used in previous high-redshift sample selections (McLure *et al.*, 2011; Finkelstein *et al.*, 2012a). We then apply the following criteria:

$$\int_{z_{sample}-0.5}^{z_{sample}+0.5} P(z)\, dz > 0.4 \tag{3.1}$$

$$\int_{z_{peak}-0.5}^{z_{peak}+0.5} P(z)\, dz > 0.6 \tag{3.2}$$

$$(\chi^2_{min}/N_{filters} - 1) < 3 \tag{3.3}$$

where z_{sample} = 4, 5, 6 and 7 for the respective bins and z_{phot} is the redshift at the peak of the probability distribution (i.e. minimum χ^2).

The first criterion (Equation 3.1) requires that a significant amount of the probability distribution lies within the redshift range we are examining. The second criterion (Equation 3.2) requires that the bulk of the PDF lies close to the peak of the distribution, i.e. that the primary solution is a dominant one. Finally, we require that EAZY provides a reasonable fit (Equation 3.3).

A signal to noise cut is placed on the J and H bands, requiring SN$(J_{125}) > 3.5$ and SN$(H_{160}) > 5$. Known AGN and sources with photometry flagged as effected by artefacts are removed. We also visually inspect each galaxy across all the HST bands, excluding sources which were caused or strongly affected by artefacts such as diffraction spikes, bright stars and image edges which were not excluded by any of the other criteria.

Of the initial 34930 objects in the CANDELS GOODS South catalog, 3164 objects satisfy our first criterion. Of those objects, 256 are excluded by the second criterion and a further 167 are rejected based on their χ^2. The signal to noise criteria exclude

Figure 3.1: Comparison between spectroscopic and photometric redshift for the galaxies in our sample with available spectroscopy and spectroscopic redshift quality of 'Good" or better. The photometric redshift shown is the peak of the probability distribution (χ^2 minimum) with 1-σ lower and upper limits. Of the 11 galaxies classed as outliers, 6 are low-redshift interlopes at $z < 3$.

a further 274 sources and the remaining criteria exclude a further 176 sources. The resulting final sample comprises 2291 galaxies.

Figure 3.1 compares the available spectroscopic redshifts for the galaxies in our sample with the corresponding best-fit photometric redshift (minimum χ^2) as found by EAZY. In total, there are 189 spectroscopic redshift matches for galaxies which pass our selection criteria and are therefore included in our samples. The matched spectroscopic redshifts are from the following surveys: Le Fèvre *et al.* (2004); Stanway *et al.* (2004); Vanzella *et al.* (2008); Hathi, Malhotra & Rhoads (2008); Popesso *et al.* (2009); Wuyts *et al.* (2009); Rhoads *et al.* (2009); Vanzella *et al.* (2009); Balestra *et al.* (2010); Kurk *et al.* (2012) (Stark *et al.* (2010) correct ref for Keck LBG spec-z's?).

We find that our redshift accuracy is good, with a scatter of just $\sigma_z/(1+z) = 0.038$ when outliers are excluded. We define outliers as $|\Delta z|/(1+z) > 0.15$, where $\Delta z = (z_{spec} - z_{phot})$ (Dahlen *et al.*, 2013), and find an outlier fraction of 5.8% (11 galaxies). This compares with Finkelstein *et al.* (2012b) who find a scatter of $\sigma_z/(1+z) = 0.044$ at $z > 3$ after excluding outliers (defined more strictly as $|\Delta z| > 0.5$) in the same CANDELS field. We also find that there is very little bias in our photometric redshifts, with $median(z_{spec} - z_{phot}) = 0.009$. Of the 11 galaxies classed as outliers, 6 lie at redshifts of $z < 3$ and are low-redshift interlopers which our selection criteria have not been able to exclude.

Dahlen *et al.* (2013) have recently shown that by combining the results from multiple photometric redshift codes, the scatter and outlier fraction in photometric redshifts can be significantly reduced compared to the results of any single code. For the same set of 189 spectroscopic redshift sources, the photometric redshifts produced through the Bayesian combination outlined in Dahlen *et al.* (2013) have $\sigma_z/(1+z) = 0.037$ with an identical outlier fraction of 5.8% and $median(z_{spec} - z_{phot}) = 0.003$.

Although utilising the photometric redshifts for the CANDELS GOODS-S field produced by this method would result in a small gain in photometric accuracy, we would no longer be able to reproduce the full selection method when running simulations.

Given this small improvement, we are confident that the use of photometric redshifts produced by a single code will not adversely affect the overall accuracy of the results.

To investigate how the SMF evolves from z = 4-7, we then constructed four redshift samples in bins across this redshift range: $z \sim 4$ $(3.5 \leq z < 4.5)$, $z \sim 5$ $(4.5 \leq z < 5.5)$, $z \sim 6$ $(5.5 \leq z < 6.5)$ and $z \sim 7$ $(6.5 \leq z < 7.5)$.

3.2.2 Monte Carlo Samples

Although we find that our photometric redshifts do well when compared with the matched spectroscopic redshifts, the group of outliers are indicative of the difficulties that exist in correctly distinguishing between the Lyman break of high-redshift galaxies at $z > 3$ and strong Balmer break galaxies at more moderate redshifts $z \approx 0.5 - 2.5$ in low S/N data. Pirzkal *et al.* (2012, 2013) have shown that it is very difficult to categorically classify sources as high-redshift galaxies and not low-redshift interlopers using photo-z's or S/N criteria on the dropout bands.

Previous work using photometric redshifts has dealt with this problem by making use of the full redshift PDF when calculating luminosity functions (Dahlen *et al.*, 2005; McLure *et al.*, 2009, 2012), thereby incorporating the uncertainty in the analysis. Due to the nature of the SED fitting code used for this work (described in Section 4.2), the computational effort required to fit the mass at each redshift in order to integrate over the full PDF becomes impractical. As such, we chose to account for these problems in a different manner whilst still dealing with them in a straight-forward way.

Rather than using only the best-fit redshift from our photometric analysis when selecting our sample, we instead draw the redshift for each galaxy randomly from its full PDF before placing it in the appropriate redshift sample. Where secure spectroscopic redshifts are available, we fix the redshift to that value for all samples (known interlopers are therefore excluded in all samples). This process was repeated 500 times to produce a set of samples to which we then apply the rest of the analysis described in the paper separately. We then average over the results from each sample, using the mean of this full set as our 'true' value along with the 1-σ upper and lower limits around this mean.

Table 3.1: Average sample size and variance for each redshift bin for the 500 Monte Carlo samples generated, see text for details.

Redshift Bin	Mean Sample Size	Variance on sample size
4	1235	180
5	416	63
6	169	25
7	42	9

Figure 3.2: The colours of our photometric redshift selected samples in relation to the two-colour cuts typically used to select Lyman break galaxies. Non-detections in a filter are converted to 2-σ upper limits when calculating the colours. The shaded blue regions show the region in colour space used to select dropout galaxies in that redshift bin as described in Bouwens *et al.* (2007). Red symbols represent galaxies selected in our sample by our selection criteria, where the transparency of the symbols is determined by the number of Monte Carlo samples in which it is selected i.e. the fainter the symbol, the smaller the fraction of MC samples that galaxy is selected in. Example error bars corresponding to 5-σ detections (for both filters in a given colour) are shown for each of the corresponding drop-out colours.

The resulting sample sizes for each redshift bin are shown in Table 3.1. The varying samples account for both scattering between redshift bins for objects at the boundaries as well as objects moved out of the sample into secondary low-redshift solutions. The effect of this scattering into and out of the samples can be seen when comparing the combined mean samples sizes (1862) the our full high-redshift sample of 2291.

The strength of using photometric redshifts for sample selection over colour cuts (especially when redshifts would still need to be calculated for a colour-cut sample in order to do SED fitting) is that the method can automatically make use of all available photometry. This is important because although photometric redshifts are still fitting primarily to the characteristic break at Lyman-α targeted by the colour selections, the filters long-ward of the break are useful in excluding low-redshift interlopers (McLure *et al.*, 2011). Additionally, the large errors in colour possible due to low signal to noise and possible non-detections in the filter just short of the Lyman break means that likely high-redshift candidates can be scattered well outside the selection region when using colour cuts.

Figure 3.2 shows the positions of our galaxy samples on the colour-colour planes commonly used to select dropout samples. It is obvious that many of the galaxies selected with photometric redshifts lie outside the selection regions (as taken from Bouwens *et al.* 2007), especially those galaxies where colours must be calculated using an upper limit. To test whether the discrepancy between the observed colours and those expected for high-redshift galaxies can be explained solely by photometric scatter, we performed a range of tests on a mock catalog generated from the semi-analytic models of (Somerville *et al.*, 2008). Full details of these tests are outlined in Appendix 3.3, however our main findings are that the observed colours can be reproduced from intrinsic Lyman break-like colours and scattering proportional to the observed photometric errors. The agreement (or lack of) between dropout selections and photometric redshifts has also been investigated for GOODS-S specifically by Dahlen *et al.* (2010).

Text of chapter.

3.2.3 Subsection

3.3 Selection method comparison

Traditionally, (star-forming) galaxies at high-redshift have been selected using the Lyman break technique. Whereby galaxies are selected based on the observed colours across the redshifted Lyman break in their spectra.

When the observed colours of our photometric redshift selected galaxies are plotted in the same way, the selected galaxies span a range of colours far wider than those encompassed by the Lyman break selection criteria. Many of the galaxies have colours which would place them in the locus spanned by low-redshift galaxies, according to the Lyman break criteria. This has been observed before by Dahlen *et al.* (2010), who find a similar range of colours for galaxies with photometric redshifts at $z \sim 4$ and 5.

This raises the question as to whether this discrepancy is solely due to photometric scatter in the relevant colours, if stellar populations different from those expected for the Lyman break criteria, or if in fact those galaxies outside the selection criteria are low-redshift interlopers or catastrophic failures in the photometric redshift estimation.

To answer these questions, we have taken a sample of galaxy mocks from the CANDELS semi-analytic models of Somerville *et al.* (2008) across all redshifts, assigned photometric errors in each band based on the observed errors in the original catalog and then perturbed the flux by those errors. The resulting colours should then indicate the effects of photometric scattering on the intrinsic colours. We have assumed the er-

Figure 3.3: Intrinsic colours of galaxies at $4.5 < z < 5.5$ from the CANDELS semi-analytic mock catalog. The colour coding corresponds to the apparent H_{160} magnitude where blue = bright and red = faint. The background blue dots show the observed colours for the full CANDELS GOODS South catalog.

Figure 3.4: Observed colours of galaxies at $4.5 < z < 5.5$ from SAM mock sample after the photometry has been perturbed by flux errors proportional to the observed flux errors in the CANDELS DEEP region of observed photometry. The colour coding corresponds to the apparent H_{160} magnitude (after perturbation by the error) where blue = bright and red = faint.

rors are gaussian (the fluxes are perturbed by a value drawn from a gaussian where $\sigma =$ Flux Error) and have applied the errors based on the UDF, DEEP and WIDE regions.

The intrinsic colours of the mock galaxies at $z \sim 5$ ($4.5 \leq z < 5.5$) are shown in Figure 3.3. It is clear that the colours spanned by the galaxies lie well within the Lyman break selection criteria of Bouwens *et al.* (2007) and González *et al.* (2011), with only a small fraction of galaxies redder than the criteria in the colour above the break or bluer across the Lyman break. Our input population therefore closely matches the colours for which the colour-colour criteria have been designed. The same is true across all redshift bins.

Figure 3.4 shows the colours of our mock galaxy catalog after being perturbed by errors drawn from the CANDELS DEEP region. Only galaxies with $SN(H_{160}) > 5$ are shown, matching the selection criteria for our high-redshift samples. The data points are also colour coded corresponded according to their observed H_{160} magnitude (after error perturbation). It is immediately clear that photometric scatter pushes the colour spanning the Lyman break (the y-axis of each colour-colour plot) to values much lower values in $V_{606} - i_{775}$ than the range covered by the selection criteria. This is true across all regions, with the lower photometric error of the UDF (and part of the DEEP region for ACS bands) only differing in the faintness of those galaxies with the lowest signal to noise in the optical bands.

These simulations show that high-redshift galaxies can exhibit colours across the Lyman break well outside the traditional selection criteria. However, it is also important to show that the galaxies selected by photometric redshift with colours outside the colour criteria are indeed these high-redshift galaxies rather than lower redshift galaxies in the same colour space.

Figure 3.5: Observed colours of galaxies from SAM mock sample selected as $z \sim 5$ by our photometric redshift method. Red circles correspond to input galaxies with an input redshift $4.5 < z < 5.5$, blue circles correspond to low-redshift interlopers incorrectly selected in the sample.

In Figure 3.5 we show the colours of galaxies with best-fitting photometric redshifts within the redshift bin of interest. Photometric redshifts have been calculated using the same method as described in Section 2. The selected galaxies span the full range of colours traced by the error perturbed colours of input high-redshift galaxies shown in the previous plots. Photometric redshift selection is therefore not as sensitive to photometric scatter across the Lyman break than the colour criteria for the same selection.

For redshifts $z = 4 - 5$, the majority of low-redshift interlopers which are selected as high-redshift exhibit colours outside of the colour criteria. However, the fraction of interlopers is very small compared to the number of 'real' high-redshift galaxies in this colour space. As redshift increases, the fraction of interlopers increases such that at $z \sim 7$ based on the best-fitting z_{phot} alone, the fraction of outliers equals ~ 0.60, 0.51 and 0.72 for DEEP, UDF and WIDE respectively.

By applying additional cuts based on the full $P(z)$ distribution, the number of outliers can be reduced at the expense excluding some real sources. How strict the selection criteria are is a balance between minimising the contamination from interlopers and maximising the number of real high-redshift galaxies in the sample. Using the simulations however, we are able to correct the number densities for those real sources which are cut by our selection criteria.

For the selection criteria used in this work, the interloper fraction is reduced to an estimated 0.02, 0.07, 0.18 and 0.23 for $z \sim 4$, 5, 6 and 7 respectively. This was estimated by combining the fractions calculated for each field (assuming ERS to be comparable to DEEP) proportional to the number of high-redshift galaxies selected from each region of the field. In addition, by doing our analysis using the full redshift probability distribution as outlined in Section 3.2.1, we account for this remaining fraction throughout our results.

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Chapter 4

Estimating Stellar Masses

4.1 Section

4.2 Mass Fitting

Stellar masses were estimated for our samples using a custom template fitting code with SEDs derived from the synthetic stellar population models of Bruzual & Charlot (2003) (BC03 hereafter). Due to the relatively young ages of the stellar populations (as constrained by the age of the Universe at the redshifts involved), the effects of thermally-pulsating asymptotic giant branch stars (TP-AGB) on resulting SEDs are minimal, e.g. Stark *et al.* (2009). As such, we chose not to use the updated SSP models which incorporate these effects. The use of Charlot & Bruzual (2007) or Maraston (2005) in place of BC03 should have no result on the conclusions found in this work.

Based on the method used in Hartley *et al.* (2013) and Mortlock *et al.* (2013), our SED fitting code has been amended and expanded to incorporate the measurement of additional parameters described below and the inclusion of nebular emission.

4.2.1 Model SEDs

First, model SEDs are generated from the single stellar populations of Bruzual & Charlot for a range of population ages, metallicities and star-formation histories (SFHs).

Each star-formation history is normalised such that at the desired model age, the total integrated SFR equals 1 $M_\odot$. At this stage, nebular emission lines are added to the pure stellar component following the method outlined in Section 4.2.2. Internal dust extinction is applied following the extinction law of Calzetti *et al.* (2000) for the desired range of extinction magnitude A_V.

When applying dust extinction to the nebular emission, we assume the differential dust extinction between stellar and nebular emissions to be fixed as $E(B-V)_{stellar} = E(B-V)_{nebular}$, in contrast to the ratio of $E(B-V)_{stellar} = 0.44E(B-V)_{nebular}$ derived by Calzetti *et al.* (2000). This choice was motivated by the conflicting evidence for the relative extinction of the two sources at $z \sim 2$ (Erb *et al.*, 2006; Förster Schreiber *et al.*, 2009) and that in the context of these models specifically, the assumed differential extinction ratio and escape fraction are degenerate.

The absolute magnitude at 1500 Å (M_{1500}) is measured for each template by integrating the flux within a 100 Å-wide flat bandpass centered on 1500 Å. Similarly, the UV-continuum slope β is calculated by fitting a simple power-law to the integrated template fluxes in the windows described in Calzetti, Kinney & Storchi-Bergmann (1994). The accuracy of this method in calculating β is explored in Finkelstein *et al.* (2012a) and Rogers, McLure & Dunlop (2013).

Next, each model SED is redshifted in the range $0 \leq z < 9$ in steps of $\Delta z = 0.02$, and attenuation by intergalactic neutral hydrogen is applied following the prescription of Madau (1995). The resulting grid of SEDs is then integrated through the response filter for each of the observed bands.

4.2.2 Nebular Emission

Nebular emission lines and continuum are added to the templates following a method similar to previous high-redshift fitting methods, e.g. Ono *et al.* (2010); Schaerer & deBarros (2010); McLure *et al.* (2011), Salmon et al. *in prep*. Line strength ratios relative to Hβ for the major Balmer, Paschen and Brackett recombination lines are taken from Osterbrock & Ferland (2006), with the total Hβ line luminosity (in erg s^{-1})

given by

$$L(H\beta) = 4.78 \times 10^{-13}(1 - f_{esc})N_{LyC} \tag{4.1}$$

from Krueger, Fritze-vAlvensleben & Loose (1995), where f_{esc} is the continuum escape fraction and the number of Lyman continuum photons N_{LyC} is calculated from each template. The strength of the nebular emission is therefore directly proportional to the number of ionizing photons (Lyman continuum) in the HII region. Since the Lyman continuum emission is dominated by young massive stars, the relative contribution of nebular emission to the total SED is highly dependent on the age of the stellar population and the amount of recent star-formation.

Line ratios for the common metal lines relative to Hβ were taken from the empirical measurements of Anders & Alvensleben (2003) for each of the input template metallicities, assuming gas metallicity is equal to the stellar metallicity. Similarly, the nebular continuum emission luminosity is given by

$$L_\nu = \frac{\gamma_\nu^{(total)}}{\alpha_B}(1 - f_{esc})N_{LyC} \tag{4.2}$$

where α_B is the case B recombination coefficient for hydrogen and $\gamma_\nu^{(total)}$ is the continuum emission coefficient given by

$$\gamma_\nu^{(total)} = \gamma_\nu^{(HI)} + \gamma_\nu^{(2q)} + \gamma_\nu^{(HeI)}\frac{n(He^+)}{n(H^+)} + \gamma_\nu^{(HeII)}\frac{n(He^{++})}{n(H^+)}. \tag{4.3}$$

$\gamma_\nu^{(HI)}$, $\gamma_\nu^{(HeI)}$, $\gamma_\nu^{(HeII)}$ and $\gamma_\nu^{(2q)}$ are the continuum emission coefficients for free-free and free-bound emission by Hydrogen, neutral Helium, singly ionized Helium and two-photon emission for Hydrogen respectively, where the values are taken from Osterbrock & Ferland (2006). The coefficients and constants used assume an electron temperature $T = 10^4$ K, electron density $n_e = 10^2$ cm^{-3} and the abundance ratios are set to be $\frac{n(He^+)}{n(H^+)} = 0.1$ and $\frac{n(He^{++})}{n(H^+)} = 0$ (Krueger, Fritze-vAlvensleben & Loose, 1995).

4.2.3 SED Fitting

The fitting of our SEDs is done through χ^2-minimisation between the observed fluxes in each wave band and the synthetic fluxes of the model grid normalised to flux in the detection band, H_{160} in this case. From the normalisation, we then have the stellar mass and instantaneous star-formation rate for each template and can calculate the rest-frame magnitudes in each band. Because we fit all templates simultaneously, in addition to the single best-fit template (from χ^2-minimisation), we also calculate the likelihood function for each parameter marginalised over all other parameters, e.g. $P(M_*) \propto exp(-\chi^2_{M_*}/2)$. For the parameters which are all well constrained, such as the mass (see Section 4.3), the resulting likelihood function should accurately represent the probability for that parameter, given the errors in the photometry, provided the template set covers the full dynamic range required.

For our mass fitting, model ages are allowed to vary from 5 Myr to the age of the Universe at a given redshift, dust attenuation is allowed to vary in the range $0 \leq A_V \leq 2$ and metallicities of 0.02, 0.2 and 1 $Z_\odot$. Due to the difficulty in obtaining spectroscopy at $z > 3$, the metallicity at high-redshift is not currently well know. Observations of samples at $z \sim 3$ and above (Shapley, Steidel & Pettini, 2003; Maiolino *et al.*, 2008; Sommariva *et al.*, 2012; Jones, Stark & Ellis, 2012) show that the average metallicity is likely to be mildly sub-solar, however there is a large scatter. Sommariva *et al.* (2012) also find that the gas-phase and stellar metallicities are consistent within errors, as such we choose to fix the metallicity for the nebular emission equal to stellar metallicity.

The star formation histories follow the exponential form $SFR \propto e^{-t/\tau}$ with characteristic timesacles of $\tau =$ 0.05, 0.25, 0.5, 1, 2.5, 5, 10, -0.25, -0.5, -1, -2.5, -5, -10 and 1000 (effectively constant SFR) Gyrs. Negative τ values represent exponentially increasing histories. Fitting is done to the templates both with and without the inclusion of nebular emission. When nebular emission is included in the templates, we assume a moderate escape fraction $f_{esc} = 0.2$, consistent with the observational constraints on reionization and simulations (Fernandez & Shull, 2011; Yajima, Choi & Nagamine, 2010; Finkelstein *et al.*, 2012a; Robertson *et al.*, 2013).

4.2.4 Star Formation Rates

In order to calculate UV star-formation rates, the rest frame absolute magnitudes (M_{1500}) measured from the SED fitting are first corrected for dust extinction using the Meurer, Heckman & Calzetti (1999) relation

$$A_{1600} = 4.43 + 1.99\beta \tag{4.4}$$

which links the observed UV continuum slope β as measured by the SED fitting code (see Section 4.2.1) and the extinction at 1600Å, A_{1600}. For measured $\beta < -2.23$, where the above relation would imply a negative extinction, the UV extinction was set to 0. UV star-formation rates are calculated using:

$$\text{SFR}(M_\odot \text{yr}^{-1}) = \frac{L_{UV}(\text{erg s}^{-1}\text{Hz}^{-1})}{13.2 \times 10^{27}}, \tag{4.5}$$

where the L_{UV} conversion factor of Madau, Pozzetti & Dickinson (1998) and Kennicutt (1998) corrected to the Chabrier IMF is used (divide by 1.65).

In addition to the the star formation rate obtained by this method ($\text{SFR}_{\text{Madau}}$ hereafter), from our SED fitting code we also obtain the instantaneous star formation rate of the best-fitting template for each galaxy ($\text{SFR}_{\text{template}}$). We find that the two measures agree well at all SFRs with the exception of the few galaxies with the highest $\text{SFR}_{\text{Madau}}$, typically $\text{SFR}_{\text{Madau}} > 100$ $\text{M}_\odot \text{yr}^{-1}$. These galaxies are red, such that the best-fitting template is an older quiescent stellar population. The Meurer relation than an actively star-forming population with high dust extinction. As we will show in the next section however, individual stellar population parameters such as age and dust extinction are very degenerate in SED fits of high-redshift galaxies. Because of these factors, and for consistency with previous works, we primarily use $\text{SFR}_{\text{Madau}}$ throughout this work.

4.3 Image and Detection Simulations

By their nature, high-redshift galaxies are small and extremely faint objects. Lying close to the limiting depth in some (or even all) of the observed filters, noise and systematic effects can have a significant effect on the detection and completeness of high-redshift galaxy samples as well as the accurate estimation of their properties. The completeness of our galaxy sample can be separated into two distinct factors: Firstly, the inclusion of an object in the initial catalog as a function of the detection image depth. Secondly, the selection of an object in a given sample (e.g $z \approx 4$ based on its

Figure 4.1: Completeness as a function of H magnitude for each region of the GOODS South field. The vertical dashed lines show the magnitude at which the recovery fraction equals 0.5 for each region of the field.

estimated redshift), which is a function of the overall SED shape and accompanying errors. In this section, we outline a set of detailed simulations undertaken to measure and correct for these effects.

4.3.1 Completeness Simulations

The detection completeness across the field was estimated by inserting thousands of mock galaxies into the detection image (H-band) used for the photometry and recovering them with the same SExtractor parameters and method used for the original sample catalog. The synthetic galaxies were first convolved with the CANDELS WFC3 H-band PSF before being placed randomly across the field with appropriate Poisson noise. The resulting image was then run through the same SExtractor procedure as the initial source detection and the process repeated until a total of $\approx 10^5$ input galaxies had been recovered across the entire field.

Galaxy sizes were drawn from a lognormal distribution of mean = 0.15″and $\sigma = 0.075$, motivated by existing observations of the size evolution of Lyman break galaxies (Ferguson *et al.*, 2004; Oesch *et al.*, 2010; Grazian *et al.*, 2011; Huang *et al.*, 2013) whilst the galaxies profiles were drawn from a distribution of Sérsic indices centred around $n = 1.5$ in the range $0.5 \leq n \leq 4.0$. Although the precise distribution of morphological profiles for high-redshift galaxies is not well known, studies of lower redshift analogues and stacked samples of LBGs suggests that they are predominantly disk-like ($n < 2$) (Ravindranath *et al.*, 2006; Hathi *et al.*, 2007). Our chosen distribution reflects this, with $\sim 80\%$ of input galaxies with $n \leq 2$.

Figure 4.1 shows the resulting completeness curves for each of the image regions. In Guo *et al.* (2013), the H_{160} 50% completeness limit is estimated using the differential number density to be 25.9, 26.6 and 28.1 for the WIDE, DEEP+ERS and UDF regions respectively. When compared to the results of a set of detection simulations similar to those undertaken in our work, Guo *et al.* (2013) find a good agreement between the two estimations. For the UDF and DEEP+ERS regions, our 50% completeness limits are in good agreement with those of Guo *et al.* (2013). However, in the WIDE region we find a 50% completeness limit ≈ 0.5 mag deeper for our input galaxy population.

Grazian *et al.* (2011) demonstrated the significant effect that sizes and morphologies can have on the completeness simulations of high-redshift galaxies. Differences due to the distribution of sizes and slightly differing galaxy profiles used are to be expected. For all regions, the effects of confusion and blending with nearby sources results in a small fraction of input galaxies which are not recovered by the photometry, even at brighter magnitudes.

4.3.2 Sample Selection

To estimate the selection functions for each of the redshift bins, a mock photometry catalog of high-redshift galaxies was created and put through the same photometric redshift and sample selection criteria as our real sample. This catalog was constructed by first creating a sample of SEDs drawn randomly from the template sets used for fitting (both with and without nebular emission) with a distribution of β centred at ≈ -1.8 to -2, but extending out to $\beta > 1$. Redshifts were allowed to vary in the range $2.5 < z < 9$ and the templates were scaled to H_{160} band magnitudes in the range $22 < H_{160} < 30$, with the corresponding magnitudes in the other filters determined by the shape of each SED.

We produced a catalog in this way, rather than using the mock photometry of semi analytic models as used in Appendix 3.3 in order to allow the inclusion of nebular emission in subsequent tests on the stellar mass fitting and ensure good number statistics across all input magnitudes.

In order to assign photometric errors to the mock photometry (or non-observations where appropriate), each simulated galaxy was assigned a position in the field drawn from the same set of input coordinates as used in the completeness simulations. Photometric errors were then assigned to each photometric band based on the observed flux errors of objects in the original catalog, specific to the region in which it resides (e.g. CANDELS Deep). The flux values for each SED were then perturbed by a gaussian of width equal to the photometric error.

Figure 4.2: Selection efficiencies for the Ultra Deep Field region of the CANDELS field. The colour scale represents the fraction of input galaxies which pass the $P(z)$ criteria for a given redshift bin as a function of input redshift and apparent magnitude. The dashed white line in the lower sections of the figure shows the 80% contour in the fraction of recovered galaxies. The upper panels show the recovery fraction as a function of redshift at a fixed input magnitude, $\mathrm{H}_{160} = 25$ (continuous) and $\mathrm{H}_{160} = 27$ (dashed).

This process does not precisely mirror the method used to produce the observed photometry as it does not include the source extraction for each band individually. However, the resulting catalog is a very good approximation with a catalog of SEDs that have realistic photometric errors and filter coverage across the field, e.g. Y_{098} observations in the ERS region alone.

To measure the selection efficiency for our high-redshift samples, 100 simulated Monte Carlo samples were created from the mock galaxy catalog using the method outlined in Section 3.2.1. From these samples, we measured the fraction of simulated galaxies which pass the selection criteria for any of the high-redshift samples as a function of input redshift and magnitude.

Figure 4.2 shows the measured selection efficiencies for the deepest region of the field, the UDF. The selection probabilities (as indicated by the colour scale) do not include the effects of completeness as measured in Section 4.3.1, therefore the lower probabilities measured at faint magnitude are a result of photometric redshift errors due to poor constraints from faint photometry.

For $z \sim 4$ and 5, where the semi-analytic mock catalog used in Appendix 3.3 has good number statistics across a wide magnitude range, we reproduce the selection function in the same manner as above and find that the shape of the resulting selection functions are unchanged. We are therefore confident that the photometric selection of our samples is robust to variations in the exact shape of the input SEDs and the limiting factor in selection is the photometric noise.

4.3.3 Uncertainties in measuring galaxy parameters

The ability of SED fitting codes to recover the properties of dropout galaxies was well explored by Lee *et al.* (2010) who found that stellar mass was the most reliably measured parameter (in comparison to star formation rate and age) and the most robust

Figure 4.3: 2D histograms showing the recovered SED parameters for a set of input SEDs incorporating nebular emission when fitted with nebular emission. The values for the age (centre) and dust (right) are those corresponding to the single best-fitting model whilst the measured mass (left) is taken as $\int MP(M)dM$. Each histogram is normalised by the number of input galaxies in each bin and the colour scale corresponds to the fraction of input galaxies at the observed mass (/age/dust extinction) i.e. darker = more galaxies.

to assumptions in star-formation history. This work however was limited to SEDs excluding the effects of nebular emission only for both the input and fitted models. The degeneracies in measuring age, dust extinction and star-formation histories from SED fitting have also been well examined e.g. Schaerer & deBarros (2010). It is however possible to reliably measure β as a proxy for the stellar population properties (Finkelstein *et al.*, 2012b; Rogers, McLure & Dunlop, 2013).

For the $\approx 10^5$ galaxies in our simulated catalog which pass the selection criteria, we ran them through the SED fitting code using the same fitting parameters as for our observed data. From these results we are able to test how well the input stellar masses are recovered for our simulated galaxies. In addition, we can also test the accuracy in recovering the other properties of the input stellar populations.

Figure 4.3 illustrates how well the SED code is able to recover the stellar masses, ages and dust extinction. As expected, stellar mass is the most robust of the parameters with age and dust extinction showing a very large scatter due to the degeneracy in fitting. For input galaxies with masses $\approx 10^9 M_\odot$, the median(M_{out}-M_{in}) = 0.11, with a standard deviation of 0.4 when input SEDs including nebular emission are fitted with comparable templates. For input masses $\approx 10^{8.5} M_\odot$ and below, both the bias and scatter increase. When mock galaxies with pure stellar SEDs are fitted with pure stellar templates, both the scatter and bias are reduced at all mass ranges. The increased bias and scatter for galaxies with nebular emission is a result of confusion between an older stellar population with a 4000Åbreak and a young star-forming galaxy with strong nebular emission (Schaerer & deBarros, 2009; Curtis-Lake *et al.*, 2013). Because the strength of nebular emission in the templates being fitted

Finally, we find that the recovered value for $M_{UV,1500}$ is extremely robust across the full dynamic range of our data, with a scatter of < 0.2 dex and negligible bias across all redshift out to the limits of our completeness as shown in Figure 4.4. From these simulations, we determine that $M_{UV,1500}$ is robust to M_{UV} $\approx$ -17 at $z \approx 4$, reducing to

Figure 4.4: Comparison of the recovered versus input M_{UV}, for the full mock galaxy sample.

-18 at $z \approx 7$. The estimated accuracy of our β measurements from these simulations is presented in Appendix **??**.

4.3.4 Subsection

Example reference in text, **?**.

Example reference list in text, **??**.

Appendices

Appendix A

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Appendix B

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