[The mass evolution of the first galaxies]The mass evolution of the first galaxies: stellar mass functions and star formation rates at $4 < z < 7$ in the CANDELS GOODS-South fieldch:smf

Introduction Thanks to the unprecedented sensitivity of the latest extragalactic surveys, the last decade has seen a revolution in the observation of galaxies in the high-redshift universe. It is now possible to study the beginnings of the mechanisms and processes that formed the diverse array of galaxies we find in the local universe today. Since the first successful detections through the Lyman break technique, via the characteristic 'break' induced by blanketing hydrogen absorption of the UV continuum 1990ApJ...357L...9G, 1992AJ....104..941S, the study of high-redshift galaxies has progressed rapidly. With the introduction of the Wide-field Camera 3 (WFC3) in 2009 and the unprecedented depth in the near-infrared it provides, the study of galaxies out to redshifts of $z > 6$ has become commonplace.

The numerous measurements of the UV luminosity function of high-redshift galaxies spanning the redshift range $4 \leq z \leq 9$ 2007ApJ...670..928B,2009MNRAS.395.2196M,Oesch:2009ew,Bouwens:2010dk,2011AA...532A..33G,Lore are not only giving an insight into the processes of galaxy formation, they are also helping us to understand the role those galaxies played in the ionization of the intergalactic medium during the epoch of reionization (EoR). These surveys have put strong constraints on the contribution of star-forming galaxies to reionization, requiring a significant contribution from faint galaxies below the current detection limits to complete reionization within the observed redshift.

Because they represent the time integral of all past star-formation, the stellar masses of galaxies provide additional independent constraints on their contribution to reionization through the observed stellar mass density 2010Natur.468...49R. Successful models of galaxy evolution and reionization must therefore be able to reconcile both the star-formation observed directly, and the record of past star-formation contained in the observed stellar masses. The galaxy stellar mass function (SMF) and its integral the stellar mass density (SMD), are therefore important tools in the study of galaxy evolution.

However, accurately measuring the stellar masses of galaxies at high-redshift is very difficult for a number of fundamental reasons. These reasons stem from the fact that the rest-frame wavelengths probed by optical/near-infrared surveys extend only to the UV continuum, requiring mid-infrared observations to extend past $\lambda_{rest} = 4000$Å. Even when rest-frame optical measurements are available through deep Spitzer 3.6 and 4.5 μm observations, e.g. 2009ApJ...697.1493S,Labbe:2010ho,Gonzalez:2011dn,Yan:2012ky, the degeneracies between dust extinction, age and metallicity are large (see 2013ASSL..396..223D 2013ASSL..396..223D for a detailed discussion).

More recently it has also been shown that the spectral energy distributions (SEDs) of high-redshift galaxies, for both photometrically selected 2009AA...502..423S,2010AA...515A..73S,Ono:2010ed,2011MNRAS.418.2074M,Lorenzoni and smaller spectroscopically confirmed samples Shim:2011cw,2013MNRAS.429..302C,Stark:2013ix, can exhibit colours that are best fit by the inclusion of nebular emission lines when measuring galaxy properties such as mass and age. The inclusion of these lines results in fitted ages that are significantly younger compared to fits without nebular emission, as well as being of lower stellar mass. Another consequence of the degeneracies in SED fitting at high-redshift is the increased importance in the assumed star formation history (SFH) of the models being fit. Observational studies of the mass growth of galaxies at a constant number density (2011MNRAS.412.1123P 2011MNRAS.412.1123P, 2015ApJ...799..183S 2015ApJ...799..183S) and hydrodynamical simulations 2011MNRAS.410.1703F imply that the star formation histories for galaxies at $z > 3$ are smoothly rising. This increase is in contrast to the smoothly falling or constant SFH commonly used at low-redshift (see Conroy:2013dk Conroy:2013dk for a review). In Maraston:2010dl, it is also shown that exponentially rising star-formation histories can provide improved fits to both simulated and observed SEDs of high redshift galaxies.

Gonzalez:2011dn were amongst the first to make use of the capabilities offered by the WFC3/IR data, using data from the Early Release Science (ERS; 2011ApJS..193...27W 2011ApJS..193...27W) to measure the stellar mass to UV luminosity ratio for a sample of dropout galaxies and applying it to the observed luminosity functions to measure the stellar mass function out to $z \sim 7$. In contrast to the steep faint-end slope of the UV luminosity function ($\alpha = -2\ to\ -1.7$) at high-redshifts, this work observed a notably shallower mass function ($\alpha = -1.6\ to\ -1.4$). Subsequent work by 2012ApJ...752...66L with much greater sample sizes from ground-based near-infrared found a similarly shallow slope at $z \sim 4$ and 5. In contrast, observations by 2011MNRAS.413..162C and Santini:2012jq observe a significantly steeper low-mass slope at $z > 3$.

In Gonzalez:2011dn, the shallow low-mass slope arises due to the observed evolution of the mass-to-light ratio with UV luminosity. Similarly, 2012ApJ...752...66L infer an evolving mass-to-light in order to reconcile the luminosity and mass function slopes observed. The primary physical explanation for this evolving mass-to-light ratio is luminosity dependent dust-extinction. However, observations of the stellar populations of high-redshift galaxies have produced conflicting results on the existence and strength of any luminosity dependence. When measuring the UV continuum slope, β 1994ApJ...429..582C, for samples of high-redshift galaxies, Wilkins:2011fs, 2012ApJ...754...83B and Bouwens:2013vf find evidence for a strong UV luminosity dependence across all redshifts at $z > 3$. In contrast, similar studies by Dunlop:2011jl, 2012ApJ...756..164F and 2013MNRAS.429.2456R find no clear evidence for a luminosity dependence on β. Several of these studies outline the importance of the selection of high redshift galaxies (through either Lyman break or photometric redshift selection) and the treatment of their biases. To this end, more recent analyses Bouwens:2013vf,Rogers:2014bn, which increase sample sizes and minimise biases in the sample selection and β measurements, are in good agreement, with both studies finding a clear luminosity dependence.

The deep near-infrared observations of the GOODS South field made as part of the Cosmic Assembly Near-infrared Deep Extragalactic Survey (CANDELS; Co-PIs: Faber & Ferguson; 2011ApJS..197...35G 2011ApJS..197...35G; Koekemoer:2011br Koekemoer:2011br), combined with the extensive existing optical observations make it a data set ideally suited to the study of galaxy evolution at the so-called 'cosmic dawn'. Covering an area approximately 200% larger than the WFC3 ERS observations alone 2011ApJS..193...27W, and incorporating the even deeper UDF observations, the CANDELS data combines the high sensitivity of the WFC3 observations with high-redshift samples large enough to attempt the first direct derivation of the completeness corrected stellar mass function at $z \geq 6$ and build upon the existing work at $z \sim 4$ and $z \sim 5$. In this chapter, we make use of this comprehensive data set to study galaxy stellar masses across the redshift range $z \sim 4$ to $z \sim 7$. In particular, we aim to estimate stellar masses for a large and robust sample of high-redshift galaxies, investigating how the inclusion of nebular emission and increasing star-formation histories affect the observed stellar mass - UV luminosity relation and the shape of the stellar mass function. For this same sample, we also aim to measure the dust-corrected star-formation rates, which will combine to make a detailed census of the stellar mass growth of high-redshift galaxies.

The structure of this chapter is as follows. In Section smf-sec:data, we describe the properties of the optical and near-IR data sets used in this study as well as the methods of photometry extraction used. In Section smf-sec:redshift, we describe the photometric redshift analysis and the selection criteria used to construct the high-redshift samples used in our analysis. Section smf-sec:selection$_{c}omptheninvestigateshowtheuseofphotometricredshi$ cosmology with $H_0 = 70$ kms^{-1}Mpc^{-1}, $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$. Quoted observables are expressed as actual values assuming this cosmology.

The Datasmf-sec:data The photometry used throughout this work is taken from the catalog of Guo:2013ig, 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.

Imaging Data The near-infrared WFC3/IR data combines observations from the CANDELS survey 2011ApJS..197...35G,Koekemoer:2011br with the WFC3 Early Release Science (ERS; 2011ApJS..193...27W 2011ApJS..193...2 and Hubble Ultra Deep Field (HUDF; PI Illingworth; Bouwens:2010dk Bouwens:2010dk) 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 2004ApJ...600L..93G with the subsequent observations obtained by 2006AJ....132.1729B and Koekemoer:2011br. The field was observed in the F435W, F606W, F775W, F814W and F850LP bands. Throughout the chapter, 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:2004eb 3.6 and 4.5μm images were taken from the Spitzer Extended Deep Survey (PI: G. Fazio, Ashby:2013cc Ashby:2013cc) 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:2009hf, VLT/ISAAC K_s Retzlaff:2010co and VLT/HAWK-I K_s (Fontana et al. in prep.) bands.

Source photometry and deconfusion The full details on how the source photometry was obtained are outlined in Guo:2013ig, 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:2007iy, 2012ApJ...752...66L and the citations within for further details of the TFIT process and the improvements gained on mixed wavelength photometry.

Photometric Redshifts and Sample Selectionsmf-sec:redshift Photometric redshifts for the entire source catalog were calculated using the EAZY photometric redshift software Brammer:2008gn. The fitting was done to all available bands using the default reduced template set based on the PEGASE spectral models of 1997AA...326..950F with an additional template based on the spectrum of 2010ApJ...719.1168E. 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), $P(z) \propto exp(-\chi^2_z/2)$, 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:2012gsa.

Selection Criteria smf-sec:sample To investigate how the SMF evolves from $z = 4$-7, we wish to construct 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 2011MNRAS.418.2074M,Finkelstein:2012hr. We then apply the following criteria:

equationeq:crit1 $\int_{z_{sample}-0.5}^{z_{sample}+0.5} P(z)\ dz > 0.4$