THE SFR–$M_*$ RELATION AND EMPIRICAL STAR-FORMATION HISTORIES FROM ZFOURGE* AT 0.5 < $z$ < 4

ADAM R. TOMCZAK$^{1,2,3}$, RYAN F. QUADRI$^{1,2}$, KIM-VY H. TRAN$^{1,2}$, IVO LABBÉ$^4$, CAROLINE M. S. STRAATMAN$^4$, CASEY PAPOVICH$^{1,2}$, KARL GLAZEBROOK$^5$, REBECCA ALLEN$^{6,9}$, GABRIEL B. BRAMMER$^7$, MICHAEL COWLEY$^{6,8}$, MARK DICKINSON$^8$, DAVID ELBAZ$^{10}$, HANAE INAMI$^9$, GLENN G. KACPRZAK$^5$, GLENN E. MORRISON$^{11,12}$, THEMUYA NANDAYAKKARA$^6$, S. ERIC PERSSON$^{13}$, GLEN A. REES$^9$, BRETT SALMON$^{1,2}$, CORENTIN SCHREIBER$^{10,13}$, LEE R. SPITLER$^{10,8}$, AND KATHERINE E. WHITAKER$^{11,13}$

$^1$ George P. and Cynthia Woods Mitchell Institute for Fundamental Physics and Astronomy, Texas A&M University, College Station, TX, 77843-4242 USA
$^2$ Department of Physics and Astronomy, Texas A&M University, College Station, TX, 77843-4242 USA
$^3$ Department of Physics, University of California-Davis, One Shields Avenue, Davis, CA 95616, USA; artomczak@ucdavis.edu
$^4$ Leiden Observatory, Leiden University, P.O. Box 9513, 2300 RA Leiden, The Netherlands
$^5$ Centre for Astrophysics & Supercomputing, Swinburne University, Hawthorn, VIC 3122, Australia
$^6$ Australian Astronomical Observatory, 105 Delhi Rd, Sydney, NSW 2113, Australia
$^7$ Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA
$^8$ Department of Physics & Astronomy, Macquarie University, Sydney, NSW 2109, Australia
$^9$ National Optical Astronomy Observatory, 950 North Cherry Avenue, Tucson, AZ 85719, USA
$^{10}$ Laboratoire AIM-Paris-Saclay, CEA/DSM/Inrf - CNRS - Université Paris Diderot, CEA-Saclay, pt courrier 131, 91191 Gif-sur-Yvette, France
$^{11}$ Institute for Astronomy, University of Hawaii, Manoa, Hawaii 96822-1897 USA
$^{12}$ Canada-France-Hawaii Telescope Corp., Kamuela, Hawaii 96743-8432, USA
$^{13}$ Carnegie Observatories, Pasadena, CA 91011, USA and

ABSTRACT

We explore star-formation histories (SFHs) of galaxies based on the evolution of the star-formation rate stellar mass relation (SFR–$M_*$). Using data from the FourStar Galaxy Evolution Survey (ZFOURGE) in combination with far-IR imaging from the Spitzer and Herschel observatories we measure the SFR–$M_*$ relation at $0.5 < z < 4$. Similar to recent works we find that the average infrared SEDs of galaxies are roughly consistent with a single infrared template across a broad range of redshifts and stellar masses, with evidence for only weak deviations. We find that the SFR–$M_*$ relation is not consistent with a single power-law of the form SFR $\propto M_*^\alpha$ at any redshift; it has a power-law slope of $\alpha \sim 1$ at low masses, and becomes shallower above a turnover mass ($M_0$) that ranges from $10^{9.5} - 10^{10.8}$ $M_\odot$, with evidence that $M_0$ increases with redshift. We compare our measurements to results from state-of-the-art cosmological simulations, and find general agreement in the slope of the SFR–$M_*$ relation albeit with systematic offsets. We use the evolving SFR–$M_*$ sequence to generate SFHs, finding that typical SFRs of individual galaxies rise at early times and decline after reaching a peak. This peak occurs earlier for more massive galaxies. We integrate these SFHs to generate mass-growth histories and compare to the implied mass-growth from the evolution of the stellar mass function. We find that these two estimates are in broad qualitative agreement, but that there is room for improvement at a more detailed level. At early times the SFHs suggest mass-growth rates that are as much as $10\times$ higher than inferred from the stellar mass function. However, at later times the SFHs under-predict the inferred evolution, as is expected in the case of additional growth due to mergers.

1. INTRODUCTION

Over the past two decades our understanding of the buildup of stellar matter in the universe has advanced markedly through a wealth of multiwavelength galaxy surveys (for a review see Madau & Dickinson 2014). However, inferring star formation and mass growth histories of individual galaxies is a non-trivial undertaking, and a variety of methods have been used in the literature. One class of methods involves “archeological” studies of nearby galaxies, either by studying resolved stellar populations or by detailed modeling of high signal-to-noise spectra (e.g. Dolphin et al. 2003; Heavens et al. 2004; Thomas et al. 2005). However degeneracies in age, metallicity, and extinction complicate modeling with these techniques. Furthermore, these techniques become difficult or impossible to apply at appreciable redshifts.

This has provided motivation for lookback studies that utilize observed relations of galaxies at discrete epochs in the universe to infer how individual galaxies evolve. One such type of study is to trace the mass-growth of galaxies selected in bins of constant cumulative co-moving number density (e.g. van Dokkum et al. 2010; Papovich et al. 2011; Patel et al. 2013). This method assumes that the rank-ordering of a population of galaxies by stellar mass does not change as they evolve with time. In reality this rank-ordering will change due to mergers and stochastic variations in star-formation rates, but it is possible to approximately correct for these effects using an evolving number density criterion (Leja et al. 2013; Behroozi et al. 2013).

Another type of lookback study involves using the observed correlation between stellar mass and star-formation...
rate, hereafter referred to as the SFR–$M_*$ relation (e.g. Brinchmann et al. 2004; Noeske et al. 2007; Gilbank et al. 2011; Whitaker et al. 2012; Speagle et al. 2014). By tracing along this evolving star-formation sequence it is possible to predict how galaxies should evolve due to starformation (e.g. Leitner 2012; Speagle et al. 2014). In general some disagreement between this approach and the number density selection (NDS) is expected since the former does not include growth due to mergers; indeed, Drory & Alvarez (2008) use this difference to derive the merger rate. Disagreements may also be caused by systematic errors in mass and/or SFR estimates, as emphasized by Weinmann et al. (2012) and Leja et al. (2015).

The most commonly used parameterization for the SFR–$M_*$ relation in the literature has been a power law of the form $\log(\Psi) = \alpha \log(M_*) + \beta$ with $\alpha$ and $\beta$ representing the slope and normalization respectively. At low stellar masses ($\lesssim 10^{10} M_\odot$) this slope needs to be close to unity in order to maintain the roughly constant low-mass slope in the observed galaxy stellar mass function (SMF). Many early studies, however, typically find a significantly shallower slope (see Table 4 of Speagle et al. (2014)). Furthermore, Leja et al. (2015) argue that the sequence must also flatten at higher masses in order to be consistent with the SMF. Fortunately, recent measurements of the SFR–$M_*$ relation find it to be more consistent with this picture (Whitaker et al. 2014; Lee et al. 2015; Schreiber et al. 2015; Tasca et al. 2015).

Many early works relied on estimating SFRs from rest-frame UV with assumed correction factors to account for extinction from dust. The launch of the Spitzer Space Telescope (Werner et al. 2004) allowed us to directly probe the attenuated UV light of star-forming regions in galaxies emitted in the far-IR for statistically large samples of galaxies at $z > 1$. However, due to technical challenges, data quality in the far-IR were much poorer than in the optical/near-IR. The launch of the Herschel Space Observatory (Pilbratt et al. 2010) expanded observational studies in the far-IR with improved data quality at longer wavelengths. Combinations of Spitzer and Herschel data make it possible to constrain IR SEDs for large enough samples of galaxies to complement modern optical/near-IR galaxy surveys (e.g. Elbaz et al. 2011; Wuyts et al. 2011).

We use the FourStar Galaxy Evolution Survey (ZFOURGE) in concert with deep far-IR imaging from Spitzer and Herschel to make new measurements of the SFR–$M_*$ relation and use this to perform an analysis of the two types of lookback studies previously mentioned. The longer wavelength data from Spitzer and Herschel allow for robust SFR measurements (e.g. Kennicutt 1998; Chary & Elbaz 2001; Papovich et al. 2007; Elbaz et al. 2011). Combining this with accurate photometric redshifts and deep stellar mass functions provided by ZFOURGE leads to improved constraints on the evolution of the SFR–$M_*$ relation and galaxy growth histories. Throughout this paper we use a Chabrier (2003) IMF and LCDM cosmological parameters of $\Omega_M = 0.3$, $\Omega_k = 0.7$ and $h = 0.7$. The symbol $\Psi$ will be used in reference to star-formation rates with subscripts to indicate how they were calculated.

2. DATA AND METHODS

2.1. ZFOURGE

The FourStar Galaxy Evolution Survey (ZFOURGE\(^1\); Straatman et al. submitted) is a deep near-IR survey conducted with the FourStar imager (Persson et al. 2013) covering one 11′×11′ pointing in each of the three legacy fields CDF-S (Giacconi et al. 2002), COSMOS (Capak et al. 2007) and UDS (Lawrence et al. 2007) reaching depths of ~26 mag in J_1, J_2, J_3, and ~25 mag in H_s, H_l, and K_s ($5\sigma$ in $d=0.6$ apertures). The medium-bandwidth filters utilized by this survey offer spectral resolutions $\lambda/\Delta\lambda \approx 10$, roughly twice that of their broadband counterparts. This increase provides for finer sampling of the Balmer/4000Å spectral break at $1 < z < 4$, leading to well-constrained photometric redshifts. In combination with ancillary imaging, the full photometric dataset covers the observed $0.3$–$8\mu$m wavelength range.

2.2. Redshifts and Stellar Masses

Photometric redshifts and rest-frame colors were measured using the public SED-fitting code EAZY (Brammer et al. 2008) on PSF-matched optical-NIR photometry. EAZY utilizes a default set of six spectral templates that include prescriptions for emission lines derived from the PEGASE models (Fioc & Rocca-Volmerange 1997) plus an additional dust reddened template derived from the Maraston (2005) models. Linear combinations of these templates are fit to the 0.3 – $8\mu$m photometry for each galaxy to estimate redshifts.

A comparison of our derived photometric redshifts to a sample of 1437 galaxies with secure spectroscopic redshifts is shown in Figure 1. We calculate a scatter of $\Delta z / (1 + z_{\text{spec}}) = 1.8\%$ at $z < 1.5$ and fraction of catastrophic outliers ($|\Delta z |/(1 + z_{\text{spec}}) > 0.15$) of 2.7%. At $z > 1.5$ these rise to 2.2% and 9% respectively. An additional analysis of $z_{\text{phot}}$ accuracy can be found in Section 2 of Kawinwanichakij et al. (2014) and Straatman et al. (submitted). Spectroscopic redshifts from CDF-S are taken from Vanzella et al. (2008), Le Fèvre et al. (2005), Szokoly et al. (2004), Doherty et al. (2005), Popesso et al. (2009), and Balestra et al. (2010). For COSMOS spectroscopic redshifts come from Lilly et al. (2009) andTrump et al. (2009). Spectroscopic redshifts for UDS come from Simpson et al. (2012) and Smail et al. (2008).

Stellar masses were derived by fitting stellar population synthesis templates to the 0.3 – $8\mu$m photometry using the SED-fitting code FAST (Kriek et al. 2009). FAST was run using a grid of Bruzual & Charlot (2003) models assuming a Chabrier (2003) IMF and solar metallicity. Exponentially declining star-formation histories ($\Psi \propto e^{-t/\tau}$) are used with $\log(\tau/\text{yr})$ ranging between 7 – 11 in steps of 0.2 and allowing $\log(\text{age/yr})$ to vary between 7.5 – 10.1 in steps of 0.1. A Calzetti et al. (2000) extinction law is also incorporated with values of $A_V$ varying between 0 – 4 in steps of 0.1.

Mass-completeness limits are estimated using a method similar to Quadri et al. (2012). Briefly, we estimate the distribution of mass-to-light ratios of galaxies that are somewhat above our $K_s = 25$ magnitude limit, and use this distribution to estimate the 90% mass-completeness limit of galaxies at $K_s = 25$. These mass-completeness limits are shown in Figure 1 along with the distribution of stellar masses and redshifts of galaxies in the ZFOURGE catalogs.

\(^1\) http://zfourge.tamu.edu
A more complete discussion of the mass-completeness limits will be presented by Straatman et al. (submitted).

2.3. Far-Infrared Imaging

We make use of Spitzer/MIPS (GOODS-S: PI Dickinson, COSMOS: PI Scoville, UDS: PI Dunlop) and Herschel/PACS data (GOODS-S: Elbaz et al. 2011; COSMOS & UDS: PI Dickinson) for measuring total far-infrared luminosities ($L_{\text{IR}}$) to derive SFRs. Imaging from these observatories used in this study include 24, 100 and 160µm. Median 1σ flux uncertainties for CDF-S/COSMOS/UDS are approximately 3.9/10.3/10.1 µJy in the 24µm imaging, 0.20/0.43/0.45 mJy in the 100µm imaging and 0.35/0.70/0.93 mJy in the 160µm imaging respectively.

Due to the large PSFs of the MIPS/PACS imaging (FWHM $\geq 4''$) source blending is a considerable effect. Therefore we use the Multi-Resolution Object PHotometry oN Galaxy Observations (MOPHONGO) code written by I. Labbè to extract deblended photometry in these far-IR data (for a detailed discussion see Labbè et al. 2006; Wuyts et al. 2007). The algorithm uses higher resolution imaging to generate a segmentation map containing information on the locations, sizes and extents of objects. In this work we use deep $K_{s}$ band as the prior (FWHM = 0.46″). Point-sources coincident in both images are used to construct a convolution kernel that maps between the high and low resolution PSFs. Objects used to construct this kernel need to be hand selected as many point-sources in the $K_{s}$ imaging are frequently undetected at far-IR wavelengths. A model of each far-IR image is generated by convolving the high-resolution segmentation map with the corresponding kernel allowing the intensities of individual objects to vary freely. Background and RMS maps are generated locally for each object on scales that are three times the 30″ tile-size used. By subtracting the modeled light of neighboring sources, “cleaned” image tiles of individual objects are produced which will be used in the stacking analysis discussed in the following section.

2.4. Sample Selection and Stacking

Modern near-infrared galaxy surveys have made it possible to detect approximately mass-complete samples of galaxies to high redshifts ($z \approx 4$). Unfortunately however, imaging used to probe obscured star-formation (typically far-IR and radio) rarely ever reach complementary depths. Thus, many studies over the past several years have turned to measuring SFRs from stacked data in order to compensate for this disparity (e.g. Dunne et al. 2009; Rodighiero et al. 2010; Karim et al. 2011; Whitaker et al. 2014; Schreiber et al. 2015). However it is important to keep in mind that the interpretation of stacked results may be complicated by the fact that the intrinsic distribution of SFRs may not be unimodal or symmetric.

We classify galaxies as either actively star-forming or quiescent using the UVJ color-color diagram (Labbè et al. 2005; Wuyts et al. 2007; Williams et al. 2009). The rest-frame (U−V) and (V−J) colors are estimated using EAZY (Section 2.2). The advantage of this diagram is that it effectively separates the two reddening vectors caused by aging and dust extinction, decreasing the likelihood of dust-enshrouded star-forming galaxies being identified as quiescent. The UVJ diagram is thus a more effective tool for categorizing galaxies into star-forming and quiescent subsamples than a simple color-magnitude criterion.

The deep near-IR photometry ($K_{s} \approx 25$) of ZFOURGE allows us to reliably select galaxies based on stellar mass. Across the entire redshift range considered in this work (0.5 < $z$ < 4) we detect 12,433 galaxies in the $K_{s}$ band imaging that lie above our estimated mass-completeness limits. From this mass-complete sample, we find that 5,875 (47%), 8,542 (69%) and 8,630 (69%) are not detected in the 24, 100 and 160µm images respectively (where detection is defined as S/N > 1). As such, we resort to stacking of the far-IR photometry for our $K_{s}$-selected sample in order to more precisely measure fluxes for ensembl-
We describe how these uncertainties are propagated to estimates of $L_{\text{IR}}$ across a broad range of redshift and stellar mass as shown in the two right panels ($m_\star \equiv \log(M_\star/M_\odot)$).

In order to estimate the error on the mean flux measured for each stack we perform 100 bootstrap resamplings on each mass-redshift subsample. Stacks of the 24, 100, and 160\,$\mu$m tiles are generated from these resamplings from which fluxes are measured as described above. We take the inter-68th percentile of these flux distributions as the corresponding uncertainties on the estimated IR fluxes. In Section 3 we describe how these uncertainties are propagated to estimates of $L_{\text{IR}}$. It is worth mentioning that fluxes measured from stacking are subject to biases due to the clustering of galaxies. However, detailed simulations have shown this effect to be negligible at the image resolution of our dataset (Viero et al. 2013; Schreiber et al. 2015) and using “cleaned” image tiles also helps to minimize contamination from neighboring sources.

We remove sources suspected of hosting active galactic nuclei (AGN) from all samples based on radio, X-ray and IR indicators. Radio AGN are identified as sources with 1.4 GHz excess having $\Psi_{1.4}/\Psi_{\text{IR}} \geq 3$ where $\Psi_{1.4}$ is the radio-inferred SFR based on equation 6 of Bell (2003) and $\Psi_{\text{IR}}$ is the IR-inferred SFR discussed in Section 2.5. More discussion of the selection and properties of radio AGN will be provided in Rees et al. (submitted). Unobscured X-ray AGN are identified as having $10^{42} \leq L_X \leq 10^{44}$ and $\text{HR} < -0.2$ where $L_X$ and HR are the rest-frame X-ray luminosity in erg/s and hardness ratio respectively. All objects with $L_X > 10^{44}$ are classified as QSOs and also rejected. Infrared AGN are identified based on an adaptation from the criteria of Messias et al. (2012) and will be presented in more detail by Cowley et al. (submitted).

2.5. Star-Formation Rate Measurements

We calculate total star-formation rates by adding contributions from UV and IR light. This approach assumes that the IR emission of galaxies ($L_{\text{IR}}$) originates from dust heated by the obscured UV light of young, massive stars. Thus by adding its contribution to that of the unobscured UV luminosity ($L_{\text{UV}}$) the total SFR for galaxies can be calculated. We use the conversion from Bell et al. (2005) scaled to a Chabrier (2003) IMF to derive SFRs from our data:

$$
\Psi_{\text{UV+IR}} [M_\odot/\text{yr}] = 1.09 \times 10^{-10} (L_{\text{IR}} + 2.2L_{\text{UV}}) \tag{1}
$$

where $L_{\text{IR}}$ is the integrated 8–1000\,$\mu$m luminosity and $L_{\text{UV}} = 1.5 \nu L_{\nu,2800}$ represents the rest-frame 1216–3000\,Å luminosity, both in units of $L_\odot$.

For our stacking analysis we aim to measure the average star-formation rate of galaxies in bins of redshift and stellar mass. In each mass-redshift bin we use the median rest-frame 2800\,Å luminosity output by EAZY for $L_{\text{UV}}$ and estimate 1σ uncertainties from 100 bootstrap resamplings. We estimate bolometric infrared luminosities ($L_{\text{IR}} \equiv L_{8–1000\mu m}$) by fitting an IR spectral template to the stacked 24-160\,$\mu$m photometry. The template introduced by Wuyts et al. (2008), hereafter referred to as the W08 template, was constructed by averaging the logarithm of the spectral template library from Dale & Helou (2002) motivated by results from Papovich et al. (2007). The validity of this luminosity-independent conversion has been demonstrated by Muzzin et al. (2010) through comparison SFRs derived from Hα versus 24\,$\mu$m fluxes for a sample of galaxies at $z \sim 2$.

Furthermore, Wuyts et al. (2011) find that at $0 < z < 3$
this luminosity-independent conversion yields consistent $L_{\text{IR}}$ estimates from 24$\mu$m when compared to $L_{\text{IR}}$ derived from PACS photometry from the Herschel PEP survey (Lutz et al. 2011). For our stacking analysis, we smooth the W08 template by the redshift distribution of the galaxies in each mass-redshift bin prior to fitting.

Errors on $L_{\text{IR}}$ were estimated from 100 Monte Carlo simulations of the stacked IR fluxes. For each mass-redshift bin we perturb the stacked 24–160$\mu$m fluxes by a normal probability density function (PDF) of width given by the estimated uncertainties described in Section 2.4. Infrared luminosities are calculated for each iteration in the same way as described above. Errors for $L_{\text{IR}}$ are derived from the 68$^{\text{th}}$ percentile range of each $L_{\text{IR}}$ distribution. We combine these with the uncertainties estimated for $L_{\text{UV}}$ to derive uncertainties on $\Psi_{\text{UV+IR}}$. All measurements of UV and IR luminosities, star-formation rates, and corresponding errors can be found in Table 1.

We test the W08 template against the present dataset using a sample of 1050 well-detected galaxies (S/N > 3 in all FIR bands). For each galaxy we fit the W08 template separately to the MIPS (24$\mu$m) and the PACS (100+160$\mu$m) photometry. In Figure 2 we show a comparison between the MIPS-only and PACS-only cases. Although we observe a general scatter of $\sim$0.2 dex we find an overall consistency with no dominant systematic trends.
Even when subsampling in redshift and stellar mass the mean offset is nearly always within the scatter. We do note, however, the presence of a weak systematic trend with redshift in the middle panel of Figure 2 which is likely caused by PAH features shifting through the MIPS 24μm passband. Nevertheless, the consistency between the MIPS-only and the PACS-only estimates of L_{IR} suggests that the W08 template effectively describes the average IR SED of galaxies. It further suggests that reasonably reliable SFR estimates can be made with just a single IR band. In this section we have focused only on galaxies that are individually detected in the FIR bands. In section 3.1 we present evidence that the systematic errors become slightly larger for our fainter stacked samples.

3. THE SFR–M_\ast RELATION

In Figure 3 we show our measurements of the SFR–M_\ast relation for all galaxies in eight redshift bins spanning 0.5 < z < 4. Evaluating completeness limits for Ψ_{UV+IR} is complicated since the depth of the far-IR imaging in CDF-S is deeper than in COSMOS and UDS. Furthermore, the ratio of IR to UV flux (infrared excess: IRX \equiv L_{IR}/L_{UV}) is strongly correlated with mass (e.g. Papovich et al. 2006; Whitaker et al. 2014), therefore, the completeness in Ψ_{UV+IR} will also be a function of stellar mass. Thus, to provide a visual guide in Figure 3 we plot the 1σ MIPS 24μm flux uncertainty converted to Ψ_{IR} as horizontal dashed lines. Due to the different depths in the three fields we use the average of the estimated 1σ flux variances in each of the fields for this conversion: $1/\sqrt{3.9^2 + 10.3^2 + 10.1^2} \approx 6\mu$Jy. We then scale the W08 template to this flux value, shifted to the upper redshift of each bin to calculate approximate limiting SFRs. Errors on stacked SFRs are determined from 100 bootstrap resamplings of their respective UV+IR stacks. The 68th-percentile range from the resulting distribution of SFRs is used to derive the 1σ error (see Table 1).

3.1. Comparison to Literature

In Figure 4 we compare our SFR–M_\ast relations to recent results from the literature. The chosen SFR–M_\ast relations come from Rodighiero et al. (2010), Karim et al. (2011), Whitaker et al. (2014), Tasca et al. (2015), Speagle et al. (2014), and Schreiber et al. (2015). All works have been scaled to a Chabrier (2003) IMF for consistency. Overall there is good agreement among all of the measurements presented in Figure 4. For the full sample of galaxies (star-forming plus quiescent), the median inter-survey discrep-
considered for this comparison. The *left* panel shows an internal comparison from the present dataset and reveals a clear trend where the estimated star-formation rates of more massive galaxies (typically with higher L_{IR}) decrease when including PACS photometry. This result is at odds with our findings for individually FIR-detected galaxies (see Fig. 2) implying that galaxies with low L_{IR} have different infrared SEDs than galaxies with high L_{IR}. The *middle* panel shows a similar systematic trend for an external comparison of our UV+IR SFRs (24–160μm) to those of 3D-HST (Whitaker et al. 2014) which only utilize 24μm photometry in the IR. Finally, the panel on the *right* shows the comparison of 24μm-only UV+IR star-formation rates. Given that the 3D-HST and ZFOURGE surveys share many similarities (see Section 3.1 for details) these differences are indicative of the minimal systematic differences that can be expected in inter-survey comparisons.

It is worth mentioning cosmic variance as a potential source for differences between SFR–M_\ast relations from different surveys. Whitaker et al. (2014) investigated this in detail by comparing the SFR–M_\ast relation as measured from each of the five CANDELS/3D-HST fields individually (see Appendix B of their paper). The field-to-field variation they find is comparable with the inter-publication scatter found by Speagle et al. (2014) which draws on a larger sample of published SFR–M_\ast relations. Furthermore, differences of this order are comparable to variations in stellar mass estimates produced by SED fitting assuming different stellar population synthesis models (Conroy 2013).

We look into this difference in more detail by making use of the library of IR templates from Chary & Elbaz (2001, hereafter CE01). For each mass-redshift bin we find the individual best-fit CE01 template to the stacked 24–160μm photometry. Comparing the IR luminosities derived from these best-fit templates to those derived from the W08 template we find a small scatter of ≈ 0.02 dex with a similar offset in log(L_{IR}/L_\odot), and a hint that this offset increases to ≈ 0.1 dex at z > 2. However, we don’t correct for this effect because these discrepancies are poorly constrained given that the FIR data do not probe the peak of the dust emission. We also note that this difference is less than the intrinsic uncertainty in individual star-formation rate calibrations (e.g. Bell et al. 2003, 2005).

The differences between the 24μm-derived star-formation rates for 3D-HST and ZFOURGE in Figure 5 are particularly interesting. These surveys cover the same fields (although ZFOURGE only covers half the area), rely on much of the same public imaging in the optical and IR bands, have had photometry performed using similar methods, and use the same conversions to calculate the star-formation rates from the 2800Å and 24μm flux. Thus the systematic differences in star-formation rates are indicative of the minimal differences that can be expected in inter-survey comparisons.

### 3.2. Comparison to Simulations

In Figure 6, we compare our measured SFR–M_\ast relations for the full sample of galaxies with results from the recent Illustris hydrodynamic simulation (Nelson et al. 2015) and the Munich semi-analytic galaxy formation
model (Henriques et al. 2014). Gray lines correspond to the mean SFR in bins of stellar mass for each redshift interval indicated. Except at \( \log(M_*/M_\odot) > 10.5 \), both simulations are consistently in good agreement with each other (for further discussion of this point see Weinmann et al. 2012). In general, the simulations reproduce the roughly constant slope at \( M_* \lesssim 10^{10} M_\odot \) albeit with an offset. This offset ranges between 0.17–0.45 dex at fixed stellar mass and decreases with redshift (Sparre et al. 2015). At higher masses, however, Illustris and the Munich galaxy formation model tend to under-predict and over-predict the strength of the turnover at \( z < 2 \) respectively.

### 3.3. Parameterizing the SFR-\( M_* \) Relation

In Figure 7 we parameterize the SFR-\( M_* \) relation as a function of redshift. For this we adopt the same parameterization as Lee et al. (2015):

\[
\log(\Psi) = s_0 - \log \left[ 1 + \left( \frac{M_*}{M_0} \right)^{-\gamma} \right]
\]

where \( s_0 \) and \( M_0 \) are in units of \( \log(M_\odot/yr) \) and \( M_\odot \) respectively. This function behaves as a power-law of slope \( \gamma \) at low masses which asymptotically approaches a peak value \( s_0 \) above a transitional stellar mass \( M_0 \). Originally this parameterization was defined for the SFR-\( M_* \) relation of star-forming galaxies, though we find it works similarly well for the SFR-\( M_* \) relation of all galaxies (star-forming plus quiescent) at the redshifts and stellar masses considered for this study. The righthand panels of Figure 7 show the best-fit parameters vs. redshift. We consider two cases for fitting: “free \( \gamma \)” and “fixed \( \gamma \).” In the “free \( \gamma \)” case, we allow all three parameters to vary independently for each redshift bin. Noticing that \( \gamma \) does not show strong evidence for evolution, we perform the “fixed \( \gamma \)” case by refitting with \( \gamma \) fixed to its mean value from the “free \( \gamma \)” fits. We then parameterize the evolution of \( s_0 \) and \( M_0 \) with second-order polynomials.

#### All Galaxies:

\[
\begin{align*}
    s_0 &= 0.195 + 1.157z - 0.143z^2 \\
    \log(M_0) &= 9.244 + 0.753z - 0.090z^2 \\
    \gamma &= 1.118
\end{align*}
\]

Evolution in the transition mass is a recent discovery, first reported quantitatively by Lee et al. (2015) from a study of the COSMOS 2 deg\(^2\) field. Results from the VUDS spectroscopic survey have also found a redshift dependence for the turnover mass (Tasca et al. 2015). However, because we include all galaxies in the analysis presented here the observed evolution of \( M_0 \) may be a consequence of the increasing population of massive quenched...
The growth of galaxies as predicted from the SFR–$M_*$ relation can be compared directly to the evolution of the stellar mass function. Leja et al. (2015) performed such an analysis using stellar mass functions from Tomczak et al. (2014) and SFR–$M_*$ relations from Whittaker et al. (2012) finding that the inferred growth from star-formation greatly over-predicts the observed number densities of galaxies, even on short cosmic timescales ($< 1$ Gyr). Those authors suggest that the SFR–$M_*$ relation must have a steeper slope ($\alpha \gtrsim 0.9$) at masses below $10^{10.5} M_\odot$ at $z < 2.5$, which is consistent with measurements from this work and recent literature (Whittaker et al. 2014; Lee et al. 2015; Schreiber et al. 2015).

Thus, we perform the same comparison using our updated SFR–$M_*$ relation. At each stellar mass for a given SMF at a given redshift, SFRs are calculated from the parameterized SFR–$M_*$ relation for all galaxies (Equations 2 and 3). In times steps of 80 Myr each mass bin is shifted out that the apparent similarity in the fitted parameters does not suggest a redshift-independent quiescent fraction; in fact, the difference between the SFR–$M_*$ relations at between the star-forming and the total sample are roughly consistent with the evolution of the quiescent fraction as derived from the Tomczak et al. (2014) mass functions, and assuming negligible star formation in the quiescent galaxies.

4. INFERRING STELLAR MASS GROWTH

4.1. Growth of the Stellar Mass Function

We remind the reader that these parameterizations may not extrapolate well outside of the redshift and/or stellar mass ranges used here. Nevertheless, our low-mass slope of $\gamma \sim 1$ is consistent with the relative constancy of the low-mass slope $\alpha \sim -1.5$ of the SMF (Tomczak et al. 2014); if $\gamma$ deviated significantly from unity then $\alpha$ would be expected to evolve strongly with redshift (Peng et al. 2010; Weinmann et al. 2012; Leja et al. 2015).

Figure 8 shows that $(s_0, M_0, \gamma)$ follow similar trends with redshift between the star-forming and total samples indicating that the presence and evolution of the turnover mass is intrinsic to the star-forming population and is not simply due to a growing quiescent population diluting the star-formation rates at the high mass end. We also point

\[ \log(\Psi) = s_0 - \log\left[1 + \left(\frac{M_*}{M_0}\right)^{-\gamma}\right] \]

\[
\begin{align*}
0.50 < z < 0.75 & : s_0 = 0.448 + 1.220z - 0.174z^2 \\
0.75 < z < 1.00 & : s_0 = 0.448 + 1.220z - 0.174z^2 \\
1.00 < z < 1.25 & : s_0 = 0.448 + 1.220z - 0.174z^2 \\
1.25 < z < 1.50 & : s_0 = 0.448 + 1.220z - 0.174z^2 \\
1.50 < z < 2.00 & : s_0 = 0.448 + 1.220z - 0.174z^2 \\
2.00 < z < 2.50 & : s_0 = 0.448 + 1.220z - 0.174z^2 \\
2.50 < z < 3.00 & : s_0 = 0.448 + 1.220z - 0.174z^2 \\
3.00 < z < 4.00 & : s_0 = 0.448 + 1.220z - 0.174z^2 \\
\end{align*}
\]

\[
\begin{align*}
\log(M_0) & = 9.458 + 0.865z - 0.132z^2 \\
\gamma & = 1.091
\end{align*}
\]
by the amount of star formation added to that bin. SFRs are recalculated at each new time step. Mass loss due to stellar evolution is accounted for according to Equation 16 of Moster et al. (2013). Using this technique, we evolve the observed SMF in each redshift bin forward and compare it to the observed SMF in the next redshift bin; results are shown in Figure 10.

In general, we typically find reasonable agreement at intermediate stellar masses ($10^{10.5} < M_*/M_\odot < 10^{11}$). At lower masses, however, we find a consistent systematic offset in number density rising to $\approx 0.2 - 0.3$ dex. It is important to note that this method does not incorporate the effect of galaxy-galaxy mergers whereas the observed evolution galaxy SMF necessarily does. Therefore, the disparity between these two curves inherently includes a signature of merging; in fact, Drory & Alvarez (2008) use this difference to constrain galaxy growth rates due to merging. Mergers will help to alleviate the discrepancy we observe if these low-mass galaxies are merging with more massive galaxies, thereby reducing their number density. However this would require between 25 – 65% of these galaxies to merge with a more massive galaxy per Gyr, which substantially exceeds current estimates of galaxy merger rates (e.g. Lotz et al. 2011; Williams et al. 2011; Leja et al. 2015). This disagreement thus implies that the SFRs are overestimated and/or the growth of the Tomczak et al. (2014) SMF is too slow. Similar issues were previously discussed by Weinmann et al. (2009) and Leja et al. (2015), but in contrast to the drastic discrepancies between star-formation rates and stellar masses reported by those authors, here we show that using new data sets greatly reduces – but does not eliminate – the discrepancies.

4.2. Empirical Star-Formation Histories

The evolution of the SFR–$M_*$ relation can be used to infer typical star-formation histories and stellar mass-growth histories for individual galaxies. However, as seen in the previous subsection, there is tension between the growth of the galaxy population as inferred from the SFR–$M_*$ relation when comparing to the observed stellar mass function. Here we explore two different approaches for empirically deriving galaxy mass-growth histories: (1) integrating differential star-formation histories extracted from the SFR–$M_*$ relation and (2) identifying descendents of high-$z$ galaxies based on number density selected (NDS) samples (Figure 11). For the former, we start with the four sets of initial conditions ($z_0$, $M_0$, $\Psi_0$) indicated by the star symbols, where $\Psi_0$ is determined by our SFR parameterizations (Equations 2 and 3). Stellar mass is then incrementally added assuming constant star-formation over small time intervals of $\approx 80$ Myr. At the end of each time step $\Psi$ adjusted according to the SFR–$M_*$ parameterization $\Psi(z, M_*)$. At lower redshifts we interpolate between our lowest redshift SFR–$M_*$ relation and Equation 13 of Salim et al. (2007). Mass loss due to stellar evolution is accounted for according to Equation 16 of Moster et al. (2013).

In order to get a rough estimate of the scatter in these SFHs we run 1000 Monte Carlo simulations, resampling...
ψ from a log-normal PDF with a mean value given by $\Psi(z, M_*)$ and $\pm 0.3$ dex scatter. The approximate range of mass-growth for each galaxy sample is calculated from the 16th and 84th percentiles of the distribution.

A number of studies have used this technique to estimate galaxy growth histories (e.g. Renzini 2009; Peng et al. 2010; Leitner 2012). An important point that should be kept in mind is that in this section we use the SFR–$M_*$ relation for all galaxies – not just actively star-forming ones – as is appropriate for a comparison to NDS samples. Some other studies investigate the growth histories of galaxies that remain star-forming without ever quenching (Renzini 2009; Leitner 2012).

Also shown in the middle panel of Figure 11 are mass-growth profiles predicted from the NDS approach. Using the same initial conditions shown by the star symbols, we calculate the corresponding cumulative co-moving number density from the stellar mass functions of Tomczak et al. (2014) as parameterized by Leja et al. (2015). Note, this parameterization is limited to $z \leq 2.25$, beyond which we interpolate between it and the best-fit Schechter function to the SMF at $2.5 < z < 3$.

Using abundance matching with a dark matter simulation, whereby dark matter halos are assigned stellar masses from observations in a rank ordering fashion, Behroozi et al. (2013) have studied the number density evolution of galaxies. These authors demonstrate that galaxy descendants do not evolve in the same way as their progenitors, mainly due to scatter in dark matter accretion rates of halos. Thus, Behroozi et al. (2013) have provided a numerical recipe for estimating the number density evolution of galaxies, which we use to generate predictions for the number density evolution from the initial conditions given in Figure 11. These predictions include the median estimated number density as well as the 68th percentile range. The hatched regions in Figure 11 show these 68th percentile ranges converted to stellar masses by mapping number densities to the observed stellar mass function.

On average we find that these two approaches agree within their combined 1σ confidence intervals. However there is a common systematic difference wherein the differential SFHs produce a steeper mass-growth rate for the same progenitor galaxy at early times which provides us with a different view of the discrepancy shown in Figure 10. This disparity is illustrated in the rightmost panel of Figure 11 which shows the difference in the mass-growth rates of both techniques from the middle panel. The differential SFHs build stellar mass more quickly at early times, but then slow down and are eventually overtaken by the NDS growth rates. We tested a wide range of initial conditions spanning $0.8 \leq z_0 \leq 2.75$ and $8.8 \leq \log(M_0/M_\odot) \leq 10.5$, always finding this systematic trend. Papovich et al. (2015) find similar results in their analysis of the progenitors of galaxies with present-day masses of the Milky Way and M31 galaxies. Finally, we have repeated this comparison using the SFR–$M_*$ parameterizations provided by Whitaker et al. (2014) and Schreiber et al. (2015) and in both cases we find similar disagreements. This suggests that the discrepancies between the star-formation rates and mass evolution that were previously reported by Leja et al. (2015) have not been completely resolved using the more up-to-date data sets.

5. CONCLUSIONS

In this paper we present new measurements of the evolution of the SFR–$M_*$ relation using deep imaging and high-quality photometric redshifts from the FourStar Galaxy Evolution Survey (ZFOURGE) in combination with ancillary far-IR imaging at 24, 100, and 160µm from Spitzer and Herschel. Bolometric IR luminosities ($L_{IR}$), used for calculating obscured star-formation rates, are obtained by scaling the IR spectral template introduced by Wuyts et al. (2008) to the 24–160µm photometry. This luminosity-independent conversion of flux to $L_{IR}$ has been shown to be more appropriate than techniques that apply different IR templates for different $L_{IR}$ regimes (Muzzin et al. 2010; Wuyts et al. 2011).

Utilizing star-formation rates derived from a UV+IR stacking analysis we examine evolution of the SFR–$M_*$ relation at $0.5 < z < 4$. We perform this analysis for all galaxies as well as a sample of actively star-forming galaxies as selected by their rest-frame $(U-V)$ and $(V-J)$ colors. In agreement with recent results, we find that SFRs are roughly proportional to stellar mass at low masses ($\lesssim 10^{10.2} M_\odot$), but that this trend flattens at higher masses (see also Whitaker et al. 2014; Lee et al. 2015; Schreiber et al. 2015; Tasca et al. 2015). Furthermore, although the evolution of the SFR–$M_*$ relation is still predominantly in normalization, the slope at high masses ($M_* \gtrsim 10^{10.2} M_\odot$) is also changing. Similar to Lee et al. (2015) and Tasca et al. (2015) we find that the transition mass at which this flattening occurs evolves with redshift; this is true whether or not quenched galaxies are included. Full parameterizations of the SFR–$M_*$ relation with respect to redshift, $\Psi(z, M_*)$, for both all and star-forming galaxies are presented in Section 3.3 and shown in
Fig. 10.—Implied growth of the galaxy stellar mass function due to star-formation. Each panel shows the observed SMF from Tomczak et al. (2014) at the redshifts indicated in the upper-right corner. Curves in each panel represent the SMF from the preceding redshift bin evolved forward in time based on our parameterized SFR–$M_*$ relation for all galaxies. Redshifts of the original SMFs (i.e. “starting” redshifts) are indicated in the legend. Residuals between the evolved and observed SMFs for each redshift bin are shown in the lower panels. We observe that the numbers of galaxies at $M_* < 10^{10.5} \, M_\odot$ are consistently overproduced at each redshift by $\approx 0.2 – 0.3$ dex. It is important to note that galaxy merging is not accounted for in the inferred SMFs, thus, at least part of this offset must be caused by this effect. However this would require between 25 – 65% of these galaxies to merge with a more massive galaxy per Gyr, which substantially exceeds current estimates of galaxy merger rates (e.g. Lotz et al. 2011; Williams et al. 2011; Leja et al. 2015).

Figures 7 and 8. By integrating along the evolving SFR–$M_*$ sequence we estimate how galaxies should grow due to star-formation. We find that galaxies with a present-day mass of roughly $10^{10} \, M_\odot$ have grown in mass by about $10\times$ since $z \sim 1.5$. In contrast, $10^{11} \, M_\odot$ galaxies have grown by only about $1.5\times$ since $z \sim 1.5$, but show more rapid evolution at higher redshifts, growing by $\sim 15\times$ between over $1.5 < z < 3$. Furthermore, we find that SFHs rise at early times and fall at late times. The peak of a galaxy’s SFH occurs earlier for galaxies with larger present-day masses; for example galaxies with a present-day stellar mass around $10^{11} \, M_\odot$ peak at $z \approx 2$, whereas $10^{10} \, M_\odot$ galaxies peak at $z \approx 0.8$.

Several recent studies have also found evidence in support of rising SFHs in individual galaxies at early times (e.g. Papovich et al. 2011; Reddy et al. 2012; Lee et al. 2011; Abramson et al. 2015).

A standard question in galaxy evolution has been whether integrated star-formation rates are consistent with evolution of the global stellar mass density (e.g. Wilkins et al. 2008, Reddy & Steidel 2009), with recent measurements suggesting that these quantities may be in reasonable – though not perfect – agreement (Madau & Dickinson 2014). Here we have taken a step further, using new data to ask whether the star-formation rates agree with the mass density evolution in bins of stellar mass. We use the
Analyzing the scatter introduced by Moustakas et al. 2013 and slowing to lesser rates at later times. This is shown clearly in the agreement between these two techniques, we note that the integrated mass-growth curves are more accelerated, growing more rapidly at early times and potentially due to the size of the difference can be taken as a measure of the growth rate due to mergers (e.g. Drory & Alvarez 2008; Moustakas et al. 2013). Nevertheless, these two approaches on average agree within their combined 1σ confidence intervals.

The disagreement at $z \gtrsim 1$ suggests that either our SFRs are overestimated, that the rate of mass-growth inferred from the stellar mass function is underestimated, or both. Errors in star-formation rate measurements may arise from low-level AGN activity, an incorrect conversion of flux to bolometric UV/IR luminosities, the assumed IMF, and variations in star-forming duty cycles as probed by UV and IR indicators. Stellar masses were estimated by fitting models to the observed spectral energy distributions (SEDs) of individual galaxies. Various assumptions that go into the SED-fitting process that are possible sources for systematic errors include smooth exponentially declining SFHs, a single dust screen, a constant IMF, solar metallicity, and assuming that emission lines do not contribute significantly to the observed photometry (for detailed discussions see Marchesini et al. 2009; Conroy 2013; Courteau et al. 2014). Analyzing the scatter introduced into the star-formation rate and stellar mass estimates by varying these assumptions would inform the range of possible stellar mass growth histories, but is beyond the scope of this work.

The measurements on which this study is based were performed using high-quality data and standard methods. Moreover, the use of the same ZFOURGE sample for measuring both the SMF and the SFR–$M_*$ relations helps provide internal consistency for this work. Although the broad qualitative agreement that we find in mass-growth histories is encouraging for current studies of galaxy evolution, the disagreements highlight the need to move beyond the simplistic assumptions that underly current data analysis methods.

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make the ZFOURGE survey possible as well as the Texas A&M University Brazos HPC cluster which contributed to this project http://brazos.tamu.edu/. This work was supported by the National Science Foundation grant AST-1009707. KG acknowledges support from ARC Grant DP1094370 and ZFOURGE acknowledges The Australian Time Assignment Committee for Magellan time. GKG was supported by Future Fellowship FT140100933. Australian access to the Magellan Telescopes was supported through the National Collaborative Research Infrastructure Strategy of the Australian Federal Government. KEW was supported by an appointment to the NASA Postdoctoral Program at the Goddard Space Flight Center, administered by Oak Ridge Associated Universities through NASA.

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**TABLE 1**

SFR–M* Relations Data
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2.50 < z < 3.00

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Notes: A downloadable ascii version of this table will be hosted at http://zfourge.tamu.edu/