The Constant Average Relationship between Dust-obscured Star Formation and Stellar Mass from $z = 0$ to $z = 2.5$

Katherine E. Whitaker$^{1,2,6}$, Alexandra Pope$^2$, Ryan Cybulski$^3$, Caitlin M. Casey$^4$, Gergö Popping$^5$, and Min S. Yun$^2$

$^1$Department of Astronomy, University of Massachusetts, Amherst, MA 01003, USA; kwhitaker@astro.umass.edu
$^2$Department of Astronomy, The University of Texas at Austin, Austin, TX 78712, USA
$^3$Department of Physics, University of Connecticut, Storrs, CT 06269, USA
$^4$Department of Astronomy, University of Texas at Austin, Austin, TX 78712, USA
$^5$European Southern Observatory, Karl-Schwarzschild-Strasse 2, D-85748, Garching, Germany

Abstract

The total star formation budget of galaxies consists of the sum of the unobscured star formation, as observed in the rest-frame ultraviolet (UV), together with the obscured component that is absorbed and re-radiated by dust grains in the infrared. We explore how the fraction of obscured star formation depends on stellar mass for mass-complete samples of galaxies at $0 < z < 2.5$. We combine GALEX and WISE photometry for SDSS-selected galaxies with the 3D-HST treasury program and Spitzer/MIPS 24 μm photometry in the well-studied five extragalactic Cosmic Assembly Near-IR Deep Extragalactic Legacy Survey (CANDELS) fields. We find a strong dependence of the fraction of obscured star formation ($f_{\text{obscured}} = \text{SFR}_{\text{IR}} / \text{SFR}_{\text{UV-IR}}$) on stellar mass, with remarkably little evolution in this fraction with redshift out to $z = 2.5$. 50% of star formation is obscured for galaxies with $\log(M/M_\odot) = 9.4$; although unobscured star formation dominates the budget at lower masses, there exists a tail of low-mass, extremely obscured star-forming galaxies at $z > 1$. For $\log(M/M_\odot) > 10.5$, >90% of star formation is obscured at all redshifts. We also show that at fixed total SFR, $f_{\text{obscured}}$ is lower at higher redshift. At fixed mass, high-redshift galaxies are observed to have more compact sizes and much higher star formation rates, gas fractions, and hence surface densities (implying higher dust obscuration), yet we observe no redshift evolution in $f_{\text{obscured}}$ with stellar mass. This poses a challenge to theoretical models, where the observed compact sizes at high redshift seem in tension with lower dust obscuration.

Key words: galaxies: evolution – galaxies: formation – galaxies: high-redshift

1. Introduction

The current census of the peak epoch of star formation, $z \sim 1–3$, reveals that the most massive galaxies are enshrouded in dust (e.g., Magnelli et al. 2009; Murphy et al. 2011; Bourne et al. 2017). These dust grains form a cocoon around nascent stars still embedded in their native birth sites, preferentially absorbing the ultraviolet (UV) stellar radiation and thermally re-radiating in the far-infrared (FIR; Seibert et al. 2005; Cortese et al. 2006; Muñoz-Mateos et al. 2009). It is this interstellar dust extinction that introduces the largest source of systematic error into global measurements of the star formation rates (SFR) of galaxies (Kennicutt 1998a).

There are several standard methods employed to account for dust attenuation in order to attain a complete view of star formation. The unobscured star formation measured from the non-ionizing rest-frame UV continuum ($\sim 130–250$ nm) of massive recently formed stars can be corrected using empirical calibrations based on the UV slope from the spectral energy distributions (SEDs; e.g., Meurer et al. 1999). However, these calibrations are uncertain due to potential intrinsic variations in the UV slope and dust attenuation curves (e.g., Battisti et al. 2016; Salmon et al. 2016). Alternatively, optical emission-line diagnostics such as Hα can be dust-corrected from the Balmer decrement (Kennicutt et al. 2009). But such observations are difficult to obtain across cosmic time and observationally expensive. One can also estimate total SFRs by directly measuring the obscured SFR$_{\text{IR}}$ from one or more components of the mid-infrared to FIR emission, and co-adding this with the unobscured UV SFR. Although systematic uncertainties remain in calibrating the infrared (IR) luminosity (Calzetti 2013), the main bottleneck has been in measuring accurate FIR emission for representative samples of star-forming galaxies across cosmic history.

Due to the onset of source confusion, the deepest attainable FIR and sub-millimeter (sub-mm) surveys to date are only sensitive to the most extreme galaxies (Casey et al. 2014a, and references therein). FIR and sub-mm selected galaxies are rare by number and likely do not represent the overall star-forming galaxy population. Given these current limitations, empirical calibrations of deep Spitzer/MIPS and Herschel stacks have instead been used to push the measurements of the average correlation between SFR and $M_*$ down to the equivalent $M_*$ limits of the Hubble Space Telescope (HST) legacy surveys (Viero et al. 2013; Whitaker et al. 2014). Although the majority of star formation is assumed to be unobscured in low-mass galaxies, the dust corrections are not insignificant. The goal of this paper is to quantify the level of obscured star formation as a function of $M_*$ and total SFR for mass-complete samples of galaxies across 80% of cosmic history (out to $z = 2.5$). We will address the following questions: (1) how does the fraction of obscured star formation depend on $M_*$ (Section 3.1), and (2) how does the fraction of obscured star formation depend on total SFR (Section 3.2). In Section 4, we discuss the redshift evolution of these relations in the context of our current understanding of galaxy-scaling relations and theoretical models. The conclusions of this paper are summarized in Section 5.
In this paper, we use a Chabrier (2003) initial mass function (IMF) and assume a $\Lambda$CDM cosmology with $\Omega_M = 0.3$, $\Omega_{\Lambda} = 0.7$, and $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

2. Data and Sample Selection

2.1. Stellar Masses, Redshifts, and Rest-frame Colors

We use the multi-wavelength data sets of five well-studied extragalactic fields (AGES, COSMOS, GOODS-N, GOODS-S, and UDS) through the Cosmic Assembly Near-IR Deep Extragalactic Legacy Survey (CANDELS; Grogin et al. 2011; Koekemoer et al. 2011) and the 3D-HST survey (Momcheva et al. 2016). With $M_*$, redshifts, and rest-frame colors from the 3D-HST $0.3-8\mu$m photometric (Skelton et al. 2014) and spectroscopic (Momcheva et al. 2016) catalogs, we leverage the analysis of the mass-complete sample of 39,106 star-forming galaxies at $0.5 < z < 2.5$ presented in Whitaker et al. (2014). The Skelton et al. (2014) photometric catalogs include a large compilation of optical to near-infrared (NIR) photometric broadband and medium-bandwidth filters, ranging from 18 filters in UDS up to 44 in COSMOS. Galaxies are identified using Source Extractor (Bertin & Arnouts 1996) with deep $F_{125W} + F_{140W} + F_{160W}$ detection images. Redshifts and rest-frame colors are determined with the EAZY code (Brammer et al. 2008). Where possible, we combine the photometry with the spatially resolved low-resolution HST/WFC3 G141 grism spectroscopy to derive improved redshifts. The “best” redshift was rank-ordered to be spectroscopic (4%) total sample, 13% of galaxies with $\log(M_*/M_{\odot}) > 10$, (12% total, 38% massive), or photometric (84% total, 49% massive), depending on the availability. Star-forming galaxies are identified from rest-frame $U-V$ and $V-J$ colors following Whitaker et al. (2012a). Luminous active galactic nuclei are identified and removed using the Spitzer/IRAC color selections of Donley et al. (2012) due to its potential contamination of SFR$_{IR}$.

Stellar masses $M_*$ are derived by fixing the redshift to “best,” as described above, and fitting stellar-population synthesis templates with the FAST code (Kriek et al. 2009). The FAST templates include a grid of Bruzual & Charlot (2003) models that assume a Chabrier (2003) IMF with solar metallicity and a range of ages (7.6–10.1 Gyr), exponentially declining star formation histories ($7 < \tau < 10$ in log years) and dust extinction ($0 < A_V < 4$). The dust content is parameterized by the attenuation in the V-band following the Calzetti et al. (2000) extinction law. $M_*$ is corrected for emission-line contamination of the broadband fluxes using values presented in Appendix A of Whitaker et al. (2014). The mass completeness limits employed herein correspond to the 90% completeness limits derived by Tal et al. (2014), calculated by comparing object detection in the CANDELS/deep with a recombined subset of the exposures that reach the depth of the CANDELS/wide fields. Although the mass completeness in the deeper GOODS-N and GOODS-S fields will extend to lower stellar masses, we adopt the more conservative limits for the shallower HST/WFC3 imaging. The resulting sample is mass-complete down to $\log(M_*/M_{\odot}) = 8.7$ (9.3) at $z = 1.0$ ($z = 2.5$).

2.2. Star Formation Rates

SFR$_{IR}$ originates from stacking analyses in Whitaker et al. (2014), using Spitzer/MIPS $24\mu$m images from the Far-Infrared Deep Extragalactic Legacy survey (AGES; Dickinson & FIDEL Team 2007), S-COSMOS survey (COSMOS; Sanders et al. 2007), GOODS Survey (GOODS-N and GOODS-S; Dickinson et al. 2003), and the Spitzer UKIDSS Ultra Deep Survey (UDS; PI: Dunlop). We use a high-resolution $F_{125W} + F_{140W} + F_{160W}$ detection image to model blended sources in the lower-resolution MIPS/24$\mu$m image, “cleaning” all galaxies of the contaminating flux of neighboring sources (Section 3, Whitaker et al. 2014). Although UV/optical emission may be spatially offset up to 1” from the IR emission (Chen et al. 2015; Koprowski et al. 2016), this is well within the 3” MIPS/24$\mu$m beam. The galaxy samples for four redshift intervals ($z = 0.75, 1.25, 1.75, 2.25$, with $\Delta z = 0.5$), are subdivided into bins of stellar mass with 0.2 dex width. The number of galaxies within a bin ranges from 7 upwards to 2498 galaxies, with an average value of 652 ± 81 galaxies. Unsurprisingly, the two bins with less than 20 galaxies represent the most massive galaxies (log($M_*/M_{\odot}) = 11.5$) at the highest redshifts ($z > 1.5$). 24$\mu$m flux densities are converted to total IR luminosity, $L_{IR} \equiv L(8–1000\mu m)$, based on a single log-average of the Dale & Helou (2002, hereafter DH02) templates. We explore this assumption in greater detail in Appendix A. We convert $L_{IR}$ to SFR$_{IR}$ by multiplying by $1.09 \times 10^{-10} M_{\odot} \text{ yr}^{-1} L_{\odot}^{-1}$ (Kennicutt 1998a), which assumes a Chabrier (2003) IMF. When considering only the sample above the SFR completeness limits, we confirm that the median stacked SFR$_{IR}$ robustly probes the peak of the individual log-normal distributions within 0.05 dex (Rodighiero et al. 2011). Although the MIPS/24$\mu$m IR SFRs are generally robust for star-forming galaxies at these redshifts in aggregate (e.g., Wuyts et al. 2011; Utomo et al. 2014), we compare the high-redshift results to Herschel and SCUBA-2 stacks from the literature in Section 3.

SFR$_{UV}$ is derived from rest-frame UV luminosities based on Bell et al. (2005). The total integrated 1216–3000 Å UV luminosity is measured from the 2800 Å rest-frame luminosity multiplied by a factor of 1.5 to account for the UV spectral shape ($L_{UV} = 1.5L_{2800}$). We adopt the $L_{2800}$ in lieu of 1600 Å to ensure that the UV continuum is sampled by at least two photometric bands for all galaxies. $L_{2800}$ is determined from the best-fit template using the same methodology as the rest-frame colors (Brammer et al. 2011). To derive the SFR$_{UV}$, Bell et al. (2005) multiplied $L_{UV}$ by both $1.09 \times 10^{-10} M_{\odot} \text{ yr}^{-1} L_{\odot}^{-1}$ and a factor of 2.2 that accounts for the unobscured starlight emitted shortward of 1216 Å and longward of 3000 Å.

Another popular alternative conversion to total SFR is presented in Murphy et al. (2011). This conversion is not only different in the absolute calibration, but also in the relative amount of star formation attributed to the obscured and unobscured phases. Although we adopt the aforementioned SFR calibration in order to remain consistent with our previous work, we consider in Section 3.1 how this alternative calibration would systematically change the observed correlations.

http://irsa.ipac.caltech.edu/data/SPITZER/SpUDS/
derive SFRIR is necessary in this regime. Above log transparent points signify where SFRIR observed relation obscured. Conversely, at lower redshift epochs between below the 3  limit for individual detections in the 24 m imaging; stacking to derive SFRIR is necessary in this regime. Above log(M*/M⊙) = 9.4 at all redshift epochs between z = 0.5 and z = 2.5, the majority of star formation is obscured. Conversely, at lower M*, star formation is unobscured on average.

3. Results
3.1. How Does the Fraction of Obscured Star Formation Depend on Stellar Mass?

In Figure 1, we present the median relation between SFRUV-IR and M* from z = 0.5 out to z = 2.5 from Whitaker et al. (2014). As described in Whitaker et al. (2014), the error bars for LIR are derived from a Monte Carlo bootstrap analysis of the 24 m stacks for each stellar mass bin, and added in quadrature to the 1σ scatter in the L UV distributions. We break down the total SFR into the respective unobscured (UV; blue triangles) and obscured (IR; red circles) components. The high transparency symbols signify SFRIR below the 3σ 24 m limit, whereas more opaque symbols are above this limit. While we adopt the stacked SFRIR values for all bins, we note that the stacks are in agreement with the detections above the 3σ 24 m limits. At all redshifts considered, >50% of the star formation is obscured for galaxies more massive than log(M*/M⊙) = 9.4. SFRUV is relatively flat with increasing M* at each epoch, whereas star formation is increasingly obscured as galaxies gain more stellar mass. This figure demonstrates the importance of using the appropriate SFR diagnostics depending upon the M* regime being considered; it is critical to obtain IR observations in order to measure robust SFRs for massive galaxies, whereas rest-UV observations will be more important at log(M*/M⊙) < 9.

We observe a remarkably tight correlation between the median obscured star formation fraction (fobsurred = SFRIR/(SFRUV + SFRIR)) and M*, generally showing little redshift evolution between z = 0.5 and z = 2.5 (Figure 2). Here, we use the error analysis presented in Figure 1 in conjunction with the number of galaxies within a particular bin to derive the error in the mean. The best-fit relation is defined by a logistic growth function

\[ f_{\text{obsurred}} = \frac{1}{1 + ae^{b \log (M*/M_\odot)}} \]  

(1)

where the best-fit parameters to Equation (1) can be found in Table 1. The grayscale in the left panel of Figure 2 shows the contours of the individual 3D-HST detections relative to the completeness limits at each redshift epoch (thin solid lines). Owing to the extremely deep optical CANDELS/3D-HST photometry, the limiting factor for individual SFRs is the Spitzer/MIPS 24 m depth. We convert 3σ 24 m limits into the limiting SFRIR for each redshift interval (see Figure 2 in Whitaker et al. 2014). When combined with the SFRUV in the 95th percentile for a given M*, and redshift bin, this yields an effective completeness limit. The shape of the completeness curves therefore depends on both the redshift evolution in the distribution of SFRUV and the limiting SFRIR. The 95th percentile is chosen to avoid extreme outliers in SFRUV, while probing the minimum obscuration fraction for a given SFRIR limit.

The scarcity of individual detections near the completeness limits for massive galaxies indicates that they are preferentially highly dust obscured; there is a dearth of massive galaxies that are relatively unobscured. Galaxies are on average >95% obscured at and above the knee of the mass function (e.g., log(M*/M⊙) = 10.8–11. Muzzin et al. 2013), and >70% obscured 1 dex below the characteristic mass (see also Dunlop et al. 2017). While the majority of star formation in the median low-mass galaxy will be observable in the rest-UV, there exists a population of highly obscured low-mass galaxies at z > 1 (e.g., Pope et al. 2017). The individual grayscale 3D-HST distribution relative to the median stacked values suggests a large scatter in the amount of obscuration in galaxies with log(M*/M⊙) < 9.5 at 0.5 < z < 2.5.

Next, we compare with results at z ~ 0 (Figure 2, right). The grayscale in the right panel represents 22,481 star-forming galaxies selected at 0.02 < z < 0.05 from the Sloan Digital Sky Survey DR12 (SDSS; Alam et al. 2015). The SFRs for this local comparison sample are measured from GALEX and WISE/22 m photometry (see R. Cybulski et al. 2017, in preparation, for the details). The SDSS mass completeness sets in at much higher masses (log(M*/M⊙) ~ 10) than for 3D-HST. Close to these limits, the data also become limited by the depth of the GALEX and WISE all-sky (but relatively shallow) photometry. We require that the far-ultraviolet (FUV) GALEX-exposure time is >100 seconds, resulting in >80% completeness across the redshift range. Quiescent galaxies are excluded from this sample on the basis of the specific SFR (SFR/M*) bimodality, consistent with the 3D-HST UVJ-selection, where we identify and remove galaxies with log(sSFR) < −11 yr−1. To test how sensitive the resulting SDSS distribution is to this assumption, we conservatively raise and lower this limit in log (sSFR) by 0.5 dex. Lowering the cut to log(sSFR) = −11.5 yr−1 intersects the peak of the quiescent distribution, whereas raising it to log(sSFR) = −10.5 yr−1 corresponds roughly to the 1σ lower envelope of the star-forming galaxy distribution. We find that the results are not sensitive to our definition of quiescence in the SDSS sample, with the median of the distribution changing...
only weakly \((\Delta f_{\text{obs}} < 0.04)\) for a correspondingly large change in the \(\log(\text{SFR})\) limit.

The mode of the SDSS distribution in Figure 2 (right) tracks the higher-redshift data well, but with a broader distribution. In Figure 2, there appears to be a dearth of highly obscured low-mass galaxies at \(z \sim 0\). We forgo interpretation of the individual distributions at the lowest \(M_\ast\) due to complications by the completeness limits of both data sets. For obscuration fractions to the left of the dotted lines, SFR completeness effects will become important.

We can illuminate the difference in the distributions from \(z = 2.5\) to \(z = 0\) for massive galaxies by selecting a bin of \(10.6 < \log(M/M_\odot) < 10.8\), where both the SDSS and 3D-HST samples are complete down to low levels of obscured star formation (Figure 3). We find that the distribution at \(z = 0\) monotonically increases toward a maximum value at 100% obscuration. The mode of the distributions (95%–100%) remains relatively unchanged out to \(z = 2.5\), whereas the width narrows. Although we only show one \(M_\ast\) bin here, we find similar trends down to \(\log(M/M_\odot) = 10\). When measuring the median of the distributions (arrows), as also done in the stacking analysis, this suggests a decrease (or flattening) in obscuration at low redshift for the most massive galaxies. This is also seen in the left panel of Figure 2, where there exists a noteworthy deviation from the best-fit relation for the most massive galaxies in the \(0.5 < z < 1.0\) (1.0 < \(z < 1.5\)) redshift bin, with \(f_{\text{obs}}\) for galaxies with \(\log(M_\ast/M_\odot) = 11\) depressed by 10% (4%) or 0.05 dex (0.02 dex; see also Figure 7). As shown in Kauffmann et al. (2003), the vast majority of the most massive galaxies in SDSS at \(z = 0\) are quiescent. This makes it difficult to push our direct comparison of the distributions presented in Figure 3 toward the highest stellar masses, owing to the sharp drop-off in the local sample.

The observation that star formation in the most massive galaxies \((\log(M/M_\odot) > 10.6)\) at intermediate redshifts is slightly less dust-obscured can also be seen in Figure 5 of Whitaker et al. (2014), who showed IRX \((\equiv L_\text{IR}/L_\text{UV})\) for this same data analysis as a function of stellar mass. This same redshift bin also has a lower IRX–\(\beta\) relation (Figure 6 Whitaker et al. 2014); the results presented in the right panel of Figure 6 that adopt an evolving template conversion for \(L_\text{IR}\) suggest that we are only underestimating \(L_\text{IR}\) when using the DHH02 log-average template for the most IR-luminous galaxies.
The Astrophysical Journal, 850:208 (11pp), 2017 December 1

Therefore, the choice of template will not significantly reduce discrepancies in the IRX–β relation or $f_{\text{obsured}}$, as we are probing the median properties of the star-forming galaxy population where the ratio of $L_{\text{IR}}(z)/L_{\text{IR, DH02}}$ is approximately unity. We explore template-dependent effects on $L_{\text{IR}}$ in greater detail below and in Appendix A. Both a relative increase in far-UV compared to near-UV attenuation and an increasing stellar population age could result in the shallower IRX–β and $f_{\text{obsured}}$ relations observed (see e.g., Figure 11 in Popping et al. 2017a).

3.1.1. The Effects of Alternative SFRIR Methodologies

There exists a range of alternative SFRIR methodologies adopted within the literature. We will explore how our results depend upon the assumed calibrations and templates in the following paragraphs. The dashed line in Figure 2 (left) corresponds to the best-fit relation when corrected to the SFRIR calibrations presented in Equations (3) and (4) of Murphy et al. (2011). Whereas the relative ratio of total star formation originating in IR relative to UV emission is assumed to be SFRIR/SFRUV = 0.45 here, Murphy et al. (2011) adopted a higher value of SFRIR/SFRUV = 0.88. This results in an overall shift of $f_{\text{obsured}}$ toward higher fractions of obscured star formation.

Studies show that the MIPS/24 μm photometry is a robust tracer of the average SFRIR out to $z \sim 2$–3 (e.g., Wuyts et al. 2011; Tomczak et al. 2016). However, to rule out potential biases associated with the 24 μm empirical SFR calibration, we compare our results to several independent studies. Bourne et al. (2017) present a stacking analysis based on the ultra-deep 450 and 850 μm over 230 arcmin$^2$ from the SCUBA-2 Cosmology Legacy Survey in the AEGIS, COSMOS, and UDS fields, together with 100–250 μm imaging from Herschel. They adopt a similar deblending approach for the longer wavelength data that relies upon the deep photometric catalogs from CANDELS/3D-HST. We adopt a correction to the stellar masses presented in Bourne et al. (2017) of −0.03 dex to convert from Kroupa to Chabrier IMF, following Zahid et al. (2012). We further correct their adopted luminosity to SFR conversion of Murphy et al. (2011) to that used in the present analysis. The utility of the deep MIPS/24 μm photometry is evident when considering the $M_*$ limits achievable with their data analysis. Though the average trends are in excellent agreement with our results, Bourne et al. (2017) are only probing the most massive, obscured galaxies just shy of the $M_*$ regime where the trend sharply falls. They push below the standard confusion limit, but the data is not able to probe the full dynamic range in $M_*$. When adopting a UV-selected sample, the data presented in Figure 3 of Heinis et al. (2014) is also consistent with no redshift evolution in $f_{\text{obsured}}$ from $z \sim 0.5$ to $z \sim 1.5$.

We have also compared to a subset of the Herschel-selected sample of dusty star-forming galaxies (DSFGs) in the COSMOS field at $0.5 < z < 2.5$ presented in Casey et al. (2014b) in Figure 2. As this sample requires direct sub-mm detections, it will be inherently biased toward high fractions of obscured star formation, although the points are consistent within the errors.

Next, we compare our results to Equation (7) in Béthermin et al. (2012); this equation is the SFRIR/SFRUV ratio based on the UV light attenuation measured in Pannella et al. (2009). Pannella et al. (2009) derived the UV and 1.4 GHz (which is assumed to be a proxy for IR) SFRs of a K-selected BzK sample in the COSMOS field, adopting photometric redshifts at $1 < z < 3$ for $\log(M_*/M_\odot) > 10$. We correct the stellar masses from the assumed Salpeter IMF to Chabrier IMF using the conversion of −0.24 dex in Zahid et al. (2012). We convert this equation to the SFRIR/SFRUV+IR ratio and include this relation in the left panel of Figure 2 for the stellar mass regime considered in Pannella et al. (dot–dash line). It is difficult to differentiate between the effects of sample selection (mass-selected versus the BzK color-selection), data quality (grism versus photometric redshifts), and SFR indicators (24 μm versus Herschel). Despite these limitations, our result that $f_{\text{obsured}}$ does not evolve with redshift agrees with the assumptions made in Béthermin et al. (2012) based on data from Pannella et al. (2009).

Finally, we test in greater detail in Appendix A whether our assumption of the single log-average of the DH02 templates is driving the results presented in Figure 2. In other words, are we sensitive to the common assumption of a redshift-independent IR SED? Béthermin et al. (2012) showed evidence that the average IR SED of star-forming galaxies evolves with redshift (see also Magdis et al. 2012). In the Bourne et al. (2017) analysis, the models of Béthermin et al. (2012) predicted IR luminosities that are a factor of 1.2 higher on average at $2.5 < z < 4$. We present a direct comparison of $f_{\text{obsured}}$ measured using the templates of (Magdis et al. 2012; Kirkpatrick et al. 2012, as used in Bethermin et al.) and Kirkpatrick et al. (2015). Although we find a systematic offset toward lower values of $f_{\text{obsured}}$ at $\log(M_*/M_\odot) < 10.5$ than inferred using the DH02 templates, the overall trends remain redshift-independent. Redshift- and $L_\text{IR}$-dependent template conversions to bolometric IR luminosity can significantly affect the measured $f_{\text{obsured}}$ values, but not the redshift evolution of the trend itself.

3.2. How does the Fraction of Obscured Star Formation Depend on Total SFR?

Next we explore how the fraction of obscured star formation depends upon the total SFRUV+IR. While we saw a marked lack of evolution in the median trends with $M_*$ out to $z = 2.5$, we show in Figure 4 that SFRUV+IR increases dramatically. However, the overall shape does not vary strongly. We include the median values from the SDSS $z \sim 0$ sample (R. Cybulski et al. 2017, in preparation); this data was reduced and analyzed completely independently, including a different IR calibration (e.g., WISE 22 μm versus Spitzer/MIPS 24 μm), yet the evolution is consistent over the full redshift range considered. The best-fit relation for each redshift epoch is defined by a logistic growth function

$$f_{\text{obsured}} = \frac{1}{1 + ae^{-6\log(\text{SFRUV+IR})}},$$

where the best-fit parameters to Equation (2) can be found in Table 2.

The strong redshift evolution of the median fraction of obscured star formation as a function of SFRUV+IR can be understood generally by the increasing normalization of the star formation sequence, as the global SFR is increasing toward earlier epochs in the Universe (Madau & Dickinson 2014; Schreiber et al. 2015; Tomczak et al. 2016). If we consider galaxies with the same fraction of obscured star formation, we are effectively considering a fixed median stellar mass according to Figure 2. Indeed, SFRUV+IR increases by roughly 0.2 dex per $\Delta z \sim 0.5$ at fixed $f_{\text{obsured}}$. For fractions $>70\%$, the
evolution in SFR$_{\text{UV}}$ at high redshift is not as dramatic, as the curves saturate at maximal levels of obscuration. If we instead consider the evolution of $f_{\text{obscured}}$ at fixed SFR, we will no longer be probing similar populations of star-forming galaxies across cosmic time. In this case, galaxies with the same SFR at high redshift have significantly lower $f_{\text{obscured}}$ than at low redshift. Santini et al. (2014) also measured lower dust mass per unit SFR at higher redshifts, in agreement with the results herein.

How do galaxies evolve in this diagram? In reality, we know that galaxies grow with time and therefore fixing stellar mass does not ensure we are tracking similar galaxies across cosmic time. To build some intuition, we can instead select galaxies based on fixed number density and use Equation (1) of van Dokkum et al. (2013) to estimate the redshift evolution of stellar mass for Milky Way progenitors, $M_{\text{MW}}$. When combining $M_{\text{MW}}(z)$ with $f_{\text{obscured}}(M_e)$ from Equation (1) in this paper, we can predict $f_{\text{obscured}}(z)$. By adopting the SFR implied by the log(SFR)-log($M_e$) relation at a given $z$ (see the Appendix in Whitaker et al. 2017), we can predict the trajectory of a Milky Way progenitor in $f_{\text{obscured}}$ and log(SFR), (star symbols in Figure 4). In this case, $f_{\text{obscured}}$ changes more rapidly at higher redshift, increasing by 14% from $z = 2.25$ to $z = 1.25$ (2 Gyr), but only 4% from $z = 1.25$ to $z = 0$ (8 Gyr).

4. Discussion

In this paper, we demonstrate that at any given fraction of obscured star formation ($f_{\text{obscured}} = \text{SFR}_{\text{IR}}/\text{SFR}_{\text{UV+IR}}$), there is little evolution in the median trends with stellar mass over 11 billion years of cosmic time ($z = 0$ to $z = 2.5$). Interestingly, studies have also found little to no redshift evolution when considering $A_{1500}$ (e.g., Pannella et al. 2009), $A_{H_\alpha}$ (e.g., Sobral et al. 2012), and $A_V$ (e.g., Martis et al. 2016) at fixed stellar mass, all quantities parameterizing the amount of dust attenuation. This marks the very epoch over which the SFR density peaks and drops precipitously (Madau & Dickinson 2014), and the metallicities of galaxies of a given mass change by $\sim$0.2–0.6 dex (e.g., Savaglio et al. 2005; Erb et al. 2006; Kewley & Ellison 2008), with more evolution at the low stellar mass end. Galaxies at higher redshift have lower metallicities, and therefore one would expect them to produce less dust. Consequently, if there is a direct scaling between dust mass and $L_{\text{IR}}$, less star formation would be obscured in these galaxies relative to similar masses at low redshift. It is therefore not immediately clear why there is a lack of redshift evolution in $f_{\text{obscured}}$ (and dust attenuation) at fixed stellar mass.

The amount of dust in these moderate to massive galaxies ($>10^9 M_\odot$) is effectively set by the balance between dust production and destruction. Dust production depends upon the process of coagulation within molecular clouds. Key additional production channels including supernovae (SNe) and stellar ejecta from stars in the asymptotic giant branch phase of stellar evolution. The ionizing UV and X-ray radiation from massive stars can also easily destroy dust grains, in addition to collisional destruction. While the ISM growth is governed to first order by the volume density of gas and the metallicity, SNe, and stellar winds are affected by the SFR volume density (e.g., Popping et al. 2017b). Given that the analysis herein is empirically driven in nature, we next explore the how the effects of dust production and destruction could explain the lack of redshift evolution of the $f_{\text{obscured}}$-$\text{log}(M_e)$ relation predominantly in the context of existing observational results.

4.1. Metallicity

First, we will consider the expected effects of metallicity on the amount of dust production through correlations with both dust-to-gas ratio and stellar mass. Observations of local galaxies show that dust-to-gas ratio scales linearly with metallicity above $\sim$0.1 $Z_\odot$ (e.g., Draine et al. 2007; Leroy et al. 2011; Rémy-Ruyer et al. 2014). This marks a reasonable metallicity threshold for the present study, given that the vast majority of galaxies in our sample should have $Z > 0.1Z_\odot$. If we assume the dust-to-gas ratio does not vary strongly with redshift, as suggested by models (Feldmann 2015; Popping et al. 2017b), we can calculate how this quantity scales with stellar mass at various redshift epochs. We describe the details of this analysis in Appendix B. Our compilation of observations of mass-metallicity and dust-to-gas ratio versus metallicity suggest that the dust-to-gas ratio is a factor of $\sim$3 larger at log($M/M_\odot$) = 11 as compared to log($M/M_\odot$) = 9, with minimal redshift evolution when normalized to the dust-to-gas ratio for the most massive galaxies at a given epoch. In Figure 2, we see a similar relative difference in the fraction of obscured star formation for the same stellar mass range. However, the overall shapes do not quite match in detail; the increase at lower stellar masses is more dramatic for the fraction of obscured star formation relative to change in dust-to-gas ratio, with a 30% larger increase from log($M/M_\odot$) = 9–10 (see Figure 8).

The tension in the comparison of the fraction of obscured star formation to dust-to-gas ratios as a function of stellar mass will only be amplified when accounting for the fact that gas fractions decrease with stellar mass at a given epoch (e.g., Saintonge et al. 2011, 2016; Tacconi et al. 2013, 2017; Morokuma-Matsui & Baba 2015; Narayanan et al. 2015;
Popping et al. 2015; Scoville et al. 2016. Owing to the increased gas fraction of lower-mass galaxies relative to more massive galaxies at a given redshift, the relation between dust mass to stellar mass will be shallower than that with dust-to-gas ratio. The total amount of dust (or the column of dust) seen by the UV photons will therefore be higher for lower-mass galaxies relative to the dust-to-gas ratio trend, suggesting a higher SFRIR and hence SFRIR/SFRUV. Although this could in principle increase the fraction of obscured star formation at the low-mass end, it acts in the wrong direction to alleviate the discrepancies. We therefore find that in $f_{\text{obs}}$ that we observe at lower $M_*$ appears to be a stronger function of stellar mass than is explainable by the stellar mass dependence of the dust-to-gas ratio. It may be that metallicity or galaxy age dependencies of our 24 μm luminosities, probing the rest-frame 7.7 μm polycyclic aromatic hydrocarbons feature, have an influence on the overall shape (see Shivaei et al. 2017).

### 4.2. Surface Density

Next, we consider the effects of gas surface density on the amount of dust production. An increase in the gas surface density will correlate with an increase in the SFR surface density (Schmidt 1959; Kennicutt 1998b), as well as the column density of dust. Consequently, any redshift evolution in the gas/SFR surface densities would suggest an increase in the level of dust-obscured star formation. We next consider implications from the well-studied average scaling relations of $r_e$ and SFR comprising the SFR surface density. At fixed stellar mass, observations show that while the average galaxy size (and area) decreases (e.g., van der Wel et al. 2014), the average SFR increases with redshift (e.g., Whitaker et al. 2014). The SFR surface density of galaxies therefore increases on average toward higher redshift (e.g., Wisnioski et al. 2012; Livermore et al. 2015). This is corroborated by a recent archival study by Fujimoto et al. (2017) of ALMA/1mm images, who find that the average size of the gas reservoirs follows a redshift evolution similar to that of the rest-frame optical sizes measured from HST imaging. However, the gas size is statistically smaller, suggesting that dust-obscured star formation occurs in compact regions. When combining these various empirical trends with observations of increasing gas fractions (e.g., Tacconi et al. 2017), the data suggest higher gas-column densities that produce conditions more suitable to form dust at high redshift, both through star formation and the accretion of metals.

Yet, it may be that the average redshift evolution of the SFR density and galaxy size cancel each other out such that $f_{\text{obs}}$ does not evolve with redshift for a given $M_*$. We show the normalized average redshift evolution in area ($r_e^2$) and (s)SFRUV for a narrow range of 9.9 $< \log(M_*/M_\odot) < 10.1$ in Figure 5 (panel a). The narrow mass bin is intentional such that we select a sample of galaxies that have a similar $f_{\text{obs}}$ on average. We also show the trend of $f_{\text{obs}}$ with redshift in the equivalent stellar mass bin (purple). Note that we are not calculating sSFR/$r_e^2$ for any particular individual galaxy, but rather using the independently measured trends between SFR and $r_e$ with stellar mass. Given that increased gas and SFR surface densities imply higher dust production at earlier times, it follows that more compact galaxy geometries would decrease dust creation if we want to explain the observed constant median $f_{\text{obs}}$ per $M_*$ with redshift (purple). This is counter-intuitive and poses a challenge to current dust models. Possible explanations can include elevated dust destruction resulting from compact geometries and increased optical thickness. Denser star-forming environments will have an elevated number of supernovae explosions on relatively short timescales, which can either destroy or remove gas and dust in outflows. In the case of more massive galaxies, self-absorption due to the increased optical thickness from higher gas fractions may also play a role.

We see in the right panels of Figure 5 that while the median changes with redshift, the distributions of both sSFR and $r_e^2$ largely overlap with one another. After removing the well-known correlations between stellar mass and SFR and $r_e$, Whitaker et al. (2017) demonstrate that star-forming galaxies show only a weak dependence of SFR on $r_e$. As there is little to no correlation between $r_e^2$ and (s)SFR, the scatter in $f_{\text{obs}}$ for individual galaxies of a similar stellar mass may be quite large in reality. Stacking could hide weaker trends that exist within the scatter, especially if the trends are stronger for some subset of the galaxies, for example. Drawing connections between average galaxy correlations and underlying dust physics is not trivial. Figure 5 serves to caution the reader that intrinsic scatter in the physical properties of galaxies may result in a more complicated redshift evolution of $f_{\text{obs}}$ on a galaxy by galaxy basis.

### 4.3. Uncertainties in Dust Creation and Destruction

It is worth noting that the obscuration of UV photons is far more complicated than our simplified assumptions regarding the dependence upon metallicity or dust-column density. Theoretical models must also explicitly take into account how the dust mass, dust-to-gas ratios, and dust-column densities translate into the fraction of obscured star formation. It has been shown that the global IR luminosity is not necessarily directly correlated with total dust mass, and consequently SFRIR, as the dust grains in different physical regions are subject to a range of radiation field strengths and hence emit over a range of blackbody temperatures in reality (e.g. Dunne et al. 2000; Draine et al. 2007; Magdis...
et al. 2012; Kirkpatrick et al. 2017). Moreover, dust geometry can change the extinction law in dense environments around nascent stars, either via dust growth by accretion, grain growth by coagulation (where small dust grains stick to larger ones), or grain disruption by shattering (e.g., Hirashita 2012, 2015). Such processes will change the UV absorption properties of the ISM. And, more generally, empirical studies show that the best-fit attenuation law varies with galaxy type and physical properties (e.g., Wild et al. 2011; Kriek & Conroy 2013; Reddy et al. 2015; Zeimann et al. 2015; Battisti et al. 2016; Salmon et al. 2016). The time evolution of these processes, together with the observational uncertainties in the empirical trends, quickly results in a complicated picture.

It also may be that global measures of IRX (analogous to $SFR_{IR}$ to $SFR_{UV}$) and $SFR_{IR}/SFR_{UV + IR}$ are imperfect tracers of true obscuration within galaxies. Are star-forming regions cohabitants with the majority of dust in the ISM? Several case studies find significant offsets between sub-mm and rest-UV/optical emission (e.g., Iono et al. 2006; Chen et al. 2015; Koprowski et al. 2016), suggesting that the bulk of the UV and IR emission may originate from different physical regions in star-forming galaxies at high redshift. If this is a ubiquitous feature of galaxies, then the interpretation of a global ratio comparing UV and IR emission becomes muddled. Though beyond the scope of this work, future spatially resolved analyses will illuminate the geometric effects at play.

Though disentangling the complex interplay between dust geometry and composition with other physical properties of galaxies is beyond the scope of this empirical work, the non-evolution in redshift of the median $f_{\text{obscured}}$ as a function of $M_*$ points to very little redshift evolution in the characteristics of dust on the whole. Rigorous theoretical analyses will be required in order to understand the exact balance between the dust creation and destruction processes mentioned above, across time, in the context of these empirical results.

5. Conclusions

In this paper, we explore how the total SFR and stellar masses of galaxies depend upon the relative amount of obscured star formation. Our main mass-complete galaxy sample comprises 39,106 star-forming galaxies at $0.02 < z < 2.5$ (Whitaker et al. 2014), selected from the 3D-HST/CANDELS treasury programs in the five premier extragalactic fields. This deep NIR photometry yields mass-complete galaxy samples down to unprecedented limits of $\log(M_*/M_\odot) = 8.7 \pm 0.3$ at $z = 1.0$ ($z = 2.5$). Unobscured SFRs are measured directly from the 3D-HST photometry, and obscured star formation is quantified based on stacks of deep Spitzer/MIPS 24 $\mu$m photometry. We expand the baseline of the analysis by combining this novel data set with a local SDSS sample of 22,481 star-forming galaxies at $0.02 < z < 0.05$, with total SFRs measured from GALEX and WISE photometry.

The main findings of our analysis are summarized as follows.

1. We observe a strong dependence of the median fraction of obscured star formation (defined as $f_{\text{obscured}} =$...
SFR_{IR}/SFR_{UV+IR} upon stellar mass. This correlation shows remarkably little evolution across the full redshift range explored (z = 0 to z = 2.5), extending earlier results (e.g., Heinis et al. 2014; Bourne et al. 2017) to lower stellar mass limits.

2. The transition from mostly unobscured to obscured star formation (f_{obscured} = 0.5) occurs at a relatively low stellar mass of log(M/M_{\odot}) = 9.4. Even though the majority of the star formation in galaxies with log(M/M_{\odot}) < 9.4 is radiated in the rest-frame UV, there exists a tail of low-mass, extremely obscured star-forming galaxies at z > 1. For the most massive galaxies, with log(M/M_{\odot}) > 10.5, >90% of star formation is obscured at all redshifts.

3. We find that the fraction of star formation obscured by dust, f_{obscured}, at fixed total SFR decreases at higher redshift. As the normalization of the log(SFR)–log(M_*) relation is increasing with redshift while f_{obscured} is unchanged, the same total SFR probes lower stellar-mass limits at higher redshifts.

We explore the implications of these findings in the context of a range of well-studied empirical trends between dust-to-gas ratio, metallicity, gas and SFR surface density, gas fraction, and stellar mass. Galaxies at high redshift are observed to have more compact sizes and significantly higher SFRs, gas fractions, and hence gas and SFR surface densities. The straightforward interpretation is therefore that star formation should be more highly obscured at early times. It is therefore puzzling that we observe no redshift evolution in the median fraction of obscured star formation with stellar mass out to z = 2.5. Given the complexity of the various physical processes governing the attenuation of UV photons, including but not limited to dust geometry and composition, key progress can be made in understanding these results with future theoretical models.

We thank the anonymous referee for useful comments and a careful reading of the paper. The authors wish to acknowledge P. van Dokkum, I. Momcheva, R. Skelton, G. Brammer, the 3D-HST team, and colleagues for their hard work in releasing public data and catalogs in the 3D-HST fields. K.E.W. is grateful for discussions with N. Katz. K.E.W. gratefully acknowledges support by NASA through Hubble Fellowship grant #HST-HF2-51368 awarded by the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., for NASA, under contract NAS 5-26555. M.S.Y. and R.C acknowledge support from the NASA ADAP grant NNX14AF80G. C.M.C. thanks the UT Austin College of Natural Science for support. This work is based on observations taken by the 3D-HST Treasury Program (GO 12177 and 12328) with the NASA/ESA HST, which is operated by the Associations of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555.

Appendix A

In order to explore the effect of template uncertainties on the calculation of IR SFRs, we compare our data to the template set adopted within Béthermin et al. (2012) and Kirkpatrick et al. (2015, hereafter K15). Béthermin et al. used a redshift-dependent IR SED template set for “typical” star-forming galaxies and starbursts from (Magdis et al. 2012, hereafter M12), based on fits of the Draine et al. (2007) models. K15 published empirical composite templates of star-forming galaxies at 0.4 < z < 1.4 for L_{IR} ~ 4 \times 10^{11} and 1 \times 10^{12} L_{\odot}, plus a higher-redshift template at 1.4 < z < 2.1 for L_{IR} ~ 1 \times 10^{12} L_{\odot}. We use the K15 together with the M12 templates for “main sequence” star-forming galaxies at 1.0 < z < 1.3 and 1.75 < z < 2.25 to recalculate L_{IR} for all of the galaxies in the 3D-HST catalog that have a positive 24 \mu m flux densities at the relevant redshifts (Figure 6).

The right panel in Figure 6 shows the ratio of L_{IR} from the K15 and M12 templates to the DH02 template used in Whitaker et al. (2012b, 2014) and this paper, color-coded based on the template adopted. In general, we find that the M12 and K15 templates predict a mild redshift and L_{IR} dependence upon...
the conversion from 24 $\mu$m flux density to bolometric IR luminosity (Figure 6, right panel). The trend is consistent between the K15 and M12 templates, though M12 does not explicitly isolate galaxy samples based on $L_{\text{IR}}$. The dashed lines in the right panel show the best-fit linear function, which we quantify as a function of redshift and $L_{\text{IR}}$ to be

$$L_{\text{IR}}(z) / L_{\text{IR, DH02}} = -0.35z + 0.65 \times \log(L_{\text{IR}}) - 6.3. \quad (3)$$

In order to isolate if template-dependent effects are driving the results shown in Figure 2, we correct $L_{\text{IR}}$ in the 3D-HST catalogs using the equation above and recalculate SFR$_{\text{IR}}$/SFR$_{\text{UV+IR}}$ versus $\log(M_*)$. To avoid over-interpreting the K15 and M12 templates, we only consider the regime of $\log(M_*/M_\odot) > 9.7$, which corresponds to the lower mass limit of galaxies in the M12 sample. Although the K15 sample does not include such low-mass galaxies, the results are consistent between the two independent template sets (right panel, Figure 6). The ratio of the measured values of $f_{\text{obsured}} = \text{SFR}_{\text{IR}}/\text{SFR}_{\text{UV+IR}}$ from the redshift- and $L_{\text{IR}}$-dependent relation relative to the original redshift-independent DH02 template decreases from $\sim$30% (0.15 dex) difference at $\log(M_*/M_\odot) \sim 10$ to $<5\%$ ($<0.02$ dex) difference at $\log(M_*/M_\odot) > 10.5$.

In Figure 7, we compare $f_{\text{obsured}}$ corrected for the redshift- and $L_{\text{IR}}$-dependence of the templates relative to the original stacks based on the DH02 templates. The middle panel directly compares to the original data, whereas the right panel compares the corrected $f_{\text{obsured}}$ to the redshift-independent best-fit to the original data (shown as the thick black line in left-most panel for reference). The M12 and K15 empirical templates suggest that $L_{\text{IR}}$ is overpredicted for lower-mass galaxies with $\log(M_*/M_\odot) \sim 10$, such that $f_{\text{obsured}}$ is also overpredicted by as much as 50% (0.3 dex). However, $f_{\text{obsured}}$ agrees regardless of the template conversion adopted for more massive galaxies above $\log(M_*/M_\odot) > 10.5$ within $<5\%$ (0.02 dex). Interestingly, the analysis presented in Wuyts et al. (2011) found that while $L_{\text{IR}}$ derived using 24 $\mu$m flux densities with the full DH02 template set is overpredicted for the most massive, higher-redshift galaxies ($\log($SFR$) > 2 M_\odot$ yr$^{-1}$) in our sample by up to $\sim$0.5 dex, the systematic offset is much weaker for the log-average of the DH02 templates. We show here that using an evolving template set for the 24 $\mu$m conversion may alleviate any remaining discrepancy.

Despite different trends that emerge when employing a different template conversion from the 24 $\mu$m flux density to bolometric IR luminosity, the lack of redshift evolution in $f_{\text{obsured}}$ with stellar mass remains a robust conclusion. Namely, the scatter between $f_{\text{obsured}}$ for different redshift epochs in the middle and right panel of Figure 7 remains small, even when utilizing a redshift-dependent conversion.

Appendix B

In order to directly compare the dust-to-gas ratio as a function of stellar mass, we take two well-measured correlations: the dust-to-gas ratio as a function of metallicity from

Figure 7. Left: changing the template conversion of 24 $\mu$m flux density to $L_{\text{IR}}$, using the equation in Figure 6(b), changes the overall shape of $f_{\text{obsured}}$ as a function of stellar mass, but the relation still does not vary strongly with redshift. This is demonstrated in the middle and right panels, where we compare the ratio of the new $f_{\text{obsured}}$ relative to the original using the DH02 templates (middle panel) and the difference between the new $f_{\text{obsured}}$ and the best-fit model (right panel). The scatter between the original data and best-fit line (open circles) increases slightly when considering the K15/M12 template conversions (filled circles). The difference due to template conversion is negligible at $\log(M/M_\odot) > 10.5$.

Figure 8. Relative change in the ratio of dust-to-gas mass with stellar mass (normalized to unity at $\log(M/M_\odot) = 11.5$ at $z = 0.8$ (purple) and $z = 2.3$ (red) is similar to that of $f_{\text{obsured}}$, massive galaxies with $\log(M/M_\odot) = 11$ have a factor of three higher dust-to-gas mass and $f_{\text{obsured}}$ than lower-mass galaxies, $\log(M/M_\odot) = 9$. However, the overall shape of the dust-to-gas mass as a function of stellar mass relative to the stellar-mass dependence of $f_{\text{obsured}}$ (black, from Figure 2) is different.
Rémy-Ruyer et al. (2014), and mass-metallicity relations that bookend our redshift distribution. We adopt the mass-metallicity relation presented in Zahid et al. (2011) at $z \sim 0.8$ from the AEGIS/DEEP-2 spectroscopic sample, and Steidel et al. (2014) at $z \sim 2.3$ from the MOSDEF survey (Sanders et al. 2015) are consistent with Steidel et al. (2014) when selecting targets from the mass-complete 3D-HST parent sample. In Figure 8, we normalize the parameterized relation between dust-to-gas ratio and stellar mass at $z = 0.8$ (purple) and $z = 2.3$ (red) at log$(M/M_\odot) = 11.5$ to facilitate a direct comparison with the best-fit relation from Figure 2 (black). We explore the relative dependence of dust-to-gas ratio and $f_{\text{obscured}}$ on stellar mass in the main body of the paper.

ORCID iDs
Alexandra Pope https://orcid.org/0000-0001-8592-2706
Ryan Cybulski https://orcid.org/0000-0002-4997-2308
Caitlin M. Casey https://orcid.org/0000-0002-0930-6466
Min S. Yun https://orcid.org/0000-0001-7095-7543

References
Alam, S., Albareti, F. D., Allende Prieto, C., et al. 2015, ApJS, 219, 12
Battisti, A. J., Calzetti, D., & Chary, R.-R. 2016, ApJ, 818, 13
Bell, E. F., Papovich, C., Wolf, C., et al. 2005, ApJ, 625, 23
Bertin, E., & Arnouts, S. 1996, A&AS, 117, 393
Béthermin, M., Daddi, E., Magdis, G., et al. 2012, ApJL, 757, L23
Bourne, N., Dunlop, J. S., Merlin, E., et al. 2017, MNRAS, 467, 1360
Brammer, G. B., van Dokkum, P. G., & Coppi, P. 2008, ApJ, 686, 1503
Brammer, G. B., Whitaker, K. E., van Dokkum, P. G., et al. 2011, ApJ, 739, 24
Bruzual, G., & Charlot, S. 2003, MNRAS, 344, 1000
Calzetti, D. 2013, in SECULAR EVOLUTION OF GALAXIES, ed. J. Falcón-Barroso & J. H. Knapp (Cambridge: Cambridge Univ. Press), 419
Calzetti, D., Armus, L., Bohlin, R. C., et al. 2000, ApJ, 533, 682
Casey, C. M., Narayanan, D., & Cooray, A. 2014a, PhR, 541, 45
Casey, C. M., Scoville, N. Z., Sanders, D. B., et al. 2014b, ApJ, 796, 95
Chabrier, G. 2003, PASP, 115, 763
Chen, C.-C., Smail, I., Swinbank, A. M., et al. 2015, ApJ, 799, 194
Cortese, L., Boselli, A., Buat, V., et al. 2006, ApJ, 637, 242
Dale, D. A., & Helou, G. 2002, ApJ, 576, 159
Dickinson, M. & FIDEL Team 2007, BAAS, 39, 822
Dickinson, M., Papovich, C., Ferguson, H. C., et al. 2003, ApJ, 587, 25
Donley, J. L., Koekemoer, A. M., Brusa, M., et al. 2012, ApJ, 748, 142
Draine, B. T., Dale, D. A., Bendo, G. J., et al. 2007, ApJ, 665, 866
Dunlop, J. S., McLure, R. J., Biggs, A. D., et al. 2017, MNRAS, 466, 861
Dunne, L., Eales, S., Edmunds, M., et al. 2000, MNRAS, 315, 115
Erb, D. K., Shapley, A. E., Pettini, M., et al. 2006, ApJ, 644, 813
Feldmann, R. 2015, MNRAS, 449, 3274
Fujimoto, S., Ouchi, M., Shibuya, T., et al. 2017, arXiv:1703.02138
Grogan, N. A., Kocevski, D. D., Faber, S. M., et al. 2011, ApJS, 197, 35
Heinis, S., Buat, V., Béthermin, M., et al. 2014, MNRAS, 437, 1268
Hirashita, H. 2012, MNRAS, 422, 1263
Hirashita, H. 2015, MNRAS, 447, 2937
Iono, D., Peck, A. B., Pope, A., et al. 2006, ApJL, 640, L1
Kauffmann, G., Heckman, T. M., White, S. D. M., et al. 2003, MNRAS, 341, 33
Kennicutt, R. C., Jr. 1998a, ARA&A, 36, 189
Kennicutt, R. C., Jr. 1998b, ApJ, 498, 541