INVESTIGATING H α, UV, AND IR STAR-FORMATION RATE DIAGNOSTICS FOR A LARGE SAMPLE OF z ~ 2 GALAXIES

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ABSTRACT

We use a sample of 262 spectroscopically confirmed star-forming galaxies at redshifts 2.08 ≤ z ≤ 2.51 to compare H α, ultraviolet (UV), and IR star formation rate (SFR) diagnostics and to investigate the dust properties of the galaxies. At these redshifts, the H α line shifts to the K s band. By comparing K s-band photometry to underlying stellar population model fits to other UV, optical, and near-infrared data, we infer the H α flux for each galaxy. We obtain the best agreement between H α- and UV-based SFRs if we assume that the ionized gas and stellar continuum are reddened by the same value and that the Calzetti attenuation curve is applied to both. Aided with MIPS 24 µm data, we find that an attenuation curve steeper than the Calzetti curve is needed to reproduce the observed IR/UV ratios of galaxies younger than 100 Myr. Furthermore, using the bolometric SFR inferred from the UV and mid-IR data (SFRIR+SFRUV), we calculated the conversion between the H α luminosity and SFR to be (7.5 ± 1.3) × 10–42 for a Salpeter initial mass function, which is consistent with the Kennicutt conversion. The derived conversion factor is independent of any assumption of the dust correction and is robust to stellar population model uncertainties.

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

1. INTRODUCTION

One of the most important diagnostics in understanding the evolution of galaxies is the star formation rate (SFR). The evolution of the SFR of galaxies can give clues as to how galaxies were enriched with heavy elements and how they build up their stellar mass through cosmic time, and it helps us to understand the bolometric output of galaxies. At redshift z ~ 2, when the universe was just ~3 Gyr old, star formation activity in the universe was at its peak and galaxies were in the process of assembling most of their stellar mass (see Reddy & Steidel 2009; Bouwens et al. 2010; Shapley 2011; Madau & Dickinson 2014). Studying this critical epoch is essential to gaining a better understanding of the evolution of the progenitors of the local galaxy population.

The ultraviolet (UV) continuum (1500–2800 Å) intensity of a galaxy is one of the most commonly used diagnostics for the SFR as it is observable over a wide range of redshifts and intrinsic luminosities. It is sensitive to massive stars (M ∗ ≥ 5 M sun), making it a direct tracer of current SFR. By extrapolating the formation rate of massive stars to lower masses, for an assumed form of the initial mass function (IMF), one can estimate the total SFR (Madau et al. 1998). Another widely used diagnostic for measuring the SFR is nebular emission, with H α being the most common because of its higher intensity compared to the other hydrogen recombination lines such as H β, Paα, Paβ, etc., and it is easier to interpret than the Ly α line. H α is an “instantaneous” tracer of SFR because it is sensitive only to the most massive stars (M ∗ ≥ 10 M sun). However, it becomes more challenging to observe H α from the ground at z ≥ 1 because the line is redshifted to the near-IR, where the terrestrial background is much higher than at optical wavelengths.

The main disadvantage of using UV/optical luminosities as tracers of the SFR is their sensitivity to dust attenuation. The dust absorption cross section is larger for shorter wavelengths, and choosing the appropriate attenuation curve to correct the observed luminosities plays an important role in determining intrinsic physical quantities. Aside from the assumed attenuation curve, the geometry of dust with respect to the stars can lead to different color excesses, E(B − V), between the ionized gas and the stellar continuum. E(B − V) is the color excess measured between the B and V bands, E(B − V) = A B − A V, where A V is the total extinction at wavelength λ in magnitudes. In particular, the nebular recombination lines arise from the H n regions around the most massive O and early-type B stars (with masses of M ∗ > 10 M sun and main-sequence lifetimes of ≤100 Myr). On the other hand, for a Salpeter IMF, solar metallicity, and a constant or rising star formation history, the UV continuum in starburst galaxies originates from stars over a broader range of mass that includes later-type B stars with lifetimes ≳100 Myr (Kennicutt 1998; Madau & Dickinson 2014). These older non-ionizing stars have more time to migrate to regions of lower dust density in the galaxy, while H-ionizing stars with shorter lifetimes do not have enough time to escape from their dusty birthplace or let the parent molecular clouds dissipate. As a result, the nebular lines can be subject to a higher degree of reddening than the UV continuum.

Calzetti et al. (1994) found that the nebular emission is more attenuated than the stellar continuum at the same wavelengths for a sample of local UV-bright galaxies. Subsequently, Calzetti et al. (2000) studied a similar sample of local galaxies and argued that the color excess is 2.27 times larger for the nebular emission lines than for the stellar continuum. This relationship was derived under the assumption that the Calzetti curve is applied to the stellar continuum and a Galactic extinction curve is applied to the nebular emission lines. In a

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The apparently conflicting results mentioned above may be reconciled if the relation between the nebular and stellar color excesses depends on the physical properties of galaxies, such as their SFRs (Yoshikawa et al. 2010), specific SFRs (Wild et al. 2011), or metallicity (Zeimann et al. 2014). For example, Wild et al. (2011) showed that the ratio of the line optical depth to the continuum optical depth decreases with increasing sSFR and at sSFR \( \sim 10^{-9} \, \text{yr}^{-1} \) the line-to-continuum optical depth ratio reaches the Calzetti et al. (2000) ratio assuming the Wild et al. (2011) attenuation curve. Price et al. (2014) investigated the attenuation of the nebular regions at \( z \sim 1.5 \) using the Balmer decrement from stacked Hubble Space Telescope (HST) grism spectra assuming the Calzetti curve and found no strong trend of \( A_{\text{V,neb}}/A_{\text{V,stellar}} \) with SFR or sSFR. In the Price et al. (2014) study, at sSFR \( \sim 10^{-8.5} \, \text{yr}^{-1} \) the ratio is consistent with 1.

The primary goal of this paper is to understand the relationship between the UV and H\( \alpha \) emission in high-redshift star-forming galaxies, with a large sample that is immune to uncertainties in slit-loss corrections that affect the H\( \alpha \) flux estimation (see Erb et al. 2006b; Yoshikawa et al. 2010), the small sample sizes inherent in previous spectroscopic studies of H\( \alpha \) (Kriek et al. 2007; Muzzin et al. 2010), and not subject to the bias of selecting high equivalent width objects from narrowband selected samples (Garn et al. 2010). We consider in our analysis only spectroscopically confirmed galaxies, enabling us to estimate the H\( \alpha \) flux from broadband photometric excess techniques without the additional uncertainties that plague photometric redshifts (Wuyts et al. 2011).

The impact of nebular lines on the broadband photometry was known and studied for many years (e.g., Guiderdoni & Rocca-Volmerange 1987; Fioc & Rocca-Volmerange 1997; Zackrisson et al. 2008; de Barros et al. 2014). Using the photometric excesses to determine the line strengths was pioneered by Shim et al. (2011), where they showed that the excess in Spitzer/IRAC 3.6 \( \mu \text{m} \) relative to the SED model continuum is due to the redshifted H\( \alpha \) emission line for their sample of galaxies at 3.8 \( < z < 5.0 \). Stark et al. (2013) also investigated a sample of galaxies at the same redshift range of Shim et al. (2011) and inferred the H\( \alpha \) emission line strengths by comparing the observed flux in Spitzer/IRAC 3.6 \( \mu \text{m} \) band and the continuum flux as expected from the SED model. Following that, Schenker et al. (2013) verified the photometric excess technique by applying it to a small sample of nine galaxies at 3.0 \( < z < 3.8 \); for eight galaxies the [O\( \text{iii} \)] line fluxes inferred by the same technique as Stark et al. (2013) were within a factor of 2.5 of the spectroscopically measured [O\( \text{iii} \)] line fluxes.

An additional advantage of our study is that we include IR data to independently assess the dust-obscured SFR. Comparing H\( \alpha \), UV, and IR-inferred SFRs in a statistical sense allows us to understand how to correct extinction-sensitive measures of SFR for the effects of dust.

The outline of this paper is as follows. In Section 2 we discuss the properties of our sample, the assumptions that have been made to model the stellar populations using the rest-frame UV to near-IR photometry, the Spitzer/MIPS photometry, and the stacking method. A detailed description of how we estimated the H\( \alpha \) line flux is provided in Section 3. The analysis of the MIPS 24 \( \mu \text{m} \) data and IR luminosities is described in Section 4. In Section 5 we compare the two different tracers of SFR—H\( \alpha \) and UV—and discuss the dust
correction recipe most consistent with our measured values. Section 6 focuses on combining SFR diagnostics (e.g., Hα and UV with IR) to deduce bolometric SFRs. The results are summarized in Section 7. Throughout this paper, a Salpeter (1955) IMF is assumed and a cosmology with $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_\Lambda = 0.7$, and $\Omega_m = 0.3$ is adopted. All magnitudes are given in the AB system (Oke & Gunn 1983).

2. SAMPLE

2.1. Sample Selection and Optical Photometry

The galaxies used in this study are drawn from a parent sample that is part of an imaging and spectroscopic survey of UV-selected galaxies at $z \sim 2$–3 (Steidel et al. 2004; Reddy et al. 2012b). The galaxies were selected based on the BX, BM, and Lyman break galaxy rest-UV color criteria (Steidel et al. 2003, 2004; Adelberger et al. 2004), where $U_{nIR}$ optical data were obtained with the Palomar Large Format Camera or Keck Low Resolution Imaging Spectrograph (LRIS; Steidel et al. 2003, 2004). Rest-UV spectroscopic follow-up with Keck/LRIS was conducted for galaxies brighter than $R = 25.5$ (Steidel et al. 2003, 2004). Near-IR $J$ and $K_s$ imaging was obtained using the Palomar/WIRC and Magellani/PANIC instruments (Shapley et al. 2005; Reddy et al. 2012b). H-band (F160w) data were obtained with the HST WFC3 camera (Law et al. 2012; Reddy et al. 2012b). All galaxies in the sample have coverage in at least one of the four Spitzer/IRAC channels (3.6, 4.5, 5.8, and 8.0 $\mu$m; Reddy et al. 2006a, 2012b). The objects are located in the GOODS-North field and 11 additional fields that were primarily selected to have one or more relatively bright background QSOs for studying the interface between the intergalactic medium and galaxies at $z \sim 2$–3 (Steidel et al. 2004, 2010).

Out of the final sample of 2283 objects with spectroscopically confirmed redshifts, a subset of galaxies is selected based on the following criteria: (1) the galaxy must be covered by the $K$-band imaging, (2) it must have a redshift in the range $2.08 \leq z \leq 2.51$ so that the $H_\alpha$ line falls into the $K_s$ band, and (3) it must be detected in at least two of the IRAC channels or one of the IRAC channels and either $J$ or F160W bands. The third condition ensures a more robust estimate of the stellar mass and the continuum level at 6564 Å. Furthermore, AGNs (making up $\geq$9% of the parent sample) were identified by either strong UV emission lines (e.g., Ly$\alpha$, C IV) or a power-law SED through the IRAC bands. These AGNs are removed from our sample. Eventually, 262 galaxies remain that satisfy the aforementioned criteria.

2.2. Stellar Population Modeling

For each galaxy in our sample, the best-fit stellar population model is found by using the rest-frame UV through near-IR broadband photometry. As mentioned above, all the galaxies in our sample have spectroscopically confirmed redshifts, thus removing a key degeneracy in the modeling of the stellar populations. In addition, for a better estimation of stellar mass and age, all galaxies in our sample have at least two detections longward of the 4000 Å break—excluding $K_s$ band.

S. Charlot & G. Bruzual (2007, in preparation) models with a Salpeter (1955) IMF and solar metallicities are used for the fitting. For each individual galaxy, different star formation histories are assumed, including constant, exponentially declining, and exponentially rising with characteristic timescales of $\tau = 10, 20, 50, 100, 200, 500, 1000, 2000, \text{ and } 5000 \text{ Myr}$ for exponentially declining and $\tau = 100, 200, 500, 1000, 2000, \text{ and } 5000 \text{ Myr}$ for exponentially rising histories. Ages are allowed to vary between 50 Myr and the age of the universe at the redshift of each galaxy. The $>50$ Myr limit corresponds to the typical dynamical timescale of star-forming galaxies at $z \sim 2$ as inferred from velocity dispersion and size measurements of these galaxies (Reddy et al. 2012b). For interstellar dust obscuration, the Calzetti et al. (2000) attenuation curve is used, allowing $E(B - V)$ to vary between 0.0 and 0.6. The $\chi^2$ values have been determined for each set of observed broadband and model magnitudes. The best-fit model is determined through $\chi^2$ minimization. There is generally no significant difference between the best-fit $\chi^2$ values of the six different population models (constant, exponentially rising, and exponentially declining star formation histories, for each considering all ages and ages greater than 50 Myr). As previous studies have shown, the assumption of declining star formation histories at these redshifts results in systematically lower SED-inferred SFRs compared to the observed IR+UV SFRs (Wuyts et al. 2011; Reddy et al. 2012b). Furthermore, Reddy et al. (2012b) showed that assuming a constant star formation history for $z \sim 2$ galaxies predicts specific SFRs (SFR/M$_*$) at higher redshifts ($z \sim 2.6$) that are substantially larger than the observed values. Given these, we adopt the models that assume exponentially rising star formation histories with ages greater than 50 Myr.

The SED models used to fit the observed magnitudes do not include nebular emission lines. For example, the H$\alpha$ line can significantly affect the photometry, and we use its contribution to the $K$ band to estimate the H$\alpha$ line flux. The [O III] emission line is the other strong line that falls into the F160W filter given the redshift range of our galaxies. Only 20% of the galaxies have F160W observations, for which we did not correct the broadband photometry for the contamination. The SED-inferred SFR of these galaxies is consistent with the SFR (UV) estimates within the uncertainties. At this redshift, $J$ band is contaminated by the [O III] emission line, but this line is generally weaker than the H$\alpha$ line, and its effect on the SED-inferred SFRs is negligible compared to the uncertainties.

2.3. MIPS Data

To further investigate the bolometric properties of our sample, we use Spitzer/MIPS 24 $\mu$m wherever available. Out of 12 fields, GOODS-North (Dickinson et al. 2003) and four other fields (Q1549, Q1623, Q1700, and Q2343; Reddy & Steidel 2009) have MIPS 24 $\mu$m coverage to a typical $3\sigma$ depth of 10–15 $\mu$Jy.

Photometry on 24 $\mu$m images is performed by using point-spread function (PSF) fitting with priors determined by the locations of the objects in the higher-resolution IRAC images (IRAC data exist in all fields). A $40 \times 40$ pixel region centered on each target is extracted with pixel size of 1.2$''$. PSFs are then fitted simultaneously to all known sources in the sub-image and one random background position. This procedure is repeated many times to obtain sufficient statistics for proper background estimation based on the random background flux measurements. The other source of uncertainty is Poisson noise, which

$^6$ For galaxies with similar SFRs at $z \sim 2$, the typical [O III] line flux is $\sim 6 \times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$ (Kriek et al. 2014). The ratio of the [O III] flux to the typical $J$-band flux errors in our observations is only $\sim 0.07$.
for objects in our sample is negligible compared to the background dispersion. We remove objects whose photometry may be compromised due to blending with nearby sources, using the criteria specified in Reddy et al. (2010). This results in 115 galaxies with secure PSF fits.

Out of 115 objects with MIPS data, 47 are detected with signal-to-noise ratio (S/N) ≥ 3. Undetected objects, those with S/N < 3, are considered either using survival analyses or through stacking of the 24 μm data.

2.3.1. Stacking Method

Throughout the paper, we employ a stacking method to determine the median 24 μm fluxes of objects that are individually detected and undetected, following the procedures described in Reddy et al. (2010, 2012a). We performed aperture photometry on the stacked images and applied an aperture correction based on the 24 μm PSF. The average background level and noise were determined by placing many apertures of the same size used for the stacked signal at random positions in the stacked image and measuring the average flux level and dispersion in flux of these “background” apertures. Furthermore, we used bootstrap resampling simulations to estimate the dispersion in the fluxes of objects contributing to each stack. This was accomplished by creating 100 samples of random images in each bin and measuring the standard deviation of the median stacked fluxes. The intrinsic dispersion in the stacked flux is larger than the background error by a factor of ~2.

3. Hα AND UV LUMINOSITY

3.1. Hα Fluxes and Equivalent Widths

Using the procedure discussed in Section 2.2, we fit all the photometry, excluding Ks, band, in order to determine the continuum level at 6564 Å. The continuum magnitude is calculated by multiplying the best-fit SED model by the Ks filter transmission curve. The difference between the observed Ks-band magnitude and the continuum magnitude is used to extract the Hα line flux as follows. The observed Ks magnitude is considered as the sum of the continuum and the Hα fluxes, while the SED-inferred Ks magnitude represents only the continuum flux. Assuming a Gaussian form for the redshifted Hα line, the change between these fluxes will yield the Hα flux (Figure 1):

\[
\frac{\Delta f_{H\alpha}}{\Delta \nu} \approx \frac{f_{H\alpha}(\nu) T_K(\nu)}{f_{\nu} T_K(\nu)} = 10^{m_{obs} - 48.5} \times 10^{m_{SED} - 48.6}.
\]  

(1)

Here, \(f_{H\alpha}(\nu)\) is the flux density of the Hα line in units of erg s\(^{-1}\) cm\(^{-2}\) Hz\(^{-1}\), \(T_K(\nu)\) is the Ks filter transmission curve, and \(m_{obs}\) and \(m_{SED}\) are the observed and the continuum magnitudes, respectively. The Hα flux is corrected for contamination from the \([\text{N}\ II]\) line based on the mass-dependent \([\text{N}\ II]\)-to-Hα flux ratios of Erb et al. (2006a). The stellar masses are determined from the SED models, and the corresponding \([\text{N}\ II]\) line contamination, as listed in Table 1, is used to correct the Hα flux. The SFRs are then calculated using the Kennicutt (1998) relation to convert the Hα line luminosity to an SFR.

There are three main sources of uncertainty in the derived Hα fluxes. The largest uncertainty is the photometric error. The typical error in the observed Ks-band magnitude is ∼0.27. The second source of uncertainty is the \([\text{N}\ II]\) correction. The uncertainty on the Erb et al. (2006a) \([\text{N}\ II]\)-to-Hα line ratios (see Table 1) is added in quadrature to the photometric error. The third source of uncertainty is the error associated with the continuum flux. In order to account for this uncertainty, we estimated the continuum flux at 6564 Å from the best-fit model assuming six different star-formation histories: exponentially rising, exponentially declining, and constant, for each considering all ages and ages greater than 50 Myr. For 94% of the galaxies, the difference in the mean of the continuum fluxes assuming different star-formation histories to those assuming a rising star-formation history with ages ≥50 Myr is less than 0.1 mag. The average error in the estimated continuum magnitude is ∼0.05 mag, which is negligible compared to the observed Ks-band magnitude errors. Combining the three sources of uncertainty discussed above yields a typical relative error in Hα flux of ∼0.29.

The equivalent width of the Hα line is estimated by dividing the Hα flux derived from Equation (1) by the continuum flux density at the wavelength of the Hα line:

\[
(1 + z) \text{EW}_0 = \frac{F_{H\alpha}}{f_{\nu}^{\text{cont}}},
\]

(2)

The \(f_{\nu}^{\text{cont}}\) is the continuum flux density in units of erg s\(^{-1}\) cm\(^{-2}\) Å\(^{-1}\) that is estimated through the best-fit SED model, \(F_{H\alpha}\), is the Hα line flux in erg s\(^{-1}\) cm\(^{-2}\), \(z\) is the redshift of the galaxy, and \(\text{EW}_0\) is the rest-frame equivalent width in Å.

We define whether a galaxy has a “detected” Hα line according to the following. Galaxies whose \(K_s\)-band photometry exceeds the continuum level by more than the \(K_s\)-band magnitude error are referred to as “Hα detections.” Galaxies where the \(K_s\)-band photometry is consistent with the continuum level to within 1σ are referred to as “Hα non-detections,” and an upper limit of 1σ above the measured \(K\) photometry is used for these objects. Out of 262 galaxies in our sample, 149 are detections and 94 are non-detections. There are 19 objects with \(K_s\) magnitudes fainter than the continuum by more than 1σ. We removed these galaxies from our discussion due to their \(K_s\) photometry being inconsistent with the photometry from adjacent bands.

As discussed in Section 1, our method of computing Hα fluxes and EWs has the advantage of being immune to slit-loss corrections. Our sample covers a wide range of Hα fluxes and EWs. Figure 2 shows the distribution of Hα EWs and fluxes as a function of the \(K_s\) magnitude 1σ uncertainty. The detection of Hα with the method adopted here depends on both the Hα line flux and the brightness of the continuum at 6564 Å. As we have defined detections to be those objects where the \(K_s\) magnitude exceeds the continuum level by more than 1σ, the number of undetected objects increases for objects that are fainter in the continuum (Figure 2).

The Hα observed fluxes of 44 objects in common with the Erb et al. (2006b) spectroscopic sample are compared in Figure 3. The Erb et al. (2006b) spectroscopic fluxes are multiplied by a factor of two to account for slit losses and the aperture used to extract the spectra (Erb et al. 2006b; Reddy et al. 2010). The slit-loss correction factor applied to the spectroscopic fluxes depends on various factors such as the accuracy of the astrometry, the size of the object convolved with the seeing at the time of observation in comparison with the size of the slit, and the accuracy of the mask alignment.

Shivaei et al.
As noted in Erb et al. (2006b), the factor of two slit-loss correction is an average estimate, and the slit losses will of course vary from object to object, likely accounting for some of the scatter in Figure 3. On the other hand, while broadband photometry has its advantages, our \( K_s \)-band measurements suffer from a larger measurement (random) uncertainty relative to the other methods given the depth of our ground-based images. Although most of the

Table 1  

| Mass Range \((10^{10} M_\odot)\) | \(N^2\) |
|-----------------|-------|
| <0.88           | \(-1.22\) |
| 0.88–2.00       | \(-1.00^{+0.09}_{-0.07}\) |
| 2.00–3.69       | \(-0.85^{+0.06}_{-0.05}\) |
| 3.69–6.03       | \(-0.78^{+0.05}_{-0.03}\) |
| 6.03–8.82       | \(-0.66^{+0.04}_{-0.03}\) |
| >8.82           | \(-0.56^{+0.02}_{-0.03}\) |

\(^a\) Based on Erb et al. (2006a).

\(^b\) Assuming a Salpeter (1955) IMF.

\(^c\) \(N^2 = \log(F([\text{N} II])/F(H\alpha))\).
detected Hα fluxes in this study (the black symbols in Figure 3) are higher than the spectroscopic fluxes, about half of the sample is estimated as upper limits (the red arrows). Considering both the detections and non-detections, the broadband estimated fluxes are generally consistent with the spectroscopic fluxes. To quantify the degree of the correlation, we conduct a generalized Kendall’s tau (τ) statistic test. The generalized Kendall’s τ rank correlation coefficient is a non-parametric test that permits non-detections in both variables (here, our estimated Hα fluxes). Kendall’s τ correlation coefficient for our flux estimation with the Erb et al. (2006b) measurements, excluding the one outlier object, is τ = 0.17, with significance of p-value = 0.11.

3.2. UV Luminosities and SFRs

UV luminosities are calculated using the fluxes of the best-fit SED models at 1700 Å. The Kennicutt (1998) relation to convert the UV luminosity (over the wavelength range 1500–2800 Å) to SFR applies only to galaxies where star formation proceeds for ≥100 Myr. However, there are galaxies in our sample with inferred ages between 50 and 100 Myr. For these younger galaxies, we used an age- and star-formation-history-dependent relation in the conversion of the UV luminosity to SFR, as discussed in Reddy et al. (2012b). The age-dependent conversion resulted in UV SFRs that are at most 14% larger than the Kennicutt (1998) SFRs for young galaxies. Throughout this analysis, we also use SFRs inferred from the best-fit SED models. As expected, within the uncertainties, the SED SFRs are highly correlated with dust-corrected UV SFRs.

4. THE IR LUMINOSITY AND BOLOMETRIC PROPERTIES

To estimate the bolometric luminosities of galaxies in our sample, we infer the infrared luminosity (integrated between 8 and 1000 μm) as discussed below, and we add this to the unobscured UV luminosity (i.e., observed UV luminosity; Section 3.2), as in Reddy et al. (2010).

Infrared luminosities, LIR, are estimated by using the Spitzer/MIPS 24 μm observations. The 24 μm band is sensitive to the rest-frame 7.7 μm PAH emission, which correlates with LIR (e.g., Chary & Elbaz 2001; Dale & Helou 2002; Elbaz et al. 2011). To convert observed 24 μm magnitudes to total IR luminosity (LIR), we used several dust SED templates, including those of Chary & Elbaz (2001), Dale & Helou (2002), and Rieke et al. (2009). Luminosities determined from the rest-frame 8 μm flux density alone, regardless of the dust template used, tend to overpredict LIR, particularly for LIRGs (e.g., Reddy et al. 2012a) and ULIRGs (e.g., Nordon et al. 2010; Magnelli et al. 2011). In order to account for the luminosity-dependent overestimation of the derived LIR, we use a correction equation described in Reddy et al. (2012a). The correction is calculated by comparing the LIR computed from 24, 100, 160 μm, and 1.4 GHz fluxes, and the LIR determined solely from 24 μm data for a similarly selected sample of galaxies:

\[ \log L_{\text{IR}}(\text{all data}) = 0.537 \times \log L_{\text{IR}}(24 \, \mu\text{m}) + 5.136. \]  

All luminosities are in L☉.

Equation (3) is based on the Chary & Elbaz (2001) models. There is a factor of ~2 variation in LIR derived from 24 μm data using Dale & Helou (2002) and Rieke et al. (2009) dust templates (e.g., see Reddy et al. 2012a). However, once corrected using the appropriate equations similar to Equation (3), all the templates result in L(IR) estimates that are consistent with each other and with the L(IR) computed from 24, 100, 160 μm, and 1.4 GHz fluxes, within the uncertainties of the measured IR luminosity as explained in Section 2.3 (see also Reddy et al. 2012a). In the subsequent analysis, we use infrared luminosities inferred from the Chary & Elbaz (2001) templates.

The IR luminosity is converted to IR (dust-obscured) SFRs using the Kennicutt (1998) relation. The sum of IR- and UV-inferred SFRs is then used to estimate the bolometric SFRs.

5. DUST ATTENUATION OF THE NEBULAR REGIONS AND STELLAR CONTINUUM

SFRs inferred from the UV luminosity and the Hα fluxes are shown in the left panel of Figure 4. Without dust corrections, the UV and Hα SFRs have a large discrepancy due to the smaller dust absorption cross section at 6564 Å relative to that at 1700 Å (see the inset panel in Figure 4). The main left panel of Figure 4 shows Hα and UV SFRs, both corrected for dust attenuation based on the Calzetti attenuation curve and assuming that the same color excess, E(B – V), as derived from the best-fit SED model, applies to the stellar continuum and the nebular regions. To better quantify the mean trend, measurements have also been performed in bins of UV dust-corrected SFR (filled circles in Figure 4). The bins are Δlog (SFRUV_corrected) = 0.3 dex wide. For all the galaxies in each bin, regardless of their redshift, we calculate the median flux densities in the observed filters. With the new set of median fluxes, the best-fit stellar population model is determined through χ² minimization for the mean redshift of the galaxies in each bin. The Hα and UV luminosities are then derived from the stacked SED in the same way as for individual galaxies (see Section 3). Reported errors are calculated based on the 1σ standard error of the mean of the Kσ magnitudes contributing to each bin.

The appropriate dust corrections to apply to the nebular emission lines is still a subject of debate, as discussed in Section 1. The attenuation of the nebular lines and the UV stellar continuum are not completely decoupled as both arise from dust around massive stars. On the other hand, whether the color excess is the same for the nebular and stellar regions (e.g., Erb et al. 2006b; Reddy et al. 2010) or not (e.g., Calzetti et al. 2000; Förster Schreiber et al. 2009; Garn et al. 2010) in high-redshift galaxies has yet to be fully investigated.

Calzetti et al. (2000) found that E(B – V)stellar = 0.44 × E(B – V)neb for a sample of local star-forming galaxies. In the absence of direct measurements of the nebular color excess (e.g., via the Balmer decrement), this relationship can in principle be used to estimate the nebular color excess and apply a dust correction to the Hα line; e.g.,

\[ A_{\text{Hα}} = \kappa_{\text{Gal}}(\text{Hα})E(B - V)_{\text{neb}} = 2.27 \kappa_{\text{Gal}}(\text{Hα})E(B - V)_{\text{stellar}} = 2.27 \times 2.52 E(B - V)_{\text{stellar}} = 5.72 E(B - V)_{\text{stellar}}, \]  

where κGal is the Cardelli et al. (1989) Galactic extinction curve, assuming that the nebular regions in the high-redshift galaxies abide by such a dust curve. A_Hα is the absolute
detected green diamonds. The dashed lines indicate the one-to-one relationships.

Figure 4. Left: comparison of SFR(Hα) and SFR(UV), both corrected for dust assuming the Calzetti attenuation curve and assuming that the same color excess applies for the stellar and nebular regions. The uncorrected values are shown in the inset panel. Green diamonds denote “detected” objects, those whose $K_s$-band magnitudes are more than 1σ brighter than the continuum. Blue arrows show the remaining “undetected” objects. Red filled circles are the results of stacked SEDs in bins of dust-corrected SFR(UV), including both the detected and undetected objects. Undetected objects bring the stacked lower than the average of the individually detected green diamonds. The dashed lines indicate the one-to-one relationships. Right: ratio of SFR(Hα)$_{corr}$ to SFR(UV)$_{corr}$ in bins of SFR(UV)$_{corr}$. The colors denote different recipes for the nebular dust correction. Using the same color excess for nebular extinction together with the Calzetti curve results in SFR$_{\alpha}$ that is significantly larger than SFR(UV) (model A). The details of each model are summarized in Table 2.

### Table 2

Dust Corrected Hα SFRs Using Different Attenuation Recipes, in Bins of SFR(UV)$_{corr}$

| SFR(UV)$_{corr}$ | $N^a$ | Calzetti Different $E(B-V)^d$ (Model A) | Galactic Different $E(B-V)^e$ (Model B) | SFR(Hα)$_{corr}$ $^{-1}$ SMC Different $E(B-V)^f$ (Model C) | Calzetti Equal $E(B-V)^g$ (Model D) | Galactic Equal $E(B-V)^h$ (Model E) |
|------------------|------|----------------------------------------|----------------------------------------|----------------------------------------|----------------------------------------|----------------------------------------|
| 18 ± 3           | 26   | 44 ± 3                                 | 38 ± 3                                 | 34 ± 2                                 | 30 ± 2                                 | 28 ± 2                                 |
| 32 ± 6           | 63   | 70 ± 4                                 | 54 ± 3                                 | 46 ± 3                                 | 38 ± 2                                 | 35 ± 2                                 |
| 65 ± 12          | 83   | 103 ± 7                                | 75 ± 5                                 | 61 ± 4                                 | 49 ± 3                                 | 43 ± 3                                 |
| 120 ± 22         | 56   | 200 ± 18                               | 140 ± 12                               | 112 ± 10                               | 88 ± 8                                 | 76 ± 7                                 |
| 258 ± 94         | 15   | 443 ± 88                               | 295 ± 59                               | 228 ± 45                               | 174 ± 35                               | 146 ± 29                               |

$^a$ The mean and standard deviation of the corrected SFR(UV) in each bin, in units of $M_\odot$ yr$^{-1}$.

$^b$ Number of objects in each bin.

$^c$ The SFR(Hα)$_{corr}$ is derived based on the stacked SEDs in bins of dust-corrected SFR(UV), in units of $M_\odot$ yr$^{-1}$. The errors are 1σ standard error of the mean of the $K_s$ magnitudes contributing to each bin, which is converted to the error in SFR.

$^d$ $A_{H\alpha} = 2.27 \kappa_{Calz}(H\alpha)E(B-V)_{stellar}$; $A_{H\alpha}$ is the total nebular extinction at 6564 Å and $\kappa_{Calz}(H\alpha)$ is the Calzetti reddening at 6564 Å.

$^e$ $A_{H\alpha} = 2.27 \kappa_{Gal}(H\alpha)E(B-V)_{stellar}$; $\kappa_{Gal}(H\alpha)$ is the Cardelli Galactic reddening at 6564 Å.

$^f$ $A_{H\alpha} = 2.27 \kappa_{SMC}(H\alpha)E(B-V)_{stellar}$; $\kappa_{SMC}(H\alpha)$ is an SMC reddening at 6564 Å.

$^g$ $A_{H\alpha} = \kappa_{Gal}(H\alpha)E(B-V)_{stellar}$; $\kappa_{Gal}(H\alpha)$ is the Calzetti reddening at 6564 Å.

$^h$ $A_{H\alpha} = \kappa_{Gal}(H\alpha)E(B-V)_{stellar}$; $\kappa_{Gal}(H\alpha)$ is the Cardelli Galactic reddening at 6564 Å.

extinction of the Hα emission line, and $E(B-V)_{stellar}$ is the SED-inferred stellar color excess.

We investigate several of the more commonly used dust-correction recipes, as described below. The Hα SFRs are corrected using five different methods:

a. the Calzetti attenuation curve for both gas and stars, and the same color excess (as we call it “equal $E(B-V)$”;
b. the Calzetti attenuation curve for the stellar continuum, and the Cardelli et al. (1989) Galactic curve for the nebular lines assuming 2.27× larger color excess;
c. the Calzetti attenuation curve for the stellar continuum, and an SMC extinction curve (Gordon et al. 2003) for the nebular lines assuming 2.27× larger color excess;
d. the Calzetti attenuation curve for both gas and stars, and the same color excess (as we call it “equal $E(B-V)$”);
e. the Calzetti attenuation curve for the stellar continuum, an SMC extinction curve (Gordon et al. 2003) for the nebular lines assuming the same color excess.

We choose to compare these different dust-correction scenarios for the stacked values instead of the individual galaxies as the former represent an average over many points including both detected and undetected quantities, each of which may be relatively uncertain. The results are plotted in the right panel of Figure 4 and are reported in Table 2.

To summarize, these are the values that are used to correct the observed Hα SFRs in each model according to
Equation (4):

\[
\begin{align*}
A_{\text{H}\alpha}^{(A)} &= 2.27 \kappa_{\text{Calz}}(\text{H}\alpha)E(B-V) = 7.56 E(B-V), \\
A_{\text{H}\alpha}^{(B)} &= 2.27 \kappa_{\text{Gal}}(\text{H}\alpha)E(B-V) = 5.72 E(B-V), \\
A_{\text{H}\alpha}^{(C)} &= 2.27 \kappa_{\text{SMC}}(\text{H}\alpha)E(B-V) = 4.54 E(B-V), \\
A_{\text{H}\alpha}^{(D)} &= \kappa_{\text{Calz}}(\text{H}\alpha)E(B-V) = 3.33 E(B-V), \\
A_{\text{H}\alpha}^{(E)} &= \kappa_{\text{Gal}}(\text{H}\alpha)E(B-V) = 2.52 E(B-V).
\end{align*}
\]

In these equations, \(E(B-V)\) is the SED-inferred color excess observed for the stellar continuum and \(A_{\text{H}\alpha}\) is the total nebular extinction at 6564 Å.

In model (A) with a larger color excess for the nebular regions with the Calzetti curve, \(A_{\text{H}\alpha}\)-inferred SFRs are significantly larger than UV SFRs. Taking the average of the SFR(\(\text{H}\alpha\)) (model A) to the corrected SFR(UV) in the five bins of SFR(UV) indicated in Table 2 yields a value of 2.1 ± 0.2, which shows a ∼5σ discrepancy from unity.

Using either model (C) or (D) results in \(\text{SFR}_{\text{corrected}}(\text{H}\alpha)\) that are in good agreement with \(\text{SFR}_{\text{corrected}}(\text{UV})\). Model (B) reproduces systematically higher SFRs but is still consistent with the range of \(\text{SFR}_{\text{corrected}}(\text{UV})\) in higher bins, and model (E) estimations are lower than expected.

Based on the data provided in Table 2 and the right panel of Figure 4, model (D) provides the best agreement between SFRs among the five models. The average of the SFR(\(\text{H}\alpha\))-to-SFR(UV) ratios in the five SFR(UV) bins of this model shows less than 1σ discrepancy from unity. This suggests that on average the best recipe to correct the \(\text{H}\alpha\)-inferred quantities of star-forming galaxies at \(z \sim 2\) is to use \(E(B-V)_{\text{nebular}} = E(B-V)_{\text{stellar}}\) with the Calzetti reddening curve.

6. BOLOMETRIC SFRs

As discussed above, a primary disadvantage of using \(\text{H}\alpha\) and UV SFR diagnostics is that we must account for dust extinction, though this is less of a problem for \(\text{H}\alpha\) as it is for the UV. The attenuation curves (e.g., the Calzetti et al. 2000 curve) that are used to correct the luminosities encode information regarding the dust grain size distribution and the geometrical distribution of dust with respect to stars (e.g., whether the dust is clumpy or uniform, a homogeneous mixture or a foreground screen, etc). On the other hand, the IR luminosity is a direct tracer of dust and thus provides an independent and more robust diagnostic of dust attenuation. Adding the IR luminosity, which accounts for the obscured star formation, to the unobscured (UV and \(\text{H}\alpha\)) tracers of SFR can give a more reliable estimate of the bolometric SFR.

6.1. The Relationship between Observed \(\text{H}\alpha\) Luminosity and Total SFR

To convert the observed \(\text{H}\alpha\) luminosity to total SFR, the most commonly used calibration is that of Kennicutt (1998), which is computed using an evolutionary synthesis model, assuming Case B recombination with \(T_e = 10,000\) K. In the absence of Balmer decrement measurements, the observed \(\text{H}\alpha\) SFR must be corrected for dust with some assumption of the attenuation curve and color excess of the ionized gas. In this section, we examine the \(L_{\text{H}\alpha}\)-to-SFR conversion by relying only on the observed data, without making any assumptions about the dust correction or electron temperature of the ionized gas. With this conversion, one can use the \(\text{H}\alpha\) observed luminosity as a proxy for total SFR without assuming a dust attenuation curve and its associated uncertainties. The conversion applies to stellar populations with constant star formation at least over 100 Myr. For bursty star formation histories over timescales shorter than 100 Myr, the \(\text{H}\alpha\) and UV+IR luminosities diverge as the \(\text{H}\alpha\) luminosity traces more instantaneous star formation over timescales of ∼10 Myr, while IR+UV is not sensitive to the change of star formation on timescales ≤100 Myr. Here, we are deriving the conversion factor based on the stacked data that represents the “average” quantities and thus should be used with caution for galaxies that may be undergoing bursty star formation.

Bolometric SFR (\(\text{SFR}(\text{IR})+\text{SFR}(\text{UV})\)) is plotted as a function of the \(\text{H}\alpha\) luminosity in Figure 5. As both the \(\text{H}\alpha\) and IR measurements have non-detections, we decided to bin the data with respect to the SED-inferred SFR. We chose the bins so that in each bin the SFR(SED) is consistent with the stacked SFR(IR)+SFR(UV) within the uncertainties, because ultimately we are using SFR(IR)+SFR(UV) to calculate the \(\text{H}\alpha\) luminosity-to-SFR conversion factor. MIPS data are stacked in each bin and the total IR luminosity is extracted in

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7 The dust heated by the visible light from older stellar populations (i.e., the cold component) also contributes to the IR luminosity. However, in case of the star-forming galaxies the contribution of the UV radiation of massive stars (the warm component) is expected to dominate the total IR luminosity (Kennicutt 1998).
the same way as for individual galaxies. The UV and Hα luminosities are derived from the stacked SEDs.

A weighted least-squares regression method is used to find the slope of the relation:

$$SFR_{\text{bol}} \left( M_\odot \text{ yr}^{-1} \right) = (7.5 \pm 1.3) \times 10^{-42} L_{\text{obs}}(\text{H}\alpha) \left( \text{erg s}^{-1} \right).$$

This relation can be used to convert the observed Hα luminosity in units of erg s\(^{-1}\) to the bolometric SFR. The factor given in Kennicutt (1998) and Kennicutt et al. (1994), to convert observed/intrinsic luminosity to observed/intrinsic SFR, is 7.9 \times 10^{-42} M_\odot yr^{-1} s^{-1}. Madau et al. (1998) reported a conversion factor of 6.3 \times 10^{-42} M_\odot yr^{-1} s^{-1}. These factors are computed using evolutionary synthesis models and are subject to those models’ uncertainties, as well as the initial assumptions that went into these models, such as IMF, star-formation history, and the stellar evolution and atmosphere models. For the same galaxy type and assumed IMF, Kennicutt (1998) reports \sim30\% variation among different calibrations, which mainly reflects the sensitivity to the SED modeling stellar evolution input data. In our analysis, converting L(IR) and L(UV) to SFR still relies on the model assumptions, but previous studies have shown that in the absence of the Balmer decrement measurements, the sum of SFR(IR) and SFR(UV) is the most reliable estimate of total SFR (Hirashita et al. 2003; Reddy et al. 2012b). Our derived slope for a Salpeter IMF is consistent with Kennicutt (1998) and Madau et al. (1998) within the errors.

Excluding galaxies with ages <100 Myr (see Section 6.2) results in a best-fit slope of 7.8 \times 10^{-42} M_\odot yr^{-1} erg^{-1}s that is consistent with the slope found above.

6.2. Validity of the Calzetti Dust Attenuation for Young Galaxies

Figure 6 shows the bolometric SFR versus median SFR inferred from the best-fit SED model, in bins of SFR(SED). Both quantities are representative of the total SFR of the galaxies, the only difference being the method by which dust is accounted for. The bolometric SFR, as mentioned before, is the sum of SFR(IR) and SFR(UV) and is independent of any dust correction. On the other hand, for SFR(SED), the effect of dust is considered by using the Calzetti attenuation curve in the SED fitting procedure. We would like to determine whether for all types of galaxies at z \sim 2 the bolometric SFRs agree with SED SFRs that are corrected by the Calzetti attenuation curve. We stack the MIPS data of individual detected and undetected galaxies in three bins of SFR(SED) as described in Section 2.3. The three bins in log(SFR(SED)) are <1.5, 1.5–2, and \geq2, with respectively 44, 56, and 15 galaxies in each bin. SFR(SED) and SFR(UV) are the median SFRs of the individual galaxies in each bin. The results of stacking are shown with open blue circles in Figure 6. In the last two bins, the SED SFR is overestimated compared to the bolometric SFR. Stacking the MIPS images for only objects that are inferred to be older than 100 Myr produces different results. The number of objects in bins with galaxies older than 100 Myr reduces to 43, 50, and 8, respectively, from the lowest SFR(SED) bin to the highest.

Once we remove galaxies with ages <100 Myr, SFR(SED) agrees well with SFR(UV)+SFR(IR). An age-dependent L(UV)-to-SFR calibration (as we use here) does not decrease the difference between SFR(SED) and the bolometric SFR for stacks of all galaxies. It seems that younger galaxies are at the same time less dusty (smaller bolometric SFR) but redder (larger SFR(SED)) than their older counterparts. These results are consistent with those of Reddy et al. (2006b, 2010) and Wuyts et al. (2012), who find that galaxies with young stellar population ages are less dusty for a given UV slope than older galaxies. An SMC-like curve may be more appropriate for these galaxies. One possibility is that young galaxies have larger dust covering fractions than older galaxies (Reddy et al. 2010). A large dust covering fraction makes the UV slope redder for a given amount of dust attenuation. This study confirms that at z \sim 2 the Calzetti attenuation curve is applicable to star-forming galaxies older than 100 Myr, but a steeper attenuation curve may be necessary for the younger galaxies.

7. SUMMARY

We have studied the multi-wavelength properties of a sample of \sim200 galaxies with spectroscopically confirmed redshifts at 2.08 \leq z \leq 2.51, to study the validity of commonly used dust correction recipes and to compare SFRs inferred from the Hα line luminosity, the UV continuum luminosity, and Spitzer MIPS 24 μm measurements that are converted to the total IR luminosity. In this study, we benefit from using the broadband photometry excess techniques to determine the Hα fluxes and, hence, conduct a large sample of z \sim 2 Hα measurements that is immune to uncertainties in the spectroscopic slit-loss corrections. The galaxies’ properties are determined from stellar population model fitting to the rest-frame UV through near-infrared data. The main conclusions are as follows:

1. By investigating several recipes for dust correcting the nebular emission lines, we find that assuming the same color excess of the ionized gas and the stellar continuum (i.e., E(B-V)_{\text{true}} = E(B-V)_{\text{ext}}), and assuming that the Calzetti attenuation curve applies to both, results in the best agreement between SFR(Hα) and SFR(UV). If we assume the Calzetti curve to both the stellar and nebular regions but use E(B-V)_{\text{nebular}} = 2.27 E(B-V)_{\text{stellar}}, the corrected SFR(Hα) measurements are inconsistent with the corrected SFR(UV) values at the \sim5σ level, averaged on the five bins of SFR(UV) (see the right panel of Figure 4).

2. Using the available Spitzer/MIPS data for \sim100 galaxies in our sample, we derive an observed L_{H\alpha}-to-SFR_{total} conversion factor of (7.5 \pm 1.3) \times 10^{-42} M_\odot yr^{-1} s^{-1}. This calibration is independent of any assumptions on the dust correction and can be used to convert the observed (extincted) Hα luminosity to a bolometric SFR when no dust attenuation measurements for the Hα luminosity are available.

3. By comparing the stacks of SFR(UV)+SFR(IR) with the SED-inferred SFRs that are corrected for dust by the locally derived Calzetti curve, we conclude that a steeper attenuation curve (such as an SMC curve) may be necessary for galaxies younger than 100 Myr, as previous studies (Reddy et al. 2006b, 2010; Wuyts et al. 2012) have found. We find that applying the Calzetti curve to the stacks of all galaxies, including the young ones, results in SFR(SED) values that are inconsistent with the SFR(UV)+SFR(IR) at \sim2σ significance (the SFR(SED) in three
mass bins of Figure 6 are inconsistent with SFR(SED) +SFR(IR) by 1σ, 2σ, and 3σ, from the lowest to highest mass bins, respectively. The young galaxies have redder UV slope and at the same time lower bolometric SFR compared to their older counterparts. As a result, applying the Calzetti curve to the young galaxies overestimates the SED-inferred SFR when compared with their bolometric SFR. The Calzetti attenuation curve shows a good overall agreement for galaxies older than 100 Myr.

A more detailed investigation will include direct tracers of nebular dust extinction (i.e., the Balmer decrement). In future studies, we plan to investigate this aspect with the MOSFIRE Deep Evolution Field (MOSDEF) survey, which uses the near-IR multi-object spectrograph MOSFIRE on the Keck I telescope to obtain spectroscopic measurements of the nebular emission lines for a sample of ≈1300 galaxies (Kriek et al. 2014).

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Figure 6. Comparison of the bolometric SFR and SED-inferred SFR. The values are divided into three bins of SFR(SED) including individual detections and individually undetected galaxies at 24 μm: open blue circles include all objects, and filled red circles include only those galaxies older than 100 Myr. Diamonds are individual detected objects, and downward arrows represent 3σ upper limits in SFR(IR)+SFR(UV) for the MIPS undetected galaxies. Young galaxies (ages < 100 Myr) are colored blue, and galaxies with ages > 100 Myr are orange. SFR(IR) error bars are estimated through bootstrap simulations and show the dispersion in the SFRs contributing to each stack. The last bin consists of galaxies with SFR(SED) > 100 $M_\odot$ yr$^{-1}$; by removing young galaxies (ages < 100 Myr), about half of the sample in this bin is dismissed and we see the change between the two measurements (including and excluding the young ones). The dotted line indicates a one-to-one correspondence.

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