

SPATIALLY RESOLVED DUST MAPS FROM BALMER DECREMENTS IN GALAXIES AT $z \sim 1.4$ ERICA JUNE NELSON¹, PIETER G. VAN DOKKUM¹, IVELINA G. MOMCHEVA², GABRIEL B. BRAMMER², STIJN WUYTS³,
MARIJN FRANX⁴, NATASCHA M. FÖRSTER SCHREIBER⁵, KATHERINE E. WHITAKER^{6,8}, AND ROSALIND E. SKELTON⁷¹ Astronomy Department, Yale University, New Haven, CT 06511, USA² Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA³ Department of Physics, University of Bath, Claverton Down, Bath, BA2 7AY, UK⁴ Leiden Observatory, Leiden University, Leiden, The Netherlands⁵ Max-Planck-Institut für extraterrestrische Physik, Giessenbachstrasse, D-85748 Garching, Germany⁶ Department of Astronomy, University of Massachusetts, Amherst, MA 01003, USA⁷ South African Astronomical Observatory, P.O. Box 9, Observatory, 7935, South Africa

Received 2015 November 13; accepted 2015 December 22; published 2016 January 20

ABSTRACT

We derive average radial gradients in the dust attenuation toward H II regions in 609 galaxies at $z \sim 1.4$, using measurements of the Balmer decrement out to $r \sim 3$ kpc. The Balmer decrements are derived from spatially resolved maps of H α and H β emission from the 3D-HST survey. We find that with increasing stellar mass M both the normalization and strength of the gradient in dust attenuation increases. Galaxies with a mean mass of $\langle \log M \rangle = 9.2 M_{\odot}$ have little dust attenuation at all radii, whereas galaxies with $\langle \log M \rangle = 10.2 M_{\odot}$ have $A_{H\alpha} \approx 2$ mag in their central regions. We parameterize this as $A_{H\alpha} = b + c \log r$, with $b = 0.9 + \log 1.0 M_{10}$, $c = -1.9 - 2.2 \log M_{10}$, r in kpc, and M_{10} the stellar mass in units of $10^{10} M_{\odot}$. This expression can be used to correct spatially resolved measurements of H α to radial distributions of star formation. When applied to our data, we find that the star formation rates (SFRs) in the central $r < 1$ kpc of galaxies in the highest mass bin are $\sim 6 M_{\odot} \text{ yr}^{-1}$, six times higher than before correction and approximately half of the total SFR of these galaxies. If this high central SFR is maintained for several Gyr, a large fraction of the stars in present-day bulges likely formed in situ.

Key words: galaxies: evolution – galaxies: star formation – galaxies: structure

1. INTRODUCTION

In the local universe, the star formation surface density is determined by the molecular gas surface density (e.g., Larson 1992). Recent studies have shown that this relation probably holds at higher redshift ($1 < z < 3$) as well (e.g., Tacconi et al. 2013; Genzel et al. 2015), suggesting that the gas reservoir is the key factor controlling the growth rate of galaxies. In the broader context of galaxy evolution, this has been interpreted as evidence for the equilibrium growth framework in which star formation is regulated by a balance between inflows and outflows (Bouché et al. 2010; Davé et al. 2012; Lilly et al. 2013; Peng & Maiolino 2014). In this model, galaxy growth in an integrated sense is driven by the cycle of baryons between galaxies and the halo gas (Davé et al. 2012) with the star formation efficiency set by stellar feedback (Hopkins et al. 2014).

However, in a resolved sense, exactly how different physical processes couple in different parts of galaxies to regulate star formation and drive structural assembly remains unknown (Davé et al. 2012). Observationally, significant progress is being made in mapping the molecular gas reservoir and the spatial distribution of star formation of galaxies. Molecular gas can now be mapped based on the spatial distribution of CO thanks to millimeter arrays such as PdB and ALMA (e.g., Genzel et al. 2013; Rybak et al. 2015). Star formation can be mapped out to $z \sim 2.5$ using the spatial distribution of the H α emission line owing to integral field units on ground-based telescopes (SINFONI, OSIRIS, KMOS; Förster Schreiber et al. 2009; Law et al. 2009; Wisnioski et al. 2015) and the Wide Field Camera 3 (WFC3) grism on *Hubble Space Telescope* (HST; Nelson et al. 2012, 2013).

However, studies of spatially resolved star formation using the H α emission line suffer from an important systematic uncertainty as they only trace the photons that are not absorbed by dust. The dust attenuation toward star-forming regions is most directly probed using Balmer recombination line flux ratios, the Balmer decrement: as dust attenuation is wavelength dependent, its effects can be measured by comparing the observed and intrinsic Balmer decrements (e.g., Calzetti 1997). Although there is significant scatter in all of these average trends, on a galaxy-integrated basis, the quantity of dust attenuation toward H II regions ($A_{H\alpha}$) measured using Balmer decrements has been shown to increase with increasing stellar mass (M), star formation rate (SFR), and attenuation toward the stars (A_V) (Calzetti et al. 2000; Wild et al. 2011; Domínguez et al. 2013; Momcheva et al. 2013; Price et al. 2014; Reddy et al. 2015). As the stellar mass surface density and the star formation surface density are typically highest in the centers of galaxies (Nelson et al. 2015), we expect the attenuation to vary within galaxies, such that the dust attenuation is highest in the centers. This is also expected from the fact that both the metallicity and, most importantly, the gas column density increase with decreasing distance from the center (e.g., Bohlin et al. 1978; Gilli et al. 2014; Nelson et al. 2014). Therefore, in order to tie the global gas reservoir to galactic structural assembly we need to correct the spatially resolved H α measurements for the attenuation toward star-forming regions.

Measuring spatially resolved Balmer decrements is now possible with the WFC3 grism capability on the *HST*, which we employed for the 3D-HST survey (Brammer et al. 2012; Momcheva et al. 2015). The grism data enable us to create emission line maps for every object in the survey (see Nelson et al. 2012, 2013, 2015; Wuyts et al. 2013). In a narrow redshift

⁸ Hubble Fellow.

window ($1.35 < z < 1.5$) we can map the spatial distribution of both the $H\alpha$ and $H\beta$ emission lines, as they both fall within the G141 wavelength coverage. Galaxy-integrated Balmer decrements were analyzed in Price et al. (2014).

Here we present spatially resolved Balmer decrements for galaxies at $z \sim 1.4$ and derive radial dust gradients. The gradients are measured from deep stacks, using the full 3D-HST data set. We study radial dust gradients as a function of M , and apply these gradients to the observed $H\alpha$ distributions to obtain spatially resolved dust-corrected star formation surface density profiles.

2. SPATIALLY RESOLVED BALMER DECREMENTS

We use data from the 3D-HST survey, a 248 orbit NIR slitless spectroscopic survey from space over the CANDELS fields with the G141 grism (Brammer et al. 2012; Skelton et al. 2014; Momcheva et al. 2015). These slitless grism observations have high spatial resolution and low spectral resolution, and therefore provide images of galaxies in the light of their emission lines for every object in the field of view. We focus on the redshift range $1.35 < z < 1.5$, for which both $H\alpha$ and $H\beta$ fall in the wavelength coverage of *HST*'s G141 grism. These space-based observations are unaffected by the multitudinous OH skylines in the NIR which impose avoidance criteria on ground-based observations in particular when targeting multiple lines. The galaxies are divided in three stellar mass bins: $[9.0 \leq \log M < 9.2]$, $[9.2 \leq \log M < 9.8]$, $[9.8 \leq \log M < 11.0]$ in units of M_\odot . The median stellar mass in these bins is $\log M = [9.17, 9.53, 10.23]$, respectively.⁹

A detailed description of how emission line maps are made from grism data is provided in Nelson et al. (2015). Briefly, the $H\alpha$ and $H\beta$ emission line maps are made by subtracting the continuum from the two-dimensional spectra and masking contaminating flux from nearby objects. We stack the $H\alpha$ and $H\beta$ emission line maps as a function of M . These properties were determined from the combination of the grism spectra and deep UV-IR photometric catalogs (Brammer et al. 2012; Skelton et al. 2014; Whitaker et al. 2014). We select all galaxies with $H_{F140W} \leq 24$, applying no emission line flux limit for $H\alpha$ or $H\beta$ so as not to introduce systematics into the line ratio measurements. $\sim 30\%$ of these galaxies are not significantly detected in $H\alpha$, removing them from the sample does not change our results. Galaxies which have $H\alpha$ or $H\beta$ emission line maps with more than half of their central 3 kpc masked due to contamination are removed; this is roughly half of the sample.

In the stacking procedure the broadband H_{F140W} emission is used to center and normalize the emission line maps. We mask the nearby [S II] $\lambda\lambda 6716, 6731 \text{ \AA}$ and [O III] $\lambda\lambda 4959, 5007$ lines with an asymmetric double pacman mask (see Nelson et al. 2015). We correct the image stacks for the effects of the point-spread function (PSF), using the method described in Szomoru et al. (2013) and Nelson et al. (2015): after fitting the stacks with GALFIT (Peng et al. 2010), the residuals of the fit are added to the unconvolved GALFIT Sérsic model.¹⁰ This method has been shown to reconstruct the true flux distribution even if the Sérsic model is a poor fit (Szomoru et al. 2013). The averaged maps are shown in Figure 1. Radial profiles of the $H\alpha$

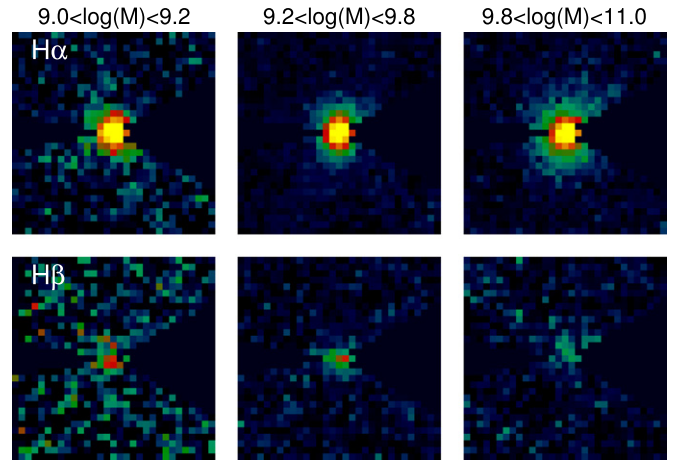


Figure 1. Averaged maps of $H\alpha$ and $H\beta$ emission, in three different stellar mass bins. These maps were obtained by stacking continuum-subtracted two-dimensional spectra of galaxies at $1.35 \leq z \leq 1.53$ from the 3D-HST survey.

and $H\beta$ emission are computed in circular apertures, again following Nelson et al. (2015).

We correct these measured profiles for [N II] emission. As a result of the low spectral resolution of the G141 grism, [N II] $\lambda 6548, 6583$ and $H\alpha \lambda 6563$ are blended in our spectra. To account for the contamination of $H\alpha$ by [N II], the blended observed line must be scaled by a factor $H\alpha_{\text{corr}} = H\alpha_{\text{meas}} / (1 + [\text{N II}]/H\alpha)$. We cannot measure [N II]/ $H\alpha$ directly, and we make use of previous measurements in the literature. The galaxy-integrated [N II]/ $H\alpha$ increases as a function of M (e.g., Erb et al. 2006; Steidel et al. 2014; Wuyts et al. 2014; Zahid et al. 2014), which is probably a reflection of the mass-metallicity relation. We use the Zahid et al. (2014) relation and scale the overall normalization of the radial $H\alpha$ profiles down accordingly. The adopted [N II]/ $H\alpha$ ratios are [0.03, 0.07, 0.24] for the low through high mass stacks, respectively.

We also consider the effects of gradients in [N II]/ $H\alpha$ within the galaxies, as abundance gradients have been widely observed in the local universe (e.g., Sánchez et al. 2014). However, trends at higher redshift are much less certain with observed [N II]/ $H\alpha$ gradients ranging from flat or negative to positive (Swinbank et al. 2012; Jones et al. 2013; Stott et al. 2014; Leethochawalit et al. 2015; E. Wuyts et al. 2016, in preparation). Given these uncertainties we do not apply a radially varying correction, but we note that adopting a radial gradient of $[\text{N II}]/H\alpha = -0.18 \text{ dex}/r_e$, as inferred from radial O/H measurements in the local universe (Sánchez et al. 2014), does not change our results.

Typically, Balmer emission lines also need to be corrected for underlying absorption. The atmospheres of stars (particularly A stars) produce Balmer absorption lines and the emission line flux must first fill in the absorption. In our analysis, the absorption is corrected for in the subtraction of the two-dimensional continuum model. This model is a linear combination of EAZY templates with emission lines removed (see Brammer et al. 2008; Momcheva et al. 2015) which is then convolved with the $J_{F125W}/H_{F140W}/H_{F160W}$ detection image. Therefore, the continuum model has, to very good approximation, both the same spectrum and morphology as the true continuum emission that underlies our emission line maps. We are essentially subtracting a negative image of the galaxy in absorption. For reference, the integrated absorption line

⁹ Masses were derived using a Chabrier (2003) IMF.

¹⁰ Different PSFs were created for the average observed wavelengths of the $H\alpha$ and the $H\beta$ lines.

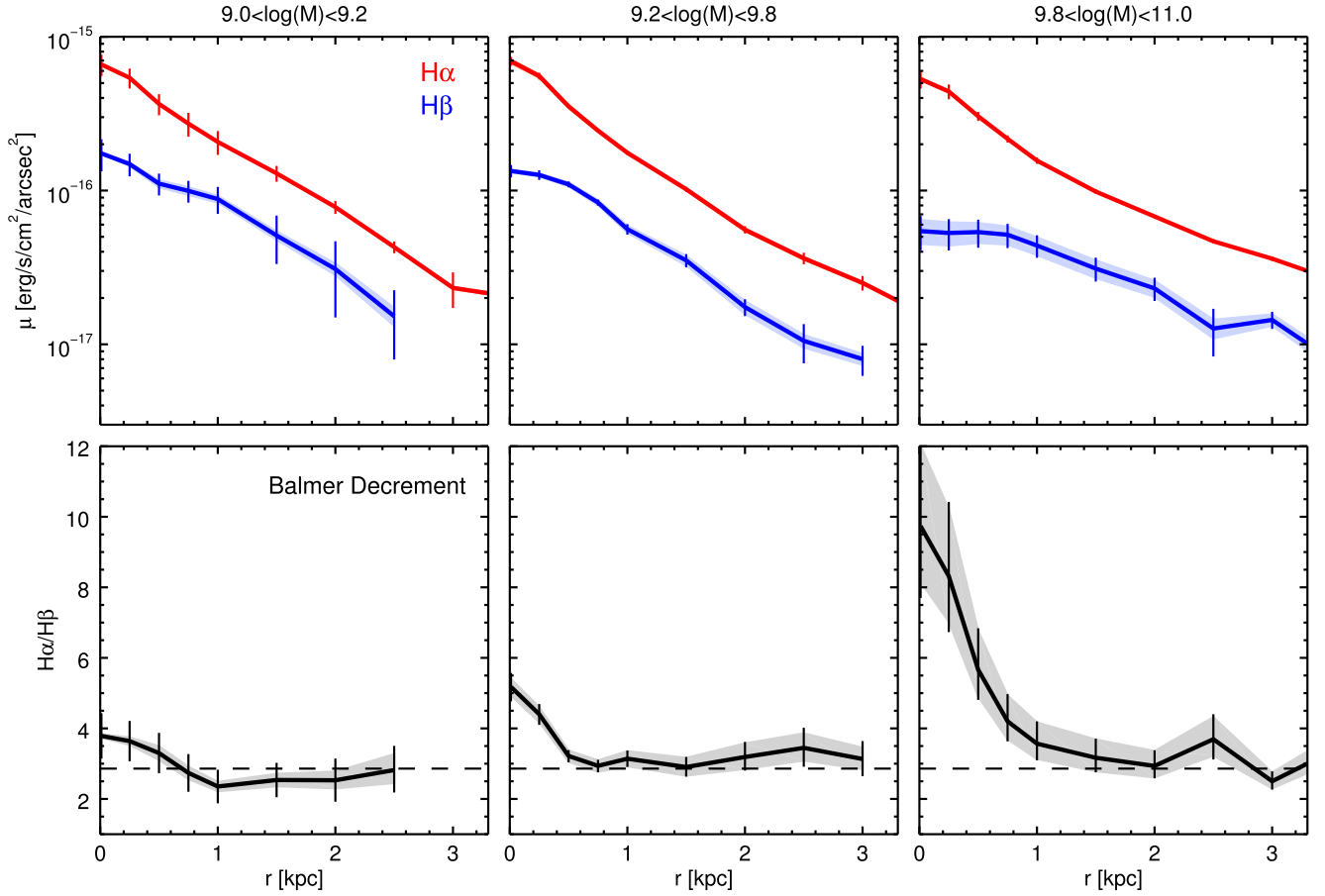


Figure 2. Average radial surface brightness profiles of $H\alpha$ (red), $H\beta$ (blue), and $H\alpha/H\beta$ (the Balmer decrement, black) in galaxies as a function of M . Random uncertainties are shown by bootstrap error bars representing 68% confidence intervals derived by resampling the data with different realizations. Systematic uncertainties derived by artificially increasing and decreasing the absorption line equivalent widths by half are shown by shaded regions. The dashed line shows $(H\alpha/H\beta)_{\text{int}}$, the “intrinsic” line ratio in the absence of dust attenuation. We can reliably measure the average Balmer decrement gradients in galaxies at $z \sim 1.4$ to nearly 3 kpc. With the Balmer decrement tracing dust attenuation toward $H\text{ II}$ regions, this figure shows that with increasing stellar mass, galaxies become increasingly dust-obscured toward their centers.

strength is $\sim 2\text{--}3.5\text{ \AA}$ in the stacks, consistent with, e.g., Domínguez et al. (2013), Momcheva et al. (2013). This is, in general, a small fraction of the emission line equivalent width, although it becomes more significant for $H\beta$ at the highest masses (up to $\sim 30\%$).

The fully corrected $H\alpha$ and $H\beta$ profiles, in units of $\text{erg s}^{-1} \text{cm}^{-2} \text{arcsec}^{-2}$, are shown in Figure 2. We can reliably trace $H\alpha$ out to $\gtrsim 6$ kpc, and the $\gtrsim 3\times$ fainter $H\beta$ out to ~ 3 kpc; at larger radii the error in the measurement is more than half of the measured flux. At low masses, the $H\alpha$ and $H\beta$ surface brightness profiles are nearly exponential. As mass increases, the $H\alpha$ emission grows more centrally concentrated while the $H\beta$ becomes *less* centrally concentrated than exponential. This is the central result of this Letter: with increasing stellar mass, galaxies become increasingly more dust obscured toward their centers.

Figure 2 also shows the effect of assuming different quantities of stellar absorption (shaded regions). These profiles were derived by artificially changing the absorption line equivalent width in the best-fitting 2D EAzy model, increasing and decreasing it by half.

A potential concern in this analysis is that by stacking small galaxies with high attenuation and large galaxies with low attenuation, we could infer a radial dust gradient where on an individual galaxy basis, there is none. To test this, we remove

all compact galaxies with sizes more than 0.1 and 0.3 dex below the size-mass relation from the stack. In both cases, the qualitative trends remain unchanged, which means that the gradients are real, and not a byproduct of stacking a heterogeneous sample. Another concern is that normalizing galaxies by their H_{F140W} flux biases the stacks toward galaxies with high $H\alpha$ and $H\beta$ equivalent widths. If galaxies with high equivalent widths have preferentially low dust attenuation, this analysis could underestimate the true dust attenuation at the median mass of the stacks. However, normalizing galaxies by their $H\alpha$ flux gives a qualitatively similar measurement, albeit with significantly lower signal-to-noise.

3. RADIAL GRADIENTS IN DUST ATTENUATION

The increase in the slope and normalization of the Balmer decrement with M implies a corresponding increase in the slope and normalization of the dust attenuation. We derive the dust attenuation toward $H\alpha$ as follows. The increase of the Balmer decrement over the intrinsic value can be expressed in terms of a Balmer color excess:

$$E(H\beta - H\alpha) = 2.5 \log \left(\frac{(H\alpha/H\beta)_{\text{obs}}}{(H\alpha/H\beta)_{\text{int}}} \right). \quad (1)$$

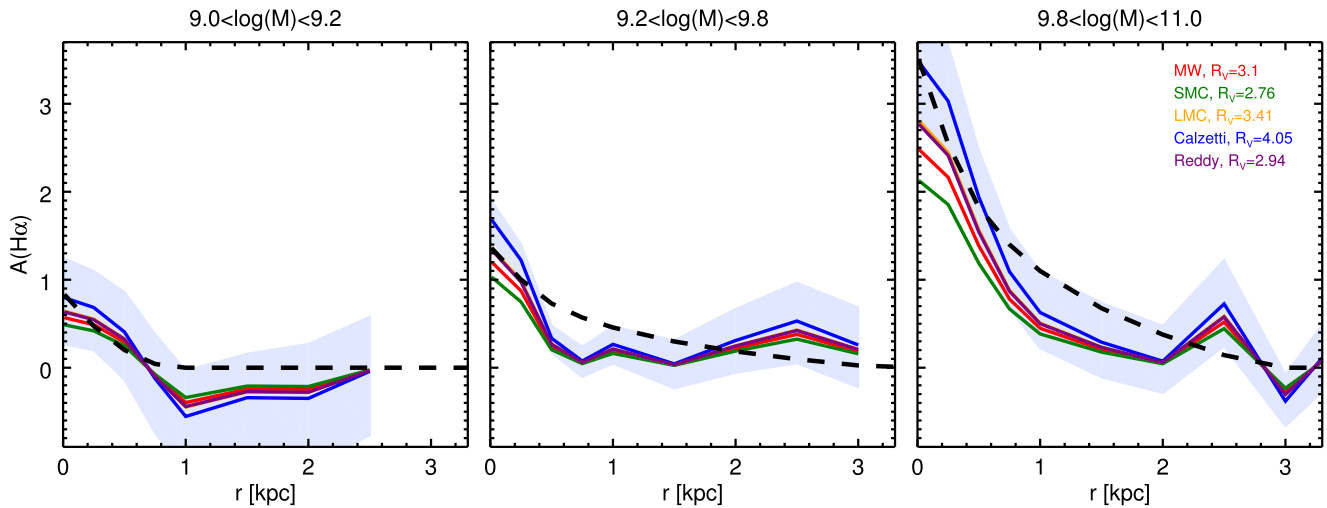


Figure 3. Radial profiles of dust attenuation toward the $H\alpha$ emission line ($A_{H\alpha}$) in galaxies as a function of M . $A_{H\alpha}$ is computed by scaling the Balmer decrement using a dust law. Different dust laws result in different conversions from the radial Balmer decrement profiles in the previous figure to the $A_{H\alpha}$ profiles here, shown in different colors. (Calzetti et al. 2000; Gordon et al. 2003; Reddy et al. 2015). In summary, the star formation in the centers of galaxies becomes more obscured with increasing stellar mass.

Here $(H\alpha/H\beta)_{\text{int}}$ is the expected ratio produced by the recombination and subsequent cascade of electrons in photo-ionized hydrogen atoms: $(H\alpha/H\beta)_{\text{int}} = 2.86$ for Case B recombination and $T = 10^4$ K (Osterbrock & Ferland 2006).

If dust is present, it will preferentially attenuate the shorter wavelength $H\beta$ $\lambda 4861$ Å more than the longer wavelength $H\alpha$ $\lambda 6563$ Å, increasing the observed value of the Balmer decrement ($(H\alpha/H\beta)_{\text{obs}}$). The Balmer color excess can therefore be used to derive the attenuation toward $H\alpha$:

$$A_{H\alpha} = \frac{E(H\beta - H\alpha)}{k(\lambda_{H\beta}) - k(\lambda_{H\alpha})} \times k(\lambda_{H\alpha}). \quad (2)$$

Deriving $A_{H\alpha}$ requires the adoption of a reddening curve $k(\lambda)$ to compute the values at $H\alpha$ ($k(\lambda_{H\alpha})$) and $H\beta$ ($k(\lambda_{H\beta})$).

In Figure 3 we show the radial trend of the absorption toward $H\alpha$, $A_{H\alpha}$ using different parameterizations of the reddening and attenuation. As expected from the trends in the Balmer decrement profiles, $A_{H\alpha}$ shows a steeper gradient and higher overall normalization for more massive galaxies. The attenuation in low mass galaxies is essentially zero at all radii. As mass increases, attenuation increases toward the center. In the highest mass bin, the attenuation in the central regions reaches values in excess of two magnitudes.

While the qualitative trends remain unchanged with different dust laws, the profiles do have quantitative differences. In particular, $A_{H\alpha}$ is higher if the slope of the attenuation curve is flatter between the wavelengths of $H\alpha$ and $H\beta$ or if R_V is larger (see e.g., Cardelli et al. 1989; Calzetti et al. 2000; Gordon et al. 2003; Reddy et al. 2015). With the exception of the centers of the highest mass galaxies, these differences are small compared to the systematic and random errors in the measurements of the Balmer decrement.

We quantify the radial dust profiles as follows:

$$A_{H\alpha} = b + c \log r, \quad (3)$$

with r in kpc. We fit the dust profiles derived using the Calzetti et al. (2000) attenuation curve, for consistency with previous work (e.g., Domínguez et al. 2013; Momcheva et al. 2013; Price et al. 2014) and because this curve gives the best

agreement with the total UV+IR SFRs (see Section 4). For the three mass bins we find $b = [0.0 \pm 0.37, 0.46 \pm 0.33, 1.10 \pm 0.31]$ and $c = [0.0 \pm 0.90, -0.90 \pm 0.72, -2.40 \pm 0.66]$. We set b and c to zero in the lowest mass bin as the formal best fit is (slightly) negative.

These fits are shown by the thick dashed lines in Figure 3. While the observed profiles show hints of more complex structure, perhaps even separate bulge and disk components, higher order fits are not justified given the low signal-to-noise ratio and the spatial resolution of the data.

We parameterize the change of the slope and normalization with M by fitting linear functions to the coefficients $b(M)$ and $c(M)$. To good approximation (± 0.05 mag), we find $b = 0.9 + 1.0 \log M_{10}$ and $c = -1.9 - 2.2 \log M_{10}$, with M_{10} the stellar mass in units of $10^{10} M_{\odot}$. Over a decade in mass, the attenuation at 2 kpc increases by ~ 0.5 mag, and the attenuation at 0.5 kpc increases by ~ 1.5 mag. The gradients are consistent with the galaxy-integrated measurements of Price et al. (2014).

4. DUST-CORRECTED RADIAL PROFILES OF STAR FORMATION

With the radial profiles of $H\alpha$ and $A_{H\alpha}$, we derive radial profiles of star formation corrected for dust. SFRs are computed from $H\alpha$ emission using Kennicutt (1998) and a Chabrier (2003) initial mass function:

$$\text{SFR}(H\alpha) = 4.68 \times 10^{-42} L_{H\alpha}. \quad (4)$$

SFRs are corrected for the dust attenuation toward $H\alpha$ regions ($A_{H\alpha}$) using:

$$\text{SFR}(\text{dust corrected}) = \text{SFR}(H\alpha) \times \exp(A_{H\alpha}/1.086), \quad (5)$$

with $A_{H\alpha}$ given by Equation (3).

Figure 4 shows the radial SFR profiles corrected for dust. As a test of our procedure, we integrate these dust-corrected SFR profiles out to $r = 2r_e$ (with r_e the half light radius of the H_{F140W} emission), and compare them to the average UV+IR SFRs of the same galaxies (see Whitaker et al. 2014; Momcheva et al. 2015). In the three mass bins, we find that the total $H\alpha$ -derived SFRs are 2.4, 3.3, and $8.6 M_{\odot} \text{ yr}^{-1}$,

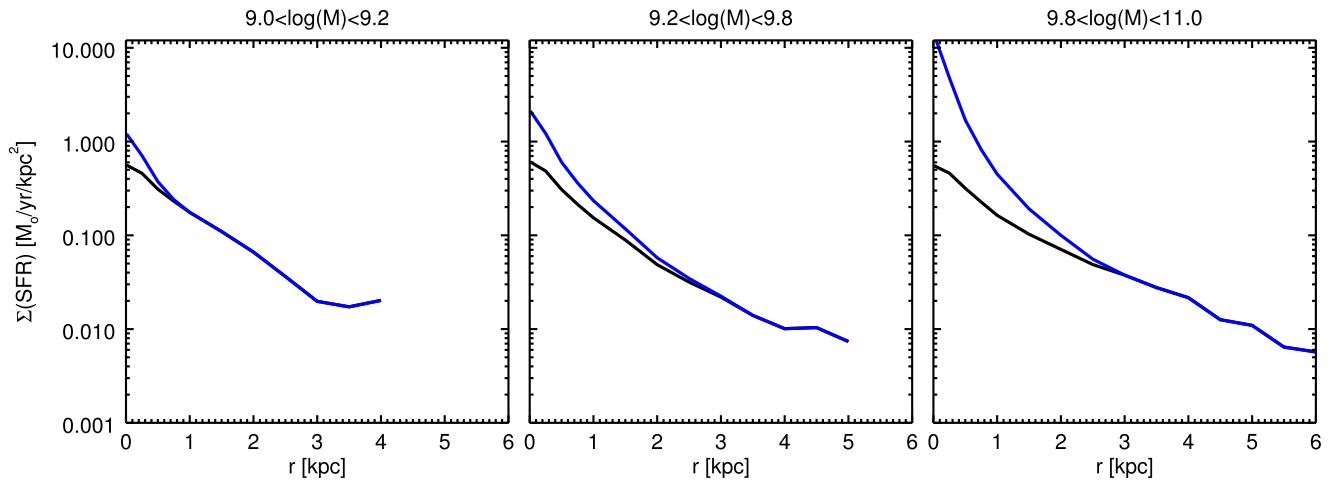


Figure 4. Radial profiles of SFR determined directly from H α emission are shown in black, radial profiles of SFR corrected for dust using radial Balmer decrement profiles are shown in blue. The excess SFR over an exponential toward the center of high mass galaxies suggests we are witnessing the growth of galactic bulges through in situ star formation.

respectively. The ratios of the H α SFRs to the UV+IR SFRs are 1.3, 1.2, and 0.7, respectively. These ratios are similar when using the Whitaker et al. (2014) UV+IR SFR measurements for the median masses in the bins. We conclude that the dust corrections are reasonable to within the systematic uncertainty of our UV+IR SFRs (see, e.g., Utomo et al. 2014).¹¹

Particularly in our highest mass bin the implied central SFRs are much higher than prior to the dust correction: the total star formation in the central $r < 1$ kpc is $5.6 M_{\odot} \text{ yr}^{-1}$ in the highest mass bin, whereas it was $0.9 M_{\odot} \text{ yr}^{-1}$ before correcting for dust. Approximately half of the total SFR takes place inside 1 kpc in the highest mass bin.

5. DISCUSSION

Using the WFC3 grism to map the distribution of H α and H β emission, we constructed the first spatially resolved maps of the Balmer decrement at $z > 1$. These measurements provide stringent constraints on the radial gradients in the dust attenuation toward star forming regions of galaxies, allowing us to derive dust-corrected radial distributions of star formation. The radial patterns in dust and star formation presented here are averages over many galaxies; individual galaxies may deviate from these trends. We find that the dust attenuation is small (< 0.5 mag) at all radii in galaxies with $M < 10^{10} M_{\odot}$. Galaxies with higher masses have significant dust attenuation toward their centers. The immediate implication is that the central ($r \lesssim 2$ kpc) observed H α emission of high mass galaxies should be corrected for dust before being converted to star formation.

A straightforward interpretation of our results is that we see the in situ building of bulges in massive galaxies at $z = 1.4$. However, a key question is whether this central star formation accounts for a significant fraction of the stars in the central kpc of present-day galaxies. The total amount of stars that are formed in the central kpc can be approximated by

$$M \sim w \text{ SFR } \tau, \quad (6)$$

with $w \approx 0.6$ a correction for mass loss due to stellar winds (see e.g., Bruzual & Charlot 2003) and τ the duration of the star

formation. For $\tau \sim 2$ Gyr (that is, assuming that the current SFR is maintained until $z \sim 0.8$), we find that the total mass that is added is $\sim 7 \times 10^9 M_{\odot}$, or $\sim 1/3$ of the total mass of the galaxy. If $\tau \lesssim 1$ Gyr the added mass is much smaller. We note that the addition of dust-obscured central star formation does not necessarily imply that galaxies are growing “outside-in”: this depends on the radial mass-to-light ratio profiles (Szomoru et al. 2013) which are driven by gradients in dust and age. This could be tested by deriving mass profiles from the high spatial resolution CANDELS multi-color imaging.

In summary, we infer that it is possible that a central mass concentration is built up through in situ star formation in the highest mass galaxies, but only if the radial distribution of star formation observed at $z \sim 1.4$ is sustained over several Gyr. This can be tested with spatially resolved absorption maps at lower redshift, which can be created using adaptive optics or the G102 grism on the WFC3 camera. Furthermore, high resolution imaging of the molecular gas and of the continuum dust emission with ALMA can provide direct information on the presence of large amounts of dust in the centers of massive galaxies at these redshifts. Finally, with future facilities such as *James Webb Space Telescope* our initial study of averaged spatially resolved Balmer decrements at moderate redshifts can be extended to higher redshifts and individual galaxies.

REFERENCES

- Bohlin, R. C., Savage, B. D., & Drake, J. F. 1978, *ApJ*, **224**, 132
 Bouché, N., Dekel, A., Genzel, R., et al. 2010, *ApJ*, **718**, 1001
 Brammer, G. B., van Dokkum, P. G., & Coppi, P. 2008, *ApJ*, **686**, 1503
 Brammer, G. B., van Dokkum, P. G., Franx, M., et al. 2012, *ApJS*, **200**, 13
 Bruzual, G., & Charlot, S. 2003, *MNRAS*, **344**, 1000
 Calzetti, D. 1997, *AJ*, **113**, 162
 Calzetti, D., Armus, L., Bohlin, R. C., et al. 2000, *ApJ*, **533**, 682
 Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, *ApJ*, **345**, 245
 Chabrier, G. 2003, *PASP*, **115**, 763
 Davé, R., Finlator, K., & Oppenheimer, B. D. 2012, *MNRAS*, **421**, 98
 Domínguez, A., Siana, B., Henry, A. L., et al. 2013, *ApJ*, **763**, 145
 Erb, D. K., Shapley, A. E., Pettini, M., et al. 2006, *ApJ*, **644**, 813
 Förster Schreiber, N. M., Genzel, R., Bouché, N., et al. 2009, *ApJ*, **706**, 1364
 Genzel, R., Tacconi, L. J., Kurk, J., et al. 2013, *ApJ*, **773**, 68
 Genzel, R., Tacconi, L. J., Lutz, D., et al. 2015, *ApJ*, **800**, 20
 Gilli, R., Norman, C., Vignali, C., et al. 2014, *A&A*, **562**, A67

¹¹ The small discrepancy in the highest mass bin could be due to star formation with very high optical depth.

- Gordon, K. D., Clayton, G. C., Misselt, K. A., Landolt, A. U., & Wolff, M. J. 2003, [ApJ](#), **594**, 279
- Hopkins, P. F., Kereš, D., Oñorbe, J., et al. 2014, [MNRAS](#), **445**, 581
- Jones, T., Ellis, R. S., Richard, J., & Jullo, E. 2013, [ApJ](#), **765**, 48
- Kennicutt, R. C., Jr. 1998, [ARA&A](#), **36**, 189
- Larson, R. 1992, in *Star Formation in Stellar Systems*, ed. G. Tenorio-Tagle, M. Prieto, & F. Sanchez (Cambridge: Cambridge Univ. Press), 125
- Law, D. R., Steidel, C. C., Erb, D. K., et al. 2009, [ApJ](#), **697**, 2057
- Leethochawalit, N., Jones, T. A., Ellis, R. S., et al. 2015, [arXiv:1509.01279](#)
- Lilly, S. J., Carollo, C. M., Pipino, A., Renzini, A., & Peng, Y. 2013, [ApJ](#), **772**, 119
- Momcheva, I. G., Brammer, G. B., van Dokkum, P. G., et al. 2015, [ApJS](#), submitted ([arXiv:1510.02106](#))
- Momcheva, I. G., Lee, J. C., Ly, C., et al. 2013, [AJ](#), **145**, 47
- Nelson, E., van Dokkum, P., Franx, M., et al. 2014, [Natur](#), **513**, 394
- Nelson, E. J., van Dokkum, P. G., Brammer, G., et al. 2012, [ApJL](#), **747**, L28
- Nelson, E. J., van Dokkum, P. G., Förster Schreiber, N. M., et al. 2015, [ApJ](#), submitted ([arXiv:1507.03999](#))
- Nelson, E. J., van Dokkum, P. G., Momcheva, I., et al. 2013, [ApJL](#), **763**, L16
- Osterbrock, D. E., & Ferland, G. J. 2006, *Astrophysics of Gaseous Nebulae and Active Galactic Nuclei* (2nd ed.; Sausalito, CA: Univ. Science Books)
- Peng, C. Y., Ho, L. C., Impey, C. D., & Rix, H.-W. 2010, [AJ](#), **139**, 2097
- Peng, Y.-j., & Maiolino, R. 2014, [MNRAS](#), **443**, 3643
- Price, S. H., Kriek, M., Brammer, G. B., et al. 2014, [ApJ](#), **788**, 86
- Reddy, N. A., Kriek, M., Shapley, A. E., et al. 2015, [ApJ](#), in press ([arXiv:1504.02782](#))
- Rybak, M., Vegetti, S., McKean, J. P., Andreani, P., & White, S. D. M. 2015, [MNRAS](#), **453**, L26
- Sánchez, S. F., Rosales-Ortega, F. F., Iglesias-Páramo, J., et al. 2014, [A&A](#), **563**, A49
- Skelton, R. E., Whitaker, K. E., Momcheva, I. G., et al. 2014, [ApJS](#), **214**, 24
- Steidel, C. C., Rudie, G. C., Strom, A. L., et al. 2014, [ApJ](#), **795**, 165
- Stott, J. P., Sobral, D., Swinbank, A. M., et al. 2014, [MNRAS](#), **443**, 2695
- Swinbank, M., Smail, I., Sobral, D., et al. 2012, [arXiv:1206.1867](#)
- Szomoru, D., Franx, M., van Dokkum, P. G., et al. 2013, [ApJ](#), **763**, 73
- Tacconi, L. J., Neri, R., Genzel, R., et al. 2013, [ApJ](#), **768**, 74
- Utomo, D., Kriek, M., Labbé, I., Conroy, C., & Fumagalli, M. 2014, [ApJL](#), **783**, L30
- Whitaker, K. E., Franx, M., Leja, J., et al. 2014, [ApJ](#), **795**, 104
- Wild, V., Charlot, S., Brinchmann, J., et al. 2011, [MNRAS](#), **417**, 1760
- Wisnioski, E., Förster Schreiber, N. M., Wuyts, S., et al. 2015, [ApJ](#), **799**, 209
- Wuyts, E., Kurk, J., Förster Schreiber, N. M., et al. 2014, [ApJL](#), **789**, L40
- Wuyts, S., Förster Schreiber, N. M., Nelson, E. J., et al. 2013, [ApJ](#), **779**, 135
- Zahid, H. J., Kashino, D., Silverman, J. D., et al. 2014, [ApJ](#), **792**, 75