THE RADIAL DISTRIBUTION OF STAR FORMATION IN GALAXIES AT $z \sim 1$ FROM THE 3D-HST SURVEY

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ABSTRACT

The assembly of galaxies can be described by the distribution of their star formation as a function of cosmic time. Thanks to the WFC3 grism on the Hubble Space Telescope (HST) it is now possible to measure this beyond the local Universe. Here we present the spatial distribution of Hα emission for a sample of 54 strongly star-forming galaxies at $z \sim 1$ in the 3D-HST Treasury survey. By stacking the Hα emission, we find that star formation occurred in approximately equal distributions at $z \sim 1$, with a median Sérsic index of $n = 1.0 \pm 0.2$. The stacks are elongated with median axis ratios of $b/a = 0.58 \pm 0.09$ in Hα consistent with (possibly thick) disks at random orientation angles. Keck spectra obtained for a subset of eight of the galaxies show clear evidence for rotation, with inclination corrected velocities of 90–330 km s$^{-1}$. The most straightforward interpretation of our results is that star formation in strongly star-forming galaxies at $z \sim 1$ generally occurred in disks. The disks appear to be “scaled-up” versions of nearby spiral galaxies: they have EW(Hα) $\sim 100$ Å out to the solar orbit and they have star formation surface densities above the threshold for driving galactic scale winds.

Key words: galaxies: evolution – galaxies: formation – galaxies: high-redshift – galaxies: kinematics and dynamics – galaxies: star formation – galaxies: structure

Online-only material: color figures

1. INTRODUCTION

Galaxy formation is a complex process involving starbursts, mergers, and strong gas flows (e.g., Hopkins et al. 2006; Brooks et al. 2009; Dekel et al. 2009). Furthermore, stellar migration and secular processes can change the structure of galaxies at late times (e.g., Roškar et al. 2008; Grand et al. 2012). Therefore, even if we could perfectly locate and age date every star in the Milky Way, we still could not say where and with what structural and kinematic properties those stars formed. The only way to establish where a galaxy’s stars formed, and hence how it was assembled, is to map the star formation while those stars were forming.

Obtaining Hα and stellar continuum maps of $z \gtrsim 1$ galaxies, with the $\sim 1$ kpc resolution necessary to put constraints on the spatial distribution of star formation, is challenging and has so far only been possible using a combination of adaptive optics and integral field units on 8–10 m class telescopes. These studies paint a complex picture: they find that star-forming galaxies at $z \sim 2$ are a mix of “puffy” and often clumpy rotating disks, mergers, and more compact dispersion-dominated objects (e.g., Genzel et al. 2008; Shapiro et al. 2008; Cresci et al. 2009; Förster Schreiber et al. 2009, 2011; Law et al. 2009; Jones et al. 2010; Mancini et al. 2011).

Some studies claim that there are trends in the structural properties of Hα as a function of redshift, implying that the way galaxies assemble their stars varies fundamentally as a function of cosmic time. In particular, Epinat et al. (2009) and Kassin et al. (2012) suggest that galaxies become cooler and more rotation-dominated with time, $z \sim 1–0$ being the epoch of “disk settling.” This is interesting because most of the stars in the disks of galaxies like the Milky Way were formed in this epoch.

It is now possible to obtain high spatial resolution ($\lesssim 1$ kpc) information on Hα emission at $z \sim 1$ with a high Strehl ratio, owing to the near-IR slitless spectroscopic capabilities provided by the WFC3 camera on the Hubble Space Telescope (HST). In Nelson et al. (2012), we used data taken as part of the 3D-HST survey to build on previous ground-based studies by mapping the Hα and stellar continuum with high resolution for a sample of 57 galaxies at $z \sim 1$ and showed that star formation broadly follows the rest-frame optical light, but is slightly more extended. Here we stack the Hα maps of these galaxies to construct high signal-to-noise ratio (S/N) radial profiles and measure structural parameters of stellar continuum emission and star formation. These unique, high spatial resolution data from 3D-HST are combined with kinematics from the Near Infrared Spectrometer (NIRSPEC) on the W. M. Keck telescope (McLean et al. 1998). We assume $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.3$, and $\Omega_{\Lambda} = 0.7$.

2. 3D-HST AND SAMPLE SELECTION

The 3D-HST survey, a 248-orbit Treasury program on the HST, supplies the two-dimensional emission line maps needed...
Figure 1. Location of selected galaxies in the SFR–mass plane. Six sources without IR photometry are not shown in the figure. The histogram shows the position of the selected galaxies relative to the rest of the galaxies by dividing without IR photometry are not shown in the figure. The purple region delineates the position of the selected galaxies relative to the rest of the galaxies by dividing without IR photometry are not shown in the figure. The purple region delineates the position of the selected galaxies relative to the rest of the galaxies by dividing without IR photometry are not shown in the figure. The purple region delineates the position of the selected galaxies relative to the rest of the galaxies by dividing without IR photometry are not shown in the figure. The purple region delineates the position of the selected galaxies relative to the rest of the galaxies by dividing without IR photometry are not shown in the figure. The purple region delineates the position of the selected galaxies relative to the rest of the galaxies by dividing without IR photometry are not shown in the figure. The purple region delineates the position of the selected galaxies relative to the rest of the galaxies by dividing without IR photometry are not shown in the figure. The purple region delineates the position of the selected galaxies relative to the rest of the galaxies by dividing without IR photometry are not shown in the figure. The purple region delineates the position of the selected galaxies relative to the rest of the galaxies by dividing without IR photometry are not shown in the figure. The purple region delineates the position of the selected galaxies relative to the rest of the galaxies by dividing without IR photometry are not shown in the figure. The purple region delineates the position of the selected galaxies relative to the rest of the galaxies by dividing without IR photometry are not shown in the figure. The purple region delineates the position of the selected galaxies relative to the rest of the galaxies by dividing without IR photometry are not shown in the figure. The purple region delineates the position of the selected galaxies relative to the rest of the galaxies by dividing without IR photometry are not shown in the figure. The purple region delineates the position of the selected galaxies relative to the rest of the galaxies by dividing without IR photometry are not shown in the figure. The purple region delineates the position of the selected galaxies relative to the rest of the galaxies by dividing without IR photometry are not shown in the figure. The purple region delineates the position of the selected galaxies relative to the rest of the galaxies by dividing without IR photometry are not shown in the figure. The purple region delineates the position of the selected galaxies relative to the rest of the galaxies by dividing without IR photometry are not shown in the figure. The purple region delineates the position of the selected galaxies relative to the rest of the galaxies by dividing without IR photometry are not shown in the figure. The purple region delineates the position of the selected galaxies relative to the rest of the galaxies by dividing without IR photometry are not shown in the figure. The purple region delineates the position of the selected galaxies relative to the rest of the galaxies by dividing without IR photometry are not shown in the figure. The purple region delineates the position of the selected galaxies relative to the rest of the galaxies by dividing without IR photometry are not shown in the figure. The purple region delineates the position of the selected galaxies relative to the rest of the galaxies by dividing without IR photometry are not shown in the figure. The purple region delineates the position of the selected galaxies relative to the rest of the galaxies by dividing without IR photometry are not shown in the figure. The purple region delineates the position of the selected galaxies relative to the rest of the galaxies by dividing without IR photometry are not shown in the figure. The purple region delineates the position of the selected galaxies relative to the rest of the galaxies by dividing without IR photometry are not shown in the figure. The purple region delineates the position of the selected galaxies relative to the rest of the galaxies by dividing without IR photometry are not shown in the figure. The purple region delineates the position of the selected galaxies relative to the rest of the galaxies by dividing with...
Figure 2. Stacks of the high spatial resolution, PSF-corrected maps of Hα emission (top). Stacking was done based on Hα size; the number of galaxies included in each size bin is listed (N_{stack}) as is the major axis effective radius (in kpc) of each stack measured by galfit (r_e). The stacks have a weighted mean Sérsic index n(Hα) ∼ 1 and axis ratio of b/a(Hα) = 0.58 ± 0.09, consistent with disks at random orientation angles. Bottom panels show corresponding radial profiles with dark purple—small, medium purple—mid-sized, and light purple—large (Figure 3, Section 3.2). The stacked Hα emission always has Sérsic index n \lesssim 1.

(A color version of this figure is available in the online journal.)

Figure 3. Stacks of Hα (left) and rest-frame R-band (middle) emission have nearly exponential (or shallower) radial profiles. The EW(Hα) profile (discussed in Section 3.2) is shown in the right panel. The bottom panels show the profiles normalized by their effective radius. The horizontal line is the SFR surface density criterion for driving large-scale outflows (Heckman 2002). As in Figure 2, the dark, medium, and light colors correspond to the small, medium, and large stacks, respectively, as shown at the top. The spatial distribution of Hα emission is exponential or shallower.

(A color version of this figure is available in the online journal.)
The derived Sérsic indices (Figure 2) of the Hα and stellar continuum profiles are $n(H\alpha) = 1.2 \pm 0.6, 0.9 \pm 0.1$, $n(F140W) < 1$ and $n(F140W) = 1.8 \pm 0.4, 1.4 \pm 0.1, 1.1 \pm 0.2$ with weighted means of $n(H\alpha) = 1.0 \pm 0.4$ and $n(F140W) = 1.4 \pm 0.2$. As shown in van Dokkum et al. (2010), structural parameters measured from stacks are close to the mean values for the individual galaxies going into the stacks. The upper limit of $n(H\alpha) < 1$ for the largest Hα stack reflects the fact that the derived $n(H\alpha)$ depends somewhat on the details of the fit (treatment of sky, fitting region) but always $n(H\alpha) < 1$.

We find that the stacked spatial distribution of Hα for galaxies in this sample is exponential or shallower. All stacks have $n < 2$, implying a bulge fraction of less than 20% (van Dokkum et al. 1998). The radial Hα profiles (Figure 3, left), seem to show a trend toward lower $n(H\alpha)$ with increasing size. However, this trend is not statistically significant given the errors in the derived Sérsic indices. Additionally, note that the median galaxy with EW(Hα) > 100 Å has a high enough star formation surface density to drive winds out to $\sim 1 r_e$ (Heckman 2002).

### 3.3. Effects of Dust

A major uncertainty in the interpretation of the radial Hα profile is the effect of differential dust extinction: if some parts of the galaxies are more obscured than others (see e.g., Wuyts et al. 2012), the derived radial profile of Hα would not reflect the radial profile of star formation. To assess the importance of this effect, we estimate the extinction as a function of radius. We determine the extinction from the radial color profile.

The color profile is determined from the combination of the F140W stacks with ACS F814W stacks, which can be converted into rest-frame $U-V$ color profiles. As shown in the left panel of Figure 4, for most of the radial extent of the stacks the color is fairly constant, but it becomes redder inside a radius of 2 kpc (see also Szomoru et al. 2012). To estimate roughly how much color translates into missed star formation, we assume that the star formation that is not captured by Hα will be captured by the IR (Kennicutt et al. 2009). Using photometry from R. E. Skelton et al. (2013, in preparation), in addition to rest-frame $U-V$ colors and IR-based SFRs from the NEWFIRM Medium Band Survey (Whitaker et al. 2012), empirical relations were derived for the translation of rest-frame $U-V$ colors into star formation corrections:

$$\log(\text{SFR(IR+Hα)}) - \log(\text{SFR(Hα)}) \sim 0.3 \times (U-V).$$

The dust-corrected radial profiles are shown in the right panel of Figure 4. The smallest galaxies appear to have star formation that is marginally steeper than exponential. The large galaxies have the largest radial gradients but their implied star formation is still less steep than exponential. Although this analysis assigns the entire observed color gradient to extinction, the centers of the radial color profiles could be red because of dust or age. Importantly, the Sérsic indices of the star formation in these stacks based on the implied dust correction remain close to one: $n = 1.4, 1.1, 0.6$ for each of the stacks, weighted mean $= 1.0 \pm 0.4$. So, even when accounting for dust, the averaged star formation in these galaxies has a nearly exponential spatial distribution.

### 4. KINEMATICS

The flattening of the stacks and the exponential Hα profiles suggest that the star formation occurs in rotating disks. To test this, we measured kinematics for a subset of this sample using NIRSPEC on the Keck II telescope on 2012 April 9–10. The sample comprises eight galaxies chosen from the small (1), middle (5), and large (2) stack, which have sizes, masses, Sérsic indices, SFRs, and axis ratios representative of the sample as a whole.

We used the low dispersion mode of NIRSPEC with 0′:5 seeing and a slit width of 0′:7, giving a spectral resolution of $\sigma \sim 80 \text{ km s}^{-1}$ in the $J$ band (compared to $\sim 500 \text{ km s}^{-1}$ in the grism spectra). The slit was aligned along the major axis of each galaxy and observations were conducted in a series of four 900 s exposures, dithering along the slit. The data reduction followed standard procedures for long-slit spectroscopy (see, e.g., van Dokkum et al. 2004). We extracted kinematic information from the two-dimensional spectra by fitting a Gaussian to the Hα and [NII] emission simultaneously at each spatial position along the slit. The median [NII]/Hα is 0.3. Assuming the velocity shear in the two-dimensional spectra is due to rotation, we take the rotational velocity to be the velocity difference between the geometrical center of the galaxy and the maximum velocity. We correct the rotation velocities for inclination angle using

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**Figure 4.** Left panel shows the radial color profiles for each of the stacks with black for the small stack, dark gray for the medium stack, and light gray for the large stack. The right panel shows the implied dust corrected radial profiles of star formation surface density with the colors as in Figures 2 and 3. Error bar on the right panel denotes a typical uncertainty. Dust-corrected radial profiles of star formation remain nearly exponential. (A color version of this figure is available in the online journal.)
Figure 5. Shown here are the rotation curves (middle row) derived from the NIRSPEC spectra (insets in corners), one example from each stack with the implied rotation velocities ($v_{\text{corr}}$—corrected and $v_{\text{uncorr}}$—uncorrected for inclination) and velocity dispersion ($\sigma$) listed in km s$^{-1}$. The top row shows the corresponding rest-frame R-band images and the bottom row shows a false color image with the H$\alpha$ emission in red and stellar continuum in blue. In these rows, ellipses mark the R-band and H$\alpha$ effective radii ($r_e(R)$, $r_e(H\alpha)$), respectively, and gray arrows have a scaled length corresponding to the projected specific angular momentum. (A color version of this figure is available in the online journal.)

We calculate one-dimensional velocity dispersions by fitting a Gaussian to the H$\alpha$ emission in the central row of each spectrum. We calculate the instrumental $\sigma$ to be $\sim 80$ km s$^{-1}$ by fitting a Gaussian to the sky lines. The intrinsic velocity dispersion is calculated by subtracting the instrumental dispersion from the measured dispersion in quadrature.

We find that all galaxies show velocity shear in their two-dimensional spectra, with derived rotation velocities of 90–235 km s$^{-1}$ uncorrected and 110–330 km s$^{-1}$ corrected for inclination. Figure 5 shows the rotation curves for one example galaxy for each stack. These spectra are of the best quality but appear to be representative of the eight. The velocity profile of the smallest galaxy in Figure 3 does not show evidence for a turnover, which means the measured maximum velocity is a lower limit on the rotation velocity at large radii. We conclude that the kinematics are consistent with the disk interpretation of the structural properties of the H$\alpha$ emission. Although different classification methods make it difficult to perform a quantitative comparison, our results are qualitatively consistent with the finding that a large fraction of star-forming galaxies at $z \sim 1$ appear to be rotating. (e.g., Wisnioski et al. 2011; Epinat et al. 2012; Swinbank et al. 2012).

5. DISCUSSION

The central result of this Letter is that the radial distribution of stacked H$\alpha$ emission in $z \sim 1$ galaxies is close to exponential out to $\sim 10$ kpc. Combined with the axis ratios of the stacks and the kinematics of a subset of the sample, the most straightforward interpretation is that star formation seems typically to occur in disks at $z \sim 1$ at least for galaxies with high EW(H$\alpha$). The factor of $\sim 10$ increase in the SFRs of galaxies from $z = 0$ to $z = 1$ (e.g., Damen et al. 2009; Fumagalli et al. 2012) is apparently driven by increased star formation activity in disks rather than a much greater prevalence of merger-driven central starbursts—consistent with other studies (e.g., Rodighiero et al. 2011; Wuyts et al. 2011, 2012).

This result raises a number of questions. First, it is not clear how these galaxies are related to $z \sim 0$ galaxies. An average galaxy in this sample has a distribution of stars with a Sersic index of $n \approx 1.4$. If this average galaxy forms stars with $n = 1.0$, it will have a lower Sersic index at later times. Either we are witnessing the build-up of only the latest of late-type galaxies (these galaxies substantially change where their star formation is

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12 Measured velocity dispersions are also relatively high, but are difficult to interpret given the low spatial resolution of the Keck spectra.
occuring between \( z \sim 1 \) and \( z \sim 0 \) or their stars, once formed, must migrate into a different configuration. In other words, if these are the ancestors of typical \( z \sim 0 \) spiral galaxies, their bulges need to be built in some way besides the star formation increasing the central concentration and central vertical velocity decreases, the gas fraction decreases, and a bar instability grows, occurring between \( z > 1 \), disks are gas-rich and turbulent. As redshift decreases, the gas fraction decreases, and a bar instability grows, increasing the central concentration and central vertical velocity dispersion. (e.g., van den Bosch 2001; DeBuhr et al. 2012; Forbes et al. 2012).

We also note the somewhat surprising presence of a population of large, rapidly rotating disks with relatively low stellar masses at \( z \sim 1 \). These galaxies have mean \( r_e(H\alpha) = 7.3 \) kpc, \( v = 240 \) km s\(^{-1}\), \( \sigma = 89 \) km s\(^{-1}\), and \( M_\star = 2.2 \times 10^{10} M_\odot \), meaning they are disks 8 Gyr ago, larger in size than the Milky Way (Drimmel & Spergel 2001), and thicker (Fleming 1987), with \( \sim \sqrt{1/3} \) of the stellar mass (McMillan 2011) and similar or higher maximum rotation velocities (Bovy et al. 2009). Both what these galaxies become in the local universe and how such extended star-forming disks were made in an epoch of high disk turbulence are open questions. The small disks on the other end of the size distribution are also of interest. With median \( r_e(H\alpha) = 1.9 \) kpc, \( r_e(R) = 2.1 \) kpc, \( M_\star = 8.9 \times 10^8 M_\odot \), and stacked \( n(H\alpha) = 1.2 \), they more closely resemble compact versions of disky star formers than merger-driven star formation in spheroids (see also van der Wel et al. 2011).

There are several caveats. First, our sample is not complete in mass or in SFR(UV+IR). In future papers (using the full 3D-HST survey) we will study the distribution of star formation as a function of these parameters. Second, the distribution of star formation in the stacks is not necessarily representative of individual galaxies. In individual galaxies the star formation is clumpy (e.g., Genzel et al. 2008, 2011; Förster Schreiber et al. 2009; Nelson et al. 2012; Figure 1) and it is difficult to quantify the structure. Stacking these clumpy objects could be hazardous, but it may also provide more insight than can be gleaned from individual galaxies: assuming that the clumps are transient and “light up” a part of the underlying gas disk for a short time (as in, e.g., Wuyts et al. 2012), our stacking technique effectively produces a time-averaged map of the star formation in the galaxies. Finally, dust attenuation remains a key uncertainty, both in the selection and in the interpretation of the profiles. This can be addressed with maps of the IR emission at the full ALMA resolution, or by measuring (spatially resolved) Balmer decrements.

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