Hα STAR FORMATION RATES OF $z > 1$ GALAXY CLUSTERS IN THE IRAC SHALLOW CLUSTER SURVEY

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ABSTRACT

We present Hubble Space Telescope near-IR spectroscopy for 18 galaxy clusters at $1.0 < z < 1.5$ in the IRAC Shallow Cluster Survey. We use Wide Field Camera 3 grism data to spectroscopically identify Hα emitters in both the cores of galaxy clusters as well as in field galaxies. We find a large cluster-to-cluster scatter in the star formation rates within a projected radius of 500 kpc, and many of our clusters (∼60%) have significant levels of star formation within a projected radius of 200 kpc. A stacking analysis reveals that dust reddening in these star-forming galaxies is positively correlated with stellar mass and may be higher in the field than the cluster at a fixed stellar mass. This may indicate a lower amount of gas in star-forming cluster galaxies than in the field population. Also, Hα equivalent widths of star-forming galaxies in the cluster environment are still suppressed below the level of the field. This suppression is most significant for lower mass galaxies ($\log M_\alpha < 10.0 M_\odot$). We therefore conclude that environmental effects are still important at $1.0 < z < 1.5$ for star-forming galaxies in galaxy clusters with $\log M_\alpha \lesssim 10.0 M_\odot$.

Key words: galaxies: clusters: general – galaxies: evolution – galaxies: high-redshift

Online-only material: color figures, machine-readable table

1. INTRODUCTION

Growing out of the cosmic web, galaxy clusters provide insights into the formation and growth of large-scale structure as well as the physics that drives galaxy evolution. Even at $z \gtrsim 1$, galaxy clusters harbor a high density of old, massive stellar populations (Eisenhardt et al. 2008; Snyder et al. 2012), providing an early glimpse of the stellar mass buildup in rich, highly biased environments (e.g., Mancone et al. 2010; Lemaux et al. 2012; Snyder et al. 2012; Rudnick et al. 2012; C. Mancone et al., in preparation).

Locally, there is a well-established relation between environment or density and star formation (e.g., Gómez et al. 2003). The centers of low-redshift clusters show no evidence of significant ongoing star formation and consist of mostly massive, red galaxies. The commonly used model for the formation of these massive cluster galaxies is a short, intense burst of star formation at high redshift ($z \sim 3$), followed by passive evolution (e.g., Stanford et al. 1998; Eisenhardt et al. 2008). However, these simple models are ruled out by observations of clusters at $1 < z < 2$, which suggest that continuous and ongoing star formation is occurring at these redshifts (Snyder et al. 2012). The cessation or suppression of that star formation in cluster cores may be caused by a variety of environmental effects (e.g., strangulation, ram pressure stripping, and galaxy harassment; Larson et al. 1980; Moore et al. 1999), and the epoch at which these effects become important is still unknown.

Studies of the star formation rate (SFR) and local density relation at high redshift ($z > 1$) have yielded varying results. There is evidence that in some clusters the environmental effect on star formation is not yet significant (Hilton et al. 2010; Tran et al. 2010; Brodwin et al. 2013). Other clusters seem to already have environmental effects in place at $z \lesssim 1.4$, with star formation ceased in the core (Tanaka et al. 2009; Grüitzerbauch et al. 2012; Muzzin et al. 2012). This may reflect a diversity of intracluster media and dynamical histories for clusters currently studied at $z > 1$, which is plausible given that they are selected from a variety of methods and cover a range of cluster masses ($M_{200} \sim 0.8-9 \times 10^{15} M_\odot$).

A large statistical sample of uniformly selected galaxy clusters at $z > 1$ can provide an ideal testbed for star formation in cluster cores and examining the role of environment in regulating star formation. The stellar-mass-selected IRAC Shallow Cluster Survey (ISCS; Eisenhardt et al. 2008) includes more than 20 spectroscopically confirmed clusters at $z > 1$ (Stanford et al. 2005; Brodwin et al. 2006, 2011; Elston et al. 2006; Eisenhardt et al. 2008; Brodwin et al. 2013). We observed 18 of these clusters with the Hubble Space Telescope’s Wide Field Camera 3 (HST/WFPC3) grism, which allows the spectral identification of Hα emission for all objects in the dense cores of these clusters.

We present the ISCS in Section 2, including all relevant data to this work, and the data reduction and Hα measurements in Section 3 and Section 4, respectively. We present the physical implications of the Hα SFRs in Section 5. We use a Chabrier (2003) initial mass function (IMF) and a WMAP7+BAO+H0/ΛCDM cosmology (Komatsu et al. 2011): $\Omega_M = 0.272$, $\Omega_\Lambda = 0.728$, and $H_0 = 70.4 \text{ km s}^{-1} \text{ Mpc}^{-1}$. 
2. IRAC SHALLOW CLUSTER SURVEY

2.1. Survey

The ISCS identified cluster candidates over an area of 7.25 deg$^2$ in the Bo"otes field of the NOAO Deep Wide-Field Survey (NDWFS; Jannuzi & Dey 1999). The clusters were identified as 3-D spatial overdensities (R.A., decl., and photometric redshift) by using accurate optical/IR photometric redshifts (Brodwin et al. 2006) calculated for the 4.5 μm flux-limited (8.8 μJy at 5σ) catalog of the IRAC Shallow Survey (ISS; Eisenhardt et al. 2004). The ISCS compiled a catalog of over 300 cluster candidates spanning 0.1 < z < 2, including more than 100 at z > 1. More than 20 clusters at 1 < z < 1.5 have been spectroscopically confirmed to date (Stanford et al. 2005; Brodwin et al. 2006, 2011; Elston et al. 2006; Eisenhardt et al. 2008; Brodwin et al. 2013). A variety of mass proxies, including X-ray luminosity and temperature, weak lensing, and near-IR (NIR) luminosity, have been measured for a subset of the ISCS clusters (Eisenhardt et al. 2008; Brodwin et al. 2011; Jee et al. 2011). These indicate masses in the range of $M_{200} \sim (1-5) \times 10^{14} M_\odot$, consistent with the mean mass obtained by comparing the clustering of the ISCS cluster sample with N-body simulations (Brodwin et al. 2007).

2.2. Optical/Near-IR/IRAC Imaging

Optical data from the NDWFS (BRI; Jannuzi & Dey 1999) are available for all ISCS clusters. Aperture-corrected 4′′ fluxes were used to match the larger point-spread functions (PSFs) of the Spitzer/IRAC photometry (see Brodwin et al. 2006 for more details). Recently, we obtained NIR data from the NOAO Extremely Wide-Field Infrared Imager in J, H, and Ks that cover all of the NDWFS.

The Spitzer Deep, Wide-Field Survey (SDWFS; Ashby et al. 2009) increased the ISS depth by a factor of four in exposure time. Combined with PSF-matched NDWFS optical catalogs, these data were used to compute new photometric redshifts for the full 4.5 μm flux-limited SDWFS sample (5.3 μJy at 5σ).

2.3. HST Spectroscopy/Imaging

Both high-resolution NIR imaging and NIR slitless spectroscopy (GO proposal ID 11597) were obtained for 18 z > 1 clusters in the ISCS sample by using the HST WFC3 (Kimble et al. 2008). The program targeted the 18 high-redshift clusters with the G141 grism, which has a throughput greater than 10% in the range of 1.08–1.69 μm and a resolution of 93 Å, sufficient to securely identify cluster members with a typical redshift accuracy of $\sigma_z \approx 0.01$. The total integration for each target with the grism was 2011s and comprised four individual dithered exposures. Accompanying each dithered grism exposure was a 103s direct image with the F160W filter, which was used for source identification and wavelength calibration of the spectra. The field of view (FoV) for both the grism and the direct image is 136′′ × 123′′ (≈1.1 Mpc × 1.0 Mpc at z = 1). Five of the 18 targets have multiple visits because of the fact that the initial pointings missed the cluster centers by 30′′–80′′. Redshifts were obtained for all pointings, but for uniformity, the analysis that follows only uses the pointing closest to the cluster center.

A variety of other programs (GO proposal IDs 10496, 11002, 11663) provided optical data for a subset of the clusters with the Advanced Camera for Surveys (Ford et al. 1998) and Wide Field Planetary Camera 2 (Holtzman et al. 1995) in filters F775W, F850LP, and F814W. Pseudo-color images (F775W+F850LP+F160W) for four clusters are shown in Figure 1.

3. HST DATA REDUCTION

The data reduction process starts with the calibration of the raw images, both grism and direct. This was done automatically by the HST Data Archive, which runs CALWF3$^{10}$ using the latest reference files. The program wF3ir orchestrates the calibration process, which flags bad pixels, measures and subtracts the bias, corrects for nonlinearity, flags saturated pixels, subtracts the dark image, calculates the flux conversion, converts data from counts to counts per second, flat-fields the image, and calculates the gain conversion. This process is the same for both the direct images and the grism images, with the exception of the flat fielding step. The grism images are flat fielded at a later stage using the aXe$^{11}$ software and a master sky flat.

In slitless spectroscopy, a direct image is a necessary companion to the grism image in order to calibrate wavelength and properly identify and extract spectra. The positions of objects detected in the direct image are used to establish the location of the corresponding spectra in the grism image. Also, the size of the objects detected in the direct image are used to define the size of the box used for extraction. It is therefore necessary to make a master catalog of sources detected in the direct image to be used later in the spectral extraction process.

The direct images were reduced using MultiDrizzle software (Fruchter et al. 2009), and the resulting distortion-corrected, cosmic-ray rejected, coadded image was run through SExtractor (Bertin & Arnouts 1996) to produce a master catalog. We use a detection threshold of 3.0σ and a detection minimum area of 6 pixels. The catalog included all sources from the SExtractor extraction except for objects on the edges (±10 pixels). The positions of the objects were then projected back to each individual direct image. This is done because the two-dimensional (2D) spectra are extracted from individual grism images and then coadded.

After the master catalog was created from the reduced direct image, we reduced the grism image by using the program aXe (version 2.1). The steps used to extract spectra are very similar to that found in WFC3 Grism Cookbook.$^{12}$ The grism reduction process begins with the task AXEprep, which checks the units and the direct images and the grism images, with the exception of the flat fielding step. The grism images are flat fielded at a later stage using the aXe software and a master sky flat.

At this step, the individual grism images were ready for 2D spectral extraction. The extraction process was performed using the task AXECORE, which defines the extraction geometry, flat-fields the region containing spectral information for each source, and determines the contamination from overlapping spectra. The extraction geometry for our program is linked to the object’s shape in the direct image in order to optimize the extraction of each spectrum. We used a variable extraction width (±4 times the projected width of the source in the direction perpendicular to the spectrum trace) and an extraction direction in the direction

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10 http://www.stsci.edu/hst/wfc3/documents/handbooks/
11 http://axe.stsci.edu/
12 http://www.stsci.edu/hst/wfc3/analysis/grism_obscookbook.html
13 http://www.stsci.edu/hst/wfc3/analysis/grism_obs/calibrations/wfc3_g141.html
of the dispersion with a tilt parallel to the orientation of the object (option 3 in Section 2.4 of Kümmel et al. 2009).

Overlapping spectra are a significant issue in slitless spectroscopy. When more than one spectrum contributes to the flux in a single pixel, we define that as contamination. Contamination can occur in spatial or dispersion directions and can come from other dispersed orders of objects that are not the target being extracted. To estimate the contamination for each object, we used a Gaussian emission model (Kümmel et al. 2009) that uses the broadband magnitude from the direct image and the size of the object to model a 2D Gaussian emission spectrum centered on the central wavelength of the filter in the direct image. This is done for all objects to create a contamination map. The contamination map is extracted using the same geometry defined in the science extraction so that in a later step the contamination can be subtracted off in the one-dimensional (1D) spectrum space.

The extraction process is run on each individual grism image, producing a 2D extracted spectrum for each object in each image. The 2D extracted spectra for a common object are run through DRZPREP and AXEDRIZZLE to reject cosmic rays and coadd the spectra to produce a higher S/N 2D spectrum (Kümmel et al. 2004, 2005). The drizzle software, which properly handles weights and produces a deep 2D grism spectrum for 1D extraction, is the standard software for combining HST images (Fruchter et al. 2009). We use an optimal extraction method, discussed in Kümmel et al. (2008), which employs a weighting scheme based on the Gaussian emission models discussed earlier. The output of AXEDRIZZLE is a coadded 2D spectrum as well as an optimally extracted 1D spectrum that includes flux, error on the flux, and contamination in units of flux.

The final step in the extraction process is the creation of a webpage that combines the 2D grism images with the

![Figure 1. HST pseudo-color images (F775W+F850LP+F160W) for four of the clusters studied in this work. The images are ∼90′ × 90′ on a side, which is roughly 750 kpc × 750 kpc for these redshifts. The images are centered on the clusters, and the white dashed circle represents a 200 kpc radius, the size of the quenching radius discussed in Bauer et al. (2011) and Grützbauch et al. (2012) for a massive galaxy cluster XMMU J2235.3-2557 at z = 1.39 (∼9×10^{14} M_⊙ yr^{-1}). Red circles mark Hα emitting cluster members, while green squares signify Hα emitting field galaxies.](image)
1D extracted spectra in a visually useful format. The program aXe2web\textsuperscript{14} uses an input catalog and the aXe output files to create a webpage summary of the full reduction. Each object is displayed on a separate row with the magnitude of the object, $X$ and $Y$ positions, the right ascension and declination, a direct image cutout, a grism image cutout, and a 1D spectrum in counts and flux. This webpage format of the spectral extractions provides an easy way to view the summary of the reductions for quality control as well as further science purposes such as emission line identification.

4. MEASUREMENTS

Using the webpage format of the grism reductions from aXe2web, emission lines in the 1D extracted spectra were identified by eye and inspected in detail. The strongest emission lines identified in the 1D extracted spectra were assumed to be H$_\alpha$, O$_{\text{III}}$, or O$_{\text{II}}$. Other commonly detected emission lines include H$_\beta$ and S$_{\text{II}}$. If only a single emission line was identified in a spectrum, then it was assumed to be H$_\alpha$. A redshift quality scale was used to quantify the robustness of the measurement. A spectrum exhibiting a single feature was given a quality value of $Q = C$, while a spectrum showing two features consistent with the same redshift was assigned a quality value of $Q = B$, and a spectrum with three or more features indicating a single redshift was denoted with a quality value of $Q = A$. Examples of all three quality redshifts are included in Figure 2. Only robust redshifts, $Q = A$ or $Q = B$, were included in the SFR analysis.

Emission lines detected as H$_\alpha$ were run through a custom program to measure both the line flux and equivalent width (EW). A fourth order polynomial was fit to the continuum, excluding regions of emission. A Gaussian (wavelength constrained to the identified peak $\pm 50$ Å, width constrained to the spatial extent of the object $\pm 23$ Å, and height unconstrained) was fit to the continuum-subtracted emission line to both measure the flux and the EW. Errors for both the flux measurement and the EW were estimated from the 16th and 84th percentiles of 1000 realizations of the data assuming Gaussian errors. Contamination from overlapping objects is subtracted off prior to the continuum fit, and for $\sim 10\%$ of our sources the estimated contamination was $> 20\%$ in the continuum around H$_\alpha$. These sources are still included in our sample, and the rejection of these does not affect our results.

A finite width is used in the extraction of the 2D grism spectra, and we expect some flux to be lost because of this. Employing the software aXeSim,\textsuperscript{15} we used template emission line spectra with known H$_\alpha$ and N$_{\text{II}}$ fluxes to estimate the flux lost because of our finite extraction width. A high-resolution emission template was used with constant flux density, $f_\lambda$, and a constant strength of H$_\alpha$+[N$_{\text{II}}$] emission relative to the continuum. Twenty-five different template spectra with magnitudes ranging from 19 to 24 AB, which determined the continuum flux level and line flux of our template galaxy, were used as input for aXeSim (all templates had the same H$_\alpha$+[N$_{\text{II}}$] EW and H$_\alpha$ flux ranged from $4 \times 10^{-17}$ erg cm$^{-2}$ s$^{-1}$ to $4 \times 10^{-15}$ erg cm$^{-2}$ s$^{-1}$). The program aXeSim uses a master catalog and template spectra as input to create a simulated direct image and grism image from which spectra can be extracted. The objects simulated were aligned in a vertical row with sizes and orientations that were representative of our galaxies, sampled directly from our catalogs, and all placed at $z = 1$. The simulated spectra were extracted using the same method described above and run through the line flux

\textsuperscript{14} http://axe.stsci.edu/axe2web.html#ref_1

\textsuperscript{15} http://axe.stsci.edu/axesim/
measurement program. We found that 91% ± 3% of the flux of Hα was recovered (and this was constant across all Hα input fluxes), with much of the loss due to the extraction aperture size and not the fitting method. We apply a correction factor to our Hα measurements to account for this flux loss in the extraction process.

Using the aXeSim software, we also simulated grism images to estimate the depth of our observations. We simulated images with the same exposure time, object positions, and magnitude distributions of some of our clusters. All sources were given the same redshift of $z = 1$. The simulated spectra were extracted using the same method as our observations, and redshifts were identified and classified in a similar manner. The 50% completeness limit (or recovery rate) in flux, $\sim 1 \times 10^{-16}$ erg cm$^{-2}$ s$^{-1}$, was determined as the flux level at which 50% of the simulated sources would have been included in our sample. This was based on robust redshifts of our simulated spectra and was converted into an SFR as shown below. The depth of our observations for different redshifts depends on the G141 wavelength throughput curve$^{16}$ as Hα falls at different wavelengths across the grism, and for different clusters the depth also depends on the background level of our grism exposures. We extrapolated our simulation depth to each individual cluster (see Figure 3) by multiplying the 50% completeness limit of the simulation by two separate factors: the square root of the background level normalized to the simulated background level and the throughput of the G141 grism at $\lambda = 6563 \times (1+z_{\text{cluster}})$ Å normalized by the throughput of the G141 grism at 13126 Å (Hα at $z = 1$).

4.1. AGN Rejection

Hα emission can be due to high rates of star formation, active galactic nucleus (AGN) activity, or a combination of the two. Since typical diagnostic emission lines (e.g., Hα and [NII]) are blended at the WFC3 grism resolution, we used X-ray observations from XBoötes (Murray et al. 2005; Kentner et al. 2005) and deeper X-ray data centered on 13 of the clusters (Martini et al. 2013) combined with the empirical mid-IR criteria from Stern et al. (2005) to distinguish AGNs from star-forming galaxies. X-ray AGNs were identified by using a simple positional match in catalog space and a matching radius of 2″. Also, objects matched to SDWFS catalogs with S/N $\geq$ 5 in all four IRAC bands that fell in the Stern et al. (2005) AGN wedge were deemed AGNs. There were 27 sources (12 in the field and 15 in the clusters) satisfying either of these AGN criteria with $1.0 < z < 1.5$, and they were removed from this star formation analysis. A more in-depth study of the AGN for these galaxy clusters was conducted by Martini et al. (2013), who found evidence that the cluster AGN population has evolved more rapidly than the field population from $z \sim 1.5$ to the present.

4.2. Redshifts

A total of 18 clusters, listed in Table 1, were observed with the WFC3 grism. Redshifts were assigned for all emission-line objects, both cluster members and interloping field galaxies, and were determined solely from grism spectroscopy as the average redshift of multiple features (if present) or the redshift of just a single feature. Only galaxies with robust redshifts, $Q = A$ or $Q = B$, were used in the star formation analysis of this paper. The resolution of the G141 grism allows a redshift identification to a precision of $\sigma_z = 0.01$. These clusters have 5–20 or more total spectroscopic members from both this work and Keck spectroscopy (see Brodwin et al. 2013 for summary). Because of the limited number of members and accuracy of the grism redshifts, we defined an Hα emitting galaxy as a cluster member if $-0.03 < z - \langle z_{\text{cluster}} \rangle < 0.03$ (see Figure 4), while all other Hα emitters with $1.0 < z < 1.5$ were considered field galaxies. Note that below $z \sim 1.2$, galaxies are less likely to exhibit two strong emission features necessary for a robust redshift (see Figure 4). This bias is not significant to our results, as when we restrict ourselves to $z > 1.2$ or include $Q = C$ sources the general trends do not change (although they are at a lower significance because of the sample size or field/cluster confusion, respectively).

Hα emitters were identified for all 18 clusters although evidence for 2 of the clusters suggests that they are actually projected structures and not one bound configuration (ISCS J1429.2+3425 and ISCS J1427.9+3430), and they are therefore not included in the following star formation analysis. The confirmation of a new cluster is included in this work, ISCS J1437.0+3459 at $z = 1.394$. The cluster includes six Hα emitters and meets the criteria of a spectroscopically confirmed cluster defined in Eisenhardt et al. (2008), which holds that a cluster is confirmed if there are at least five cluster members within a radius of 2 Mpc whose spectroscopic redshifts match to within $\pm 2000(1 + z_{\text{spec}})$ km s$^{-1}$.

A complete list of all redshifts from the grism observations are presented in Table 2.

4.3. Stellar Masses

We estimate stellar masses for the Hα emitters in our sample by using iSEDfit (Moustakas et al. 2013), a Bayesian spectral energy distribution (SED) fitting code that uses population synthesis models to infer the physical properties of a galaxy.

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16 http://www.stsci.edu/hst/wfc3/documents/handbooks/currentIHB/c08_slitless4.html
Figure 4. Left: Histogram of the redshift distribution for all identified emission line galaxies in red and robust redshifts in blue (Q = A or Q = B). Right: Histogram of the redshift distribution for all cluster fields shifted to the cluster redshift. Hα emitters enclosed by the vertical black dashed lines are defined as cluster members (−0.03 < z − ⟨z⟩ < 0.03), while all other Hα emitters are considered part of the field population.

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

Table 1

| ISCS WFC3 Grism High-redshift Cluster Sample |
|---------------------------------------------|
| ID | R.A. (J2000) | Decl. (J2000) | ⟨zsp⟩ | N_{Hα} | N_{spec} | Reference |
|----|-------------|--------------|-------|--------|---------|-----------|
| ISCS J1429.2+3357 | 14:29:15.16 | 33:57:08.5 | 1.058 | 1 | 8 | Eisenhardt et al. (2008) |
| ISCS J1432.4+3332 | 14:32:29.18 | 33:32:36.0 | 1.113 | 2 | 26 | Elston et al. (2006); Eisenhardt et al. (2008) |
| ISCS J1426.1+3403 | 14:26:29.51 | 34:03:41.1 | 1.135 | 2 | 12 | Eisenhardt et al. (2008) |
| ISCS J1429.2+3425 | 14:29:15.16 | 34:25:46.4 | 1.161/1.203 | 0 | 6/6 | This work |
| ISCS J1426.5+3339 | 14:26:30.42 | 33:39:33.2 | 1.164 | 5 | 14 | Eisenhardt et al. (2008) |
| ISCS J1427.9+3430 | 14:27:54.88 | 34:30:16.3 | 1.235 | 0 | 4 | This work |
| ISCS J1434.5+3427 | 14:34:30.44 | 34:27:12.3 | 1.238 | 6 | 19 | Elston et al. (2006) |
| ISCS J1429.2+3437 | 14:29:18.51 | 34:27:38.8 | 1.262 | 9 | 18 | Eisenhardt et al. (2008) |
| ISCS J1432.6+3436 | 14:32:38.38 | 34:36:49.0 | 1.260 | 4 | 12 | Eisenhardt et al. (2008) |
| ISCS J1425.3+3428 | 14:25:19.33 | 34:28:38.2 | 1.350 | 7 | 14 | This work |
| ISCS J1434.7+3519 | 14:34:46.33 | 35:19:33.5 | 1.374 | 7 | 10 | Eisenhardt et al. (2008) |
| ISCS J1433.8+3432 | 14:33:51.14 | 33:25:51.1 | 1.376 | 3 | 6 | This work |
| ISCS J1437.0+3459 | 14:37:00.07 | 34:59:38.8 | 1.394 | 5 | 6 | This work |
| ISCS J1432.3+3255 | 14:32:18.31 | 32:53:07.8 | 1.396 | 6 | 10 | This work |
| ISCS J1425.3+3250 | 14:25:18.50 | 32:50:40.5 | 1.400 | 3 | 7 | This work |
| ISCS J1438.1+3414 | 14:38:08.71 | 34:14:19.2 | 1.413 | 6 | 16 | Stanford et al. (2005); Eisenhardt et al. (2008) |
| ISCS J1431.1+3459 | 14:31:08.06 | 34:59:43.3 | 1.463 | 3 | 6 | This work |
| ISCS J1432.4+3250 | 14:32:24.16 | 32:50:03.7 | 1.487 | 3 | 11 | Brodwin et al. (2011) |

Notes. * Number of Hα emitting members used in this analysis, which requires "good" stellar masses (see Section 4.3).
### Table 2
WFC3 Grism Spectroscopic Redshifts

| Cluster ID       | Name                     | R.A. (J2000) | Decl. (J2000) | $z$  | Quality | Flux$_{\alpha}$ $^{a}$ (erg s$^{-1}$ cm$^{-2}$) | Flux$_{\alpha}$ $^{b}$ (erg s$^{-1}$ cm$^{-2}$) | EW$_{\alpha}$ (Å) | EW$_{\alpha}$ (Å) | log $M_*$ (M$_\odot$) | AGN |
|------------------|--------------------------|--------------|--------------|------|---------|-----------------------------------------------|-----------------------------------------------|-------------------|-------------------|-----------------------|-----|
| ISCS J1426.5+3339 J142626.1+333827 | 14:26:26.09 | 33:38:27.6 | 1.170 | B   | 79.1 | 5.3 | 843 | 81 | 10.8 | ... |
| ISCS J1426.5+3339 J142633.8+333844 | 14:26:33.84 | 33:38:44.4 | 1.138 | B   | 8.7 | 2.0 | 260 | 71 | 9.9 | ... |
| ISCS J1426.5+3339 J142633.9+333915 | 14:26:33.87 | 33:39:15.8 | 1.173 | B   | 6.5 | 1.9 | 133 | 45 | 9.5 | ... |
| ISCS J1426.5+3339 J142632.7+333922 | 14:26:32.68 | 33:39:22.0 | 1.165 | B   | 6.6 | 1.7 | 116 | 32 | 10.1 | ... |
| ISCS J1426.5+3339 J142631.8+333914 | 14:26:31.75 | 33:39:14.8 | 1.167 | B   | 9.6 | 3.0 | 109 | 34 | 10.8 | ... |
| ISCS J1426.5+3339 J142629.0+333941 | 14:26:29.04 | 33:39:41.0 | 1.165 | B   | 12.3 | 2.6 | 111 | 23 | 9.6 | ... |
| ISCS J1426.5+3339 J142626.1+333826 | 14:26:26.12 | 33:38:26.8 | 1.170 | B   | 83.7 | 4.8 | 439 | 34 | 10.8 | ... |
| ISCS J1426.5+3339 J142629.5+333912 | 14:26:29.52 | 33:39:12.0 | 1.158 | C   | 15.3 | 2.6 | 264 | 53 | 10.0 | ... |
| ISCS J1426.5+3339 J142628.3+333909 | 14:26:28.25 | 33:39:09.1 | 1.178 | C   | 7.0 | 2.4 | 83 | 28 | 10.5 | ... |
| ISCS J1426.5+3339 J142627.5+333912 | 14:26:27.52 | 33:39:12.4 | 1.145 | C   | 18.3 | 3.5 | 113 | 21 | 10.9 | ... |

**Notes.**

$^a$ H$_{\alpha}$+[N II].

$^b$ Observed for H$_{\alpha}$+[N II].

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)
the assumed stellar population synthesis models as well as the assumed priors, we use a stellar mass error of 0.3 dex for all masses.

4.4. Star-formation Rates

SFR is directly proportional to Hα line luminosity (Kennicutt 1998) as this recombination line is sensitive to the most massive stars (>10 M⊙) whose lifetimes are quite short (<20 Myr). This relation (shown in Equation (1)) assumes continuous star formation, Case B recombination at T_e = 10^4 K, and is adjusted by a multiplicative factor of 0.64 to correct for a Chabrier IMF (Chabrier 2003).

SFRtot = 5.0 × 10^{-42} × L_{Hα} × 10^{0.4×A_{Hα}} = SFR_{Hα} × 10^{0.4×A_{Hα}}

The last term in Equation (1) is used to correct for attenuation due to dust (A_{Hα}). We use the empirical relation of Garn & Best (2010) and a Calzetti extinction law (Calzetti et al. 2000), which relates dust attenuation to stellar mass (see Equation (2), where M = log M*/10^{10} M⊙).

\[ A_{Hα} = 0.91 + 0.77M + 0.11M^2 - 0.09M^3 \]  

This relation was calculated with the same IMF used in our analysis and seems to hold out to z ~ 1.5 (Sobral et al. 2012).

The Hα line luminosity is calculated with the standard formula (see Equation (3)), where d_L is the luminosity distance for our adopted cosmology and F_{Hα+[NII]} is what is measured.

\[ L_{Hα} = 4πd_L^2 F_{Hα} \]  

\[ F_{Hα} = F_{Hα+[NII]} × \frac{1}{1 + [NII]/Hα} \]

The spectral resolution of the G141 grism is 93 Å (FWHM ~ 2 pixels), which is sufficient to securely identify cluster members with a typical redshift accuracy of σ_z ~ 0.01 but blends Hα and [NII]λ6584,6584 emission. The ratio of [NII] to Hα (specifically, [NII]λ6584/Hα) is commonly used as an indirect gas-phase metallicity indicator (e.g., Storchi-Bergmann et al. 1994; Denicolo et al. 2002; Maiolino et al. 2008). Recently, a tight relation, known as the fundamental metallicity relation (FMR), between stellar mass, SFR, and metallicity was observed both locally and at higher redshift (e.g., Mannucci et al. 2010, 2011; Belli et al. 2013; Yuan et al. 2013). We can use this tight relation to infer the metallicities of our galaxies and convert those metallicities into an [NII]λ6584-to-Hα ratio. Equations (5) and (6) are from Mannucci et al. (2011) where M = log M/10^{10} M⊙ and S = log SFR, who measured the FMR locally, but the relation seems to hold out to z ~ 3 (e.g., Belli et al. 2013). Stellar masses and SFRs used in Mannucci et al. (2010, 2011) were calculated with the same IMF and SFR indicator used in this analysis.

\[ 12 + \log(O/H) = 8.90 + 0.37M - 0.14S - 0.19M^2 + 0.12M S - 0.54S^2 \quad \text{(for } 10^M - 0.32S > 9.5) \]

\[ 12 + \log(O/H) = 8.93 + 0.51 × (10^M - 0.32S - 10) \quad \text{(for } 10^M - 0.32S \leq 9.5) \]

The metallicities used in Mannucci et al. (2011) were empirically calibrated from Maiolino et al. (2008). We can convert the metallicity from Equations (5) and (6) into a ratio of [NII]/Hα by using a relation found in Maiolino et al. (2008) (shown in Equation (7), where T = (12 + log(O/H)) − 8.69).

\[ \log ([NII]/Hα) = -0.7732 + 1.2357T - 0.2811T^2 - 0.7201T^3 - 0.3330T^4 \]  

Assuming a constant ratio of 3–1 for [NII]λ6584/[NII]λ6548 and Equation (7), we can calculate [NII]/Hα and substitute it back into Equation (4). However, there is a complication; Equations (1) and (7) are coupled through Equations (3)–(6). To measure the SFR, one must know the ratio of [NII] to Hα, but to know the ratio of [NII] to Hα one must know the SFR. We solve these equations through iteration with an initial guess of [NII]/Hα = 0.2, and solutions typically converge in less than five iterations.

We assume the calculation above results in an error of 50% for the total SFR and is dominated by the uncertainty in the extinction correction.

5. RESULTS

5.1. Stacking

A key aspect of this analysis is our correction of the Hα unobscured SFR to the total SFR, assuming Equation (2). The individual grism spectra are too noisy to accurately measure the Balmer decrement (specifically, the intensity ratio of Hα to Hβ). Instead, to verify our approach, we performed a median stacking analysis of the 1D extracted spectra to investigate the average reddening properties of the star-forming galaxies. By measuring the ratio of Hα to Hβ in a median stacked spectrum, we are able to estimate the extinction due to dust for the median object in the sample.

Generating a median composite spectra requires rebinning the spectra to the rest frame, scaling the spectra, and stacking the spectra into a final composite using the median value at each rebinned wavelength (see Francis et al. 1994 for a detailed discussion of stacking). We rebinned each spectrum to 18 Å, approximately the pixel size of the observed spectra shifted to the rest frame, and scaled each spectrum by the median value of the continuum, excluding regions of expected emission. It is important to remember that the median spectrum preserves the relative fluxes of emission features.

Assuming a Calzetti et al. (2000) extinction law and an assumed ratio (Hα/Hβ) = 2.86 from the Case B recombination (Storey & Hummer 1995), we measured the extinction of the median stacked spectrum of star-forming galaxies at z > 1.24, the redshift when Hβ enters the wavelength coverage of the G141 grism. We performed this stacking 1000 times using bootstrap re-sampling with replacement and found the extinction to be E(B-V) = 0.39 ± 0.07 (A_{Hα} = 1.25 ± 0.18). The upper and lower ranges were estimated with the 16th and 84th percentiles of the 1000 bootstrap realizations. This is consistent with the calculated median value and range (16th and 84th percentiles), A_{Hα} = 1.09 ± 0.04, from Equation (2).

We also fit the spectrum by using a linear continuum model and eight Gaussians (Hβ, [O III]λλ4959,5007, Hα, [N II]λ6548, 6584, and [S II]λλ6717, 6731). We assumed fixed rest frame wavelengths of the emission lines and further constrained the ratios of the [O III] and [N II] line doublets to be 1/3 as well as having the same full width at half maximum. The ratio of [N II] to Hα is degenerate in the fit but ranges from 0 to 0.20 (95% interval) with a median value of [N II]/Hα = 0.08. This is consistent with the median value and range (95% interval)
of our calculation from Equation (7), \([\text{[N}\,\text{II}]}/\text{H}\alpha = 0.04_{-0.00}^{+0.20}\) and measurements in the literature for lensed galaxies at 0.9 < \(z < 1.5\) ([\text{[N}\,\text{II}]}/\text{H}\alpha = 0.03–0.17; Wuyts et al. 2012) and more massive galaxies at \(z \sim 1.2\) (median [\text{[N}\,\text{II}]}/\text{H}\alpha = 0.18; Queyrel et al. 2012). Furthermore, the common emission line diagnostic of \(\text{H}\beta/\text{[O}\,\text{II}]\lambda5007\) versus \([\text{N}\,\text{II}]\lambda6584/\text{H}\alpha\) (e.g., Baldwin et al. 1981) suggests that the median stacked spectrum is that of a star-forming galaxy and not an AGN.

Locally, extinction is positively correlated with stellar mass (e.g., Garn & Best 2010; Zahid et al. 2013), and this correlation is even seen at higher redshift (\(z \sim 1.47\); Sobral et al. 2012). We investigate if extinction is correlated in our sample of star-forming galaxies, as we assumed. We split our sample into three different stellar mass bins (9.0 \(\leq \log M_\ast \leq 10.0\), 10.0 \(\leq \log M_\ast \leq 10.5\), and 10.5 \(\leq \log M_\ast \leq 11.5\)) for the cluster \(\text{H}\alpha\) emitters, field \(\text{H}\alpha\) emitters, and all \(\text{H}\alpha\) emitters at \(z > 1.24\) (the redshift when \(\text{H}\beta\) enters the wavelength coverage; see Figure 5). We find that there is indeed higher extinction for more massive star-forming galaxies, which is consistent with our assumed relation in Equation (2); however, because of low number statistics and noisy spectra, we cannot constrain the correlation well. Also, as seen in Patel et al. (2011), we find that for a fixed stellar mass, star-forming galaxies in the field have higher extinction on average than star-forming galaxies in clusters, albeit within the error bars. If there is less dust per stellar mass in cluster star-forming galaxies than field star-forming galaxies, then there may also be less gas per stellar mass for new star formation.

### 5.2. Star Formation Analysis

Figure 6 shows the sum of the total \(\text{H}\alpha\) SFR (restricted to galaxies above the 50% completeness limit at \(z = 1.5\) from Figure 3, \(\text{SFR}_{\text{H}\alpha} > 4 M_\odot \text{ yr}^{-1}\)) within a projected radius of 500 kpc (roughly the FoV of our observations) for each of the 16 clusters in this work. There is a large scatter from cluster to cluster with a range of enclosed SFRs from 0 to 200 \(M_\odot \text{ yr}^{-1}\) and little evidence for redshift evolution given the spread. For a subset of our clusters with strong lensing cluster masses (six clusters with \(M_{200} \sim (2.5–5) \times 10^{14} M_\odot\); Jee et al. 2011), we found that the scatter in the enclosed SFR from cluster to cluster remains when normalized by cluster mass. A larger sample with
The Astrophysical Journal, 779:137 (13pp), 2013 December 20

Zeimann et al.

Figure 6. Sum of the total (extinction-corrected) SFR within 500 kpc of our \( z > 1 \) clusters for galaxies with \( SFR_{\text{H}\alpha} > 4 \, M_{\odot} \, \text{yr}^{-1} \) (50% completeness limit at \( z = 1.5 \) for uncorrected H\( \alpha \) SFR, see Figure 3). Blue diamonds indicate clusters that have star formation within the inner 200 kpc, while red circles are those that do not. There is a wide spread in total SFR within a 500 kpc radius and little evolution evident with redshift given the spread. The error bars were estimated with the 16th and 84th percentiles of the 1000 bootstrap realizations. (A color version of this figure is available in the online journal.)

Figure 7. SFR vs. stellar mass. The “main sequence” of star-forming galaxies at \( z = 1.0 \) and \( z = 1.5 \) is plotted as two dashed black lines (Whitaker et al. 2012). Normalized histograms of stellar mass and SFR for both the field (blue) and cluster (red) populations are plotted at the top and right, respectively. (A color version of this figure is available in the online journal.)

The six clusters that do not show evidence of star formation within a 200 kpc radius cover the entire redshift range of our sample (1.05 < \( z < 1.49 \)). Our definition of a cluster member (\( −0.03 < z − \langle z_{\text{cluster}} \rangle < 0.03 \)) allows for a large volume along the line of sight and may lead to project effects. When we used a more restrictive cut on a cluster member (spectroscopic redshifts match to within ±2000(1 + \( \langle z_{\text{cluster}} \rangle \) \, km \, s\(^{-1} \)), we still found that 9 of 16 clusters have significant levels of unobscured star formation within a 200-kpc radius.

Figure 7 plots SFR versus stellar mass for both cluster and field star-forming galaxies. We assumed an inherent correlation between stellar mass and SFR in Equations (1) and (2), which is a reasonable assumption since SFR and stellar mass form a “main sequence” of normal star-forming galaxies (Noeske et al. 2007). At 1.0 < \( z < 1.5 \), the distribution of star-forming galaxies in clusters are similar to that of the field and lie on the SFR-mass relation found in the literature (Whitaker et al. 2012), confirming that our extinction correction for total SFR is statistically consistent with other works.

We also investigated the SFRs of cluster galaxies with respect to their cluster centric radius. The top panel of Figure 8 displays the SFR density of cluster galaxies at two different redshifts (1.00 < \( z < 1.37 \) and 1.37 < \( z < 1.50 \), which splits the cluster sample in half). There is a significant rise in the SFR density from the outer core to the inner core; however, there is no apparent redshift evolution in the relation. The calculation for SFR density was corrected on a cluster-to-cluster basis for the grism FoV, which typically was \( \sim 1.1 \, \text{Mpc} \times 0.9 \, \text{Mpc} \) but varied as a function of redshift, and for some clusters there were small offsets between the center of the observation and the center of the cluster. Note that the stellar masses of the inner core are higher than that of the outer core and may be the cause of the trend. Plotted in the bottom panel of Figure 8 is the median sSFR for the same two redshift bins as a function of cluster centric radius. The median sSFR for both redshifts is roughly an order of magnitude higher than local star-forming galaxies in clusters (Wetzel et al. 2012). We found a flat trend in the median sSFR.
Figure 8. Top panel: SFR density vs. cluster centric radius in projection. Blue circles are galaxies in clusters at $1.00 < z < 1.37$, and red squares are galaxies in clusters at $1.37 < z < 1.50$, each binned by projected radius and slightly offset for clarity. The error bars were estimated with the 16th and 84th percentiles of 1000 bootstrap realizations. Bottom panel: median sSFR versus cluster centric radius in projection. The symbols are the same as the top panel. There is no evidence for a decline in sSFR for galaxies closer in projection toward the cluster center. The error bars were estimated with the 16th and 84th percentiles of 1000 bootstrap realizations. (A color version of this figure is available in the online journal.)

as a function of radius similar to what was found in Figure 10 of Muzzin et al. (2012) at $0.85 < z < 1.20$.

Brodwin et al. (2013) also studied the (s)SFRs of this sample but used the $24 \mu m$ luminous galaxies, which are more closely associated with obscured star formation and timescales on the order of $\sim$Gyr. They found a similar rise in SFR density with smaller radii, but they observed a redshift evolution that was most significant for clusters above $z > 1.37$. Their observations went out to $\sim2 \times r_{\text{virial}}$, included photometrically selected sources (photo-z’s), and were limited to starbursting galaxies ($\sim 50 M_{\odot} \text{yr}^{-1}$) with $\log_{10} M_*>10.1$ (our sample only contains nine galaxies above these two limits).

5.3. Equivalent Widths

The H$\alpha$ EW (rest frame) is proportional to the mass-to-light ratio at 6563 Å times the specific star formation rate (sSFR) and the differential extinction between the gas and stars (see Equation (8)), where $\mathcal{F}_{6563}$ is the flux density at 6563 Å, $L_{6563,\text{cor}}$ is the extinction-corrected luminosity density at 6563 Å, and $A_{6563}$ is the extinction from dust for the stellar continuum). The last term in Equation (8) was included because some studies have found that the extinction due to dust experienced by continuum star light is less than that of nebular emission lines from gas (Calzetti 2001, $A_{6563} = 0.44 \times A_{H\alpha}$). For simplicity, we assumed $A_{6563} = A_{H\alpha}$ and discuss later how a differential extinction would affect our EW measurements.

$$
EW_{H\alpha} = \frac{F_{H\alpha}}{F_{6563}} \times \frac{L_{H\alpha}}{L_{6563}} \propto \frac{\text{SFR}_{H\alpha}}{L_{6563,\text{cor}}} \frac{\text{SFR}_{H\alpha}}{M_*} \frac{M_*}{L_{6563}}
$$

The Kolmogorov–Smirnov test reveals that there is only a 0.2% chance that the two distributions are the same. This result holds if you include star-forming galaxies without “good” stellar mass estimates (see Section 4.3). There is no systematic difference in the selection of field versus cluster galaxies as they show the same magnitude distribution (F160W), were selected at the same flux limits, and were drawn from the same set of observations. The sources without “good” stellar masses ($\sim 25\%$) cover a wide range of F160W magnitudes for both the field and the cluster and are not relegated to the faint end.

Plotted in Figure 9 is the EW versus stellar mass for both field and cluster star-forming galaxies. Field star-forming galaxies, on average, have higher EWs than those in the cluster environment, and this is most noticeable for lower stellar masses ($\log M_* < 10.0$). According to the nonparametric Kolmogorov–Smirnov test, there is only a 0.2% chance that the two distributions are drawn from the same underlying parent population (the Anderson–Darling test shows there is only a 1% chance that the two distributions are the same). This result holds if you include star-forming galaxies without “good” stellar mass estimates (see Section 4.3). There is no systematic difference in the selection of field versus cluster galaxies as they show the same magnitude distribution (F160W), were selected at the same flux limits, and were drawn from the same set of observations. The sources without “good” stellar masses ($\sim 25\%$) cover a wide range of F160W magnitudes for both the field and the cluster and are not relegated to the faint end.

Starting from Equation (8), it is easy to see that EW is sensitive to differential extinction as well as the calculated [N ii]-to-H$\alpha$ ratio as it enters through the calculation of $F_{H\alpha}$. For the two distributions to be the same, cluster star-forming galaxies would have to have more extinction at a given stellar mass than the field population. From our stacking analysis in Figure 5, we see that this is not the case, and in fact, the opposite seems to be more
likely. To verify that the calculated ratio of [N\textsc{ii}] to Hα does not have a large effect on the EW measurement, we performed the same analysis for a variety of assumed constant ratios, [N\textsc{ii}]/Hα = 0.05, 0.10, and 0.20, and the results were the same. The difference in EW distributions seems to be robust and not a systematic effect.

To investigate the difference between the two EW distributions further, it is informative to look at the right side of Equation (8). The EW depends on the sSFR, mass-to-light ratio, and differential extinction. As discussed earlier, accounting for differential extinction (emission from gas is attenuated more than star light) would only make the two distributions more disparate and does not explain why they are offset. Since EW is not as dramatic for sSFR as it is for EW. The remainder of the difference may be attributed to different mass-to-light ratios for the field population compared with the cluster population. This would reflect different star formation histories for the field and cluster galaxies at fixed stellar mass.

6. CONCLUSIONS

Using the HST/WFC3 grism, we observed Hα emission in the core of 16 M_200 ~ (1−5) \times 10^{14} M_\odot galaxy clusters. The observations allowed us to identify cluster members and field galaxies at 1.0 < z < 1.5 in a consistent way with identical selection methods. Using a suite of multiwavelength data, high-resolution imaging, and grism spectroscopy, we compared the average extinctions, SFRs, and EWs of star-forming galaxies as a function of stellar mass, redshift, and environment. Our key findings are as follows.

1. We find tentative evidence that extinction is a function of stellar mass for star-forming galaxies in both the cluster and the field environment, with higher extinction values on average for the field than for the cluster. A larger sample size is needed to confirm this.
2. There is a large scatter in the SFRs of the cluster cores (<500 kpc). Also, many of the clusters (10 of 16) have high levels of star formation in the inner core (<200 kpc), which other studies have suggested to be a quenching radius for more massive systems (Grützbauch et al. 2012).
3. The Hα EWs of the field star-forming galaxies are higher than those in clusters for log M_\star \lesssim 10. The suppression of EW in the cluster environment suggests that environmental effects are still apparent to at least z = 1.5.

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