Measuring the Total Ultraviolet Light from Galaxy Clusters at $z = 0.5–1.6$: The Balance of Obscured and Unobscured Star Formation

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Received 2021 December 23; revised 2022 January 25; accepted 2022 January 31; published 2022 March 29

Abstract

Combined observations from UV to IR wavelengths are necessary to fully account for the star formation in galaxy clusters. Low-mass galaxies with $\log(M_*/M_\odot) < 10$ are typically not individually detected, particularly at higher redshifts ($z \sim 1–2$) where galaxy clusters are undergoing rapid transitions from hosting mostly active, dust-obscured star-forming galaxies to hosting quiescent, passive galaxies. To account for these undetected galaxies, we measure the total light emerging from GALEX/near-UV stacks of galaxy clusters at $z = 0.5–1.6$. Combined with existing measurements from Spitzer, WISE, and Herschel, we study the average UV through far-IR spectral energy distribution (SED) of clusters. From the SEDs, we measure the total stellar mass and amount of dust-obscured and unobscured star formation arising from all cluster-member galaxies, including the low-mass population. The relative fraction of unobscured star formation we observe in the UV is consistent with what is observed in field galaxies. There is tentative evidence for lower than expected unobscured star formation at $z = 0.5$, which may arise from redshift evolution in the low-mass quenching efficiency in clusters reported by other studies. Finally, the GALEX data place strong constraints on derived stellar-to-halo mass ratios at $z < 1$, which anticorrelate with the total halo mass, consistent with trends found from local X-ray observations of clusters. The data exhibit steeper slopes than implementations of the cluster star formation efficiency in semianalytical models.

Unified Astronomy Thesaurus concepts: Galaxy evolution (594); High-redshift galaxy clusters (207); Galaxy clusters (584); Star formation (1569)

1. Introduction

The secular properties of galaxies are a function of their local extragalactic environment. Indeed, galaxies residing in overdense clusters are distinct from the lower density “field” population. Relative to the field, $z < 1$ clusters tend to host galaxies that are more massive, redder, and have a low star formation rate (e.g., Gómez et al. 2003; Baldry et al. 2006; Peng et al. 2010)—evidence for more rapid evolution at earlier times than field galaxies. Therefore, environment plays a fundamental role in setting the evolution of galaxies. Locally, ultraviolet (UV) and optical/near-infrared (IR) observations have shown that clusters have efficiently quenched their star formation, particularly in low-mass ($\log(M_*/M_\odot) < 10$) galaxies, via hot halo starvation and/or ram pressure stripping (e.g., Boselli et al. 2011, 2014; Haines et al. 2011). At high redshifts ($z \sim 1–2$), mid- and far-IR observations have revealed a significant amount of dust-obscured star formation occurring within galaxy clusters (e.g., Brodwin et al. 2013; Alberts et al. 2016). Combined multiwavelength studies of galaxy clusters have identified $z \sim 1–2$ as a key epoch in which cluster environments transition from sites of intense star formation and supermassive black hole assembly to those dominated by quenched galaxies (Martini et al. 2013; Alberts et al. 2014; Nantais et al. 2017).

A stellar mass-complete and multiwavelength census of galaxy growth in clusters is necessary to understand the important role played by environment in shaping galaxy evolution. Optical and near-IR surveys can reach stellar mass limits of $\sim 10^9 M_\odot$ (van der Burg et al. 2018); however, such sensitivity is not yet possible at UV and IR wavelengths, where significant star formation is detected in massive cluster galaxies (Haines et al. 2011; Alberts et al. 2016). To push the study of cluster members to higher redshifts while accounting for the light from less massive and faint galaxies that typically go undetected, Alberts et al. (2021, hereafter A21) developed a “total light” stacking method whereby near- through far-IR maps of many galaxy clusters were averaged to study the total cluster spectral energy distribution (SED) from $z \sim 0.5–1.6$. They find the SED to be well fit by a star-forming galaxy template, albeit with less warm dust than found in massive star-forming galaxies (Kirkpatrick et al. 2015), and that the star formation in the average cluster from $z \sim 0.5–1.6$ is predominantly occurring within $M_*/M_\odot < 10^{10}$ galaxies. From observations of field galaxies $\sim 30\%–70\%$ of the total star formation is obscured by dust at such stellar masses (Whitaker et al. 2017); by $M_*/M_\odot \sim 10^{11}$ nearly $100\%$ of the star formation is dust-obscured. If such lower-mass galaxies contain similar amounts of dust to their field counterparts, and exhibit comparable ratios of obscured to unobscured star formation (e.g., Whitaker et al. 2017), then a significant amount of star formation could be missed by the IR observations alone.

To account for all of the star formation, we extend the A21 methodology into the UV using GALEX coverage of the same...
sample drawn from the IRAC Shallow Cluster Survey. We combine the subsequent UV through IR observations to measure the average amount of dust-obscured and unobscured star formation in clusters relative to the field. At $z < 1$, the GALEX data trace the rest-frame emission from young, massive stars and provide a good constraint on the mass-to-light ratio. This increases the constraint on total cluster stellar masses, the uncertainties on which were previously too large to distinguish between various star formation efficiency scenarios with halo mass.

This paper is organized as follows: in Section 2 we describe the GALEX/near-UV data. Section 3 summarizes our total light stacking method (A21) and notable modifications for the treatment of GALEX data. Section 4 explores the results of combined UV through IR stacked cluster spectral energy distributions and radial profiles, which we discuss in further detail in Section 5. Section 6 summarizes our work, and our most notable conclusions. In this paper, we adopt a ΛCDM cosmology with $h = 0.7$, $Ω_m = 0.3$, and $Λ = 0.7$.

2. Data

2.1. Cluster Sample

As in A21, we measure the redshifts of the cluster candidates in the Boötes field ($α = 14:32:05.7, +34:16:47.5$ J2000) from the IRAC Shallow Cluster Survey (ISCS, Eisenhardt et al. 2008). This catalog comprises 30 cluster candidates at $0.1 < z < 2$, with $≈ 100$ candidates at $z > 1$. Clusters are identified as overdensities of $4.5 \mu$m flux-selected galaxies in three-dimensional (R.A., decl., photometric redshift) space using a wavelet detection algorithm (Brodwin et al. 2013). At high redshift, more than 20 clusters from the sample have been spectroscopically confirmed (Stanford et al. 2005; Eisenhardt et al. 2008; Brodwin et al. 2006, 2011, 2013; Zeimann et al. 2013), and the rate of contamination by spurious line-of-sight associations is expected to be $≈ 10\%$ over the sample (Eisenhardt et al. 2008). From clustering measurements and halo mass ranking simulations, the median halo mass of the cluster sample is $log(M_{\text{200}}/M_\odot) \sim 13.8–13.9$ and does not change within the redshift range of our study (Brodwin et al. 2007; Lin et al. 2013; Alberts et al. 2014). The corresponding virial radius is $R_{\text{200}} \sim 1$ Mpc and this value is used throughout the remainder of this paper. We restrict our analysis to the redshift range $0.5 < z < 1.6$, with the lower bound chosen to ensure that the angular size does not change drastically with redshift and the upper bound being chosen due to the small number of clusters in the sample at $z > 1.6$. There are 232 clusters in the ISCS catalog within this redshift range. We make use of the photometric redshift catalogs presented in Alberts et al. (2016) for these clusters in our analysis.

2.2. GALEX Imaging

The Galaxy Evolution Explorer (GALEX) satellite operated between 2003 and 2013, obtaining data at near-UV (NUV, 1750–2750 Å) and far-UV (FUV, 1350–1750 Å) wavelengths. We restrict our analysis to the NUV data because (1) the FUV coverage of the Boötes field is not uniform, with exposure times only $≈ 0.005–0.05$ times that of the NUV pointings, and (2) the FUV band samples largely blueward of the Lyman limit over the redshift range considered. Thus, the usefulness of the FUV data on $z > 0.5$ cluster galaxies is limited. The Boötes field was imaged in the NUV band as part of the GALEX Deep Imaging Survey (DIS, Morrissey et al. 2007; Bianchi 2009) in 11 pointings, each consisting of a circular exposure with diameter $1′′25$. Ten of eleven tiles have exposure times between $≈ 20$ and $40$ ks, whereas the tile at the center of the Boötes field (tile NGPDS_00) has an exposure time of 145 ks. The pixel scale of the tiles is $1′′5$ per pixel. The tiles overlap from $≈ 0′′1$ to $0′′3$.

3. “Total Light” Stacking of GALEX Data

In A21, we carried out total light cluster stacking of Spitzer IRAC, Wide-field Infrared Survey Explorer (WISE), Spitzer MIPS, and Herschel SPIRE data to construct the average infrared SED for the ISCS clusters. In the present work we add to this analysis by carrying out total cluster stacking of GALEX NUV data. In this section, we briefly summarize the technique and detail the modifications made to appropriately stack GALEX data. We also describe the procedure to extract the total NUV flux and radial profile measurements from the stacked images. For a detailed description of both procedures we refer the reader to A21.

We process the GALEX images in a similar manner to that described in A21 for the WISE W1/W2 and Spitzer IRAC 3.6/4.5 μm images. This is because the measurements of both the total near-IR and total NUV fluxes from clusters suffer from similar difficulties due to individual, bright foreground sources and variable sky counts.

We obtained the raw GALEX tiles covering the Boötes field from the Space Telescope Science Institute website. The procedure to construct the “total light” stacks from these tiles consists of four steps:

1. Removal of bright contaminating sources (i.e., individually detectable non-cluster sources) from the individual tiles.
2. Subtraction of sky background from each tile (such that local sky is zero).
3. Creation of equally sized cutouts centered on each cluster to be stacked from the processed images.
4. Stacking of the cutouts by taking the pixel-wise mean/median/weighted mean.

In order to carry out the first step, we run SExtractor (Bertin & Arnouts 1996) on the individual GALEX tiles and output the segmentation map, which marks all pixels belonging to a source. We use the segmentation maps to mask pixels associated with detected sources from the calculations of pixel-wise mean/median/weighted means used to produce the final stack.

In addition to the segmentation map, we also make use of the SExtractor output catalog, which lists the sky coordinates of the detected sources. Before performing the masking of these sources, we compare this output catalog with the photometric redshift catalogs for the ISCS clusters, which gives the positions of the cluster members. We remove the cluster sources from the segmentation map to ensure that they remain unmasked.

To remove the variable sky background, we subtract GALEX-provided sky background maps. These background backgrounds are calculated using the SExtractor output catalog and the sky coordinates of the detected sources. The sky background is then calculated as the median of the pixel values within a large radial annulus, typically $> 10$ Mpc.

6 http://galex.stsci.edu/GR6/

7 We run SExtractor with DETECT_THRESH of 3.0 and DETECT_MINAREA of 3; however, by varying the detection settings, we have previously found that the stacked flux measurements are insensitive to them (A21).
maps are created using an algorithm that is optimized for the low sky counts of UV data (Morrissey et al. 2007). The sky background in these maps is calculated over scales of 192″×192″ (Morrissey et al. 2007), which at the lowest redshift we consider, z = 0.5, corresponds to 1.2 Mpc.

After processing the tiles, we create equally sized cutouts for each cluster, 27′′5 to a side. This corresponds to 10.2 (14.2) Mpc at z = 0.5 (1.6), which is enough to cover the entire cluster as well as the background for robust statistics. To stack the cutouts, we divide the clusters into four predefined redshift bins as detailed in A21: z = 0.5–0.7, 0.7–1.0, 1.0–1.3 and 1.3–1.6. The bin centers and widths balance the number of clusters in each redshift window, and ensure a minimal change in angular scale per bin. Specifically, each bin contains 40–70 clusters, each containing ∼10–30 cluster members with photometric redshifts (A21). The mean redshifts of the clusters in each bin are z = 0.57, 0.86, 1.13, and 1.44 respectively. The cutouts within a given redshift bin are compiled into a three-dimensional data cube, over which we compute a pixel-wise weighted mean to produce the final stacked image. We do not expect to see much (if any) UV emission in the stack of the highest redshift bin, given that the GALEX NUV filter lies mostly blueward of the Lyman limit at these redshifts.

The main difference between our procedure and that of A21 is the use of a weighted mean to stack the cutouts. As described in Section 2.2, the GALEX tiles covering the Boötes field vary considerably in exposure times, unlike the WISE and IRAC images. Therefore, we weight each pixel by the inverse variance of the sky noise (1/σ2_sky, where σ_sky is the standard deviation of the sigma-clipped pixel distribution for the cutout), such that all the pixels in a given cutout have the same weight. Masked pixels do not contribute to the weighted mean or to the calculation of the weight for a cutout.

To verify the robustness of our procedure, we also create “offset” stacks centered on random positions instead of the location of clusters. We create a random cutout associated with each cluster in a given stack, centered on a point 0.2°–0.4° away from the nominal cluster position, and carry out the stacking in an identical manner to that for the fiducial stacks. For simplicity, the random cutout is made from the same processed GALEX image as the cluster cutout. The magnitude of the offset from the cluster center is chosen to be large enough to ensure that the offset cutout does not include any cluster signal, but not so large that the offset cutout falls outside the processed GALEX image. None of the offset stacks exhibit detectable signal above the sky background level, suggesting that any signal in the fiducial stacks does indeed originate from the clusters and is not the result of random noise fluctuations.

3.1. Measurement of UV Flux and Radial Profiles

From each map, we perform aperture photometry using a series of circular apertures to measure the cumulative flux profile as a function of cluster-centric radius. In addition, we measure the flux in progressively larger annuli to find the radial surface brightness profiles.

We place the center of the apertures at the image center, which corresponds to the nominal cluster center. In practice, there is uncertainty in the cluster centroiding of the order of ∼15″ (10 pixels) from the 15″ pixel scale of the density maps used to select the ISCS clusters. Gonzalez et al. (2019) carry out a detailed analysis for the MaDCoWS cluster sample, which is also selected from density maps with a pixel scale of 15″, and confirm that the scatter in cluster position is ∼15″. Given that this uncertainty is small, we do not expect it to significantly affect the cumulative flux; however, there could be some effect on the differential flux profile. We investigate the effects of centroiding uncertainty in A21, and find that the overall effect on the observed radial flux profile as compared to the intrinsic radial profile is a depression in the innermost radial bins and an excess at 20″–40″.

We measure and subtract out sky signal by taking the outlier-resistant mean of the pixel values in an annular bin between 150″ and 200″ in radius. We then measure the aperture flux and surface brightness in circular and annular apertures respectively, starting at a radius of 5′/5 and with an increment of 5′/5. We choose this step size in order to directly compare our results with the near-IR radial profiles of the ISCS clusters from A21. The cumulative flux for a given radial bin is the sum of all pixel values within the aperture, while the surface brightness is the mean of all pixels within the annulus. As such, the cumulative flux is measured in units of μJy, while the differential flux is measured in units of μJy pix⁻¹.

We calculate the sigma-clipped standard deviation of the pixel distribution, again within an annulus of radius 150″–200″ and assume this to be the per-pixel uncertainty σ_sky. In addition, we calculate the uncertainty in the measured sky level σ_sky by placing 500 annular apertures at random points in the offset stack and calculating the standard deviation of the resulting distribution of mean sky values. To each measurement of the cumulative flux, made in a circular aperture containing N_circ pixels, we assign an error of σ² = N_circσ²_sky, where σ_sky is the standard deviation of the per-pixel uncertainty for the GALEX NUV filter. To each measurement of the surface brightness, made in an annulus containing N_annulus pixels, we assign an error of σ_SB = (σ²_sky + σ² rms) / N_annulus, where σ_rms is the standard deviation of the pixel values in the annular aperture.

In the two lowest redshift bins, we detect signal in the aperture-integrated GALEX/NUV photometry at ≥5σ within R = 0.5 Mpc, and at a similar significance within R = 1 Mpc, approximately the virial radius. At z ~ 1.1, we report a marginal detection of the cluster-associated UV light at 2.5σ within R = 0.5 Mpc. We do not detect any signal in the NUV stack in the highest redshift bin, as expected, given that at z > 1.3 the majority of the GALEX/NUV band falls blueward of the Lyman limit. In the third redshift bin, where the detection is marginal, we place a 3σ upper limit on the UV flux using 3σ_SB. Aperture photometry is listed in Table 1, including fluxes measured within 0.5 and 1 Mpc for the GALEX data and for the longer wavelengths stacks from A21.

4. Results

4.1. Total Cluster Flux and Spectral Energy Distributions

Using the aperture-integrated photometry, we fit the UV-to-IR SEDs of the average cluster stack at each redshift using CIGALE (Burgarella et al. 2005; Noll et al. 2009; Boquien et al. 2019), a stellar population synthesis code that assumes energy conservation in dust-reprocessing to also model the far-IR SED. In this work, we update the SED fits from A21 where we have UV detections to further constrain stellar masses and the unobscured star formation rates. Specifically, we fit both the R = 0.5 Mpc and R = 1 Mpc aperture photometry at z = 0.57 and z ~ 0.86. For the z ~ 1.1 bin, we only fit the R = 0.5 Mpc data where we report a ~2.5σ detection of UV signal (Table 1). The SED fit parameters are mostly the same as described
| Redshift | NUV [μJy] | W1 [mJy] | W2 [mJy] | I1 [mJy] | I2 [mJy] | I3 [mJy] | I4 [mJy] | MIPS 70 [mJy] | S250 [mJy] | S350 [mJy] | S500 [mJy] |
|----------|-----------|----------|----------|----------|----------|----------|----------|----------------|----------|----------|----------|
| z ~ 0.57 | 7.5 ± 1.3 | 1.13 ± 0.03 | 0.60 ± 0.03 | 1.23 ± 0.03 | 0.87 ± 0.03 | 0.74 ± 0.06 | 0.82 ± 0.07 | 7.2 ± 1.2 | 56 ± 12 | 33 ± 10 | 16.2 ± 5.9 |
| z ~ 0.86 | 5.9 ± 0.7 | 0.66 ± 0.02 | 0.43 ± 0.02 | 0.79 ± 0.02 | 0.55 ± 0.02 | 0.46 ± 0.03 | 0.37 ± 0.03 | 7.5 ± 0.9 | 52 ± 8 | 39 ± 7 | 19.8 ± 3.8 |
| z ~ 1.1 | 2.5 ± 0.9 | 0.44 ± 0.02 | 0.37 ± 0.02 | 0.51 ± 0.02 | 0.43 ± 0.02 | 0.41 ± 0.06 | 0.35 ± 0.05 | 10.0 ± 1.0 | 66 ± 11 | 58 ± 8 | 29.1 ± 5.2 |
| z ~ 1.4 | <0.38 | 0.19 ± 0.02 | 0.25 ± 0.02 | 0.18 ± 0.02 | 0.23 ± 0.02 | 0.20 ± 0.04 | 0.21 ± 0.03 | 3.9 ± 1.1 | 53 ± 12 | 50 ± 9 | 30.4 ± 6.2 |

**Table 1**

Total Cluster Light Photometry Used in SED Fits

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*The Astrophysical Journal, 928:88 (12pp), 2022 March 20 McKinney et al.*
in A21: we model the dust emission following Casey (2012) as a single-temperature graybody plus a power law spanning the mid-IR regime. We omit the W3, W4, and MIPS 24 μm stacked photometry from the SED fits because they probe the broad polycyclic aromatic hydrocarbon (PAH) features which, owing to our large redshift bin widths of Δz = 0.3, are diluted in the stacked spectrum, leading to a ∼10% systematic uncertainty on the broadband photometry (see Section 4.2 in A21). We assume a fixed dust-emissivity index of β = 1.5, a mid-IR power-law slope of α = 2, and a star formation history with short (1–5 Myr) and long (100–1000 Myr) decaying e-folding factors to model an initial period of star formation followed by a burst with an onset at later times. The boundaries on star formation history priors are expanded relative to the fits described in A21 because of the added UV photometry’s sensitivity to, among other quantities, the age of the young starburst population; however, all fits favor zero contribution from the short-burst mode (i.e., short-burst mass fractions converge to zero). The best-fit SEDs for each redshift bin are shown in Figure 1. Derived properties and their corresponding uncertainties are given in Table 2.

4.1.1. Derived Stellar Mass Estimates with NUV Data
In A21, we presented stellar mass estimates derived from the R = 1 Mpc photometry. Here we update these estimates with the new GALEX/NUV values using aperture-integrated photometry at both R = 0.5 Mpc and R = 1 Mpc. We expect to improve the uncertainties on Mₖ because the NUV data constrain recent star formation that can influence the stellar mass-to-light ratio; indeed, we report improvements at z < 1 where the UV signal is detected at >3σ. Specifically, the Mₖ uncertainties at z ∼ 0.57 and z ∼ 0.86 improved by ∼25%–40% when the UV data are included in the SED fitting of 1 Mpc aperture photometry (Table 2). In general, stellar masses measured with and without the NUV data are consistent within 1σ. Similarly, stellar masses within 0.5 Mpc and 1 Mpc are in good agreement at z < 1, suggesting that the 0.5 Mpc aperture traces most of the stellar mass at z ∼ 1.1.

4.2. The Fraction of Dust-obscured Star Formation in Clusters
From the UV and IR stacked photometry and fits to the cluster SED we measure dust-obscured and unobscured star formation rates to test the evolution in dust obscuration in clusters at z ∼ 0.5–1.1. We infer a dust-obscured SFR (SFR_{IR}) from the IR luminosity output by CIGALE, which is well constrained by the Herschel photometry, using SFR_{IR}[\text{M}_\odot \text{yr}^{-1}] = 1.5 \times 10^{-10} L_{\text{IR}}/L_\odot \text{ (Murphy et al. 2011).} The values we report on L_{\text{IR}} and SFR_{IR} are consistent with A21 within 1σ. From the UV data, we measure an unobscured SFR (SFR_{UV}) by first inferring a rest-frame GALEX/FUV luminosity from the best-fit SED, which we then convert into a star formation rate using SFR_{IR}/[\text{M}_\odot \text{yr}^{-1}] = 4.42 \times 10^{-44} L_{\text{FUV}}/[\text{erg} \text{ s}^{-1}] \text{ (Murphy et al. 2011).}
The SFR calibrations used to measure SFR\textsubscript{IR} and SFR\textsubscript{UV} are both derived from calibrations against extinction-free 33 GHz measurements of the SFR (Murphy et al. 2011), and are therefore aptly suited for empirically estimating total star formation rates in dusty systems like the cluster members in our study (A21). While CIGALE returns time-averaged star formation rates from the best-fit star formation history, we use empirical calibrations when measuring SFR\textsubscript{UV} and SFR\textsubscript{IR} to derive independent obscured and unobscured star formation rates. In this manner we avoid biasing our SFR measurements by the particular choice of shape for the star formation history, which can introduce \textasciitilde 15\% systematic uncertainty on measured SFRs (e.g., Buat et al. 2014). We note that 1\sigma errors on SFRs in Table 2 from observational and calibration uncertainties are generally \textgreater 15\%.

From SFR\textsubscript{IR} and SFR\textsubscript{UV} measured using the empirical calibrations of Murphy et al. (2011), we compute the fraction of dust-obscured star formation within each cluster, first defined by Whitaker et al. (2017) as

\[ f_{\text{obs}} = \frac{\text{SFR}_{\text{IR}}}{\text{SFR}_{\text{IR}} + \text{SFR}_{\text{UV}}} \]

which is reported alongside the stellar masses and IR luminosities in Table 2 with propagated systematic and measurement 1\sigma uncertainties. The total star formation rates measured in each redshift bin are predominantly dust-obscured \((f_{\text{obs}} > 0.8)\).

The sensitivity of the GALEX/NUV filter to the unobscured SFR in the highest redshift bin is diminished by the sampling of wavelengths below the Lyman limit for any cluster at \(z \gtrsim 1.45\) input into the stack. Indeed, of the 40 clusters in this redshift bin, 13 have \(z > 1.45\). To test whether or not our reported 3\sigma upper limit is still constraining for SFR\textsubscript{UV}, we refit the 1 Mpc \(z \sim 1.4\) SED while treating the upper limit as a data point to measure the maximum values of SFR\textsubscript{UV} allowable by the observations. From this fit, we measure SFR\textsubscript{UV} = \(1.5 \, M_\odot \, \text{yr}^{-1}\), which corresponds to \(f_{\text{obs}} \sim 1\). Thus, we are unlikely to be missing a significant amount of unobscured star formation even in the highest redshift bins due to the rest-frame sampling of the SED by the NUV filter.

### 4.3. Radial Flux Profiles

The radial distribution in the stacked GALEX maps traces the distribution of unobscured star formation in clusters. A21 reported evidence for suppressed dust-obscured star formation at \(R < 0.3–0.5\) Mpc relative to the stellar mass profiles from \(0.5 < z < 1.6\); we now test whether or not this also extends to the unobscured stellar light by comparing the GALEX/NUV radial profiles with the multiwavelength profiles from A21. The GALEX/NUV surface brightness measurements in the two highest redshift bins do not have sufficient signal-to-noise ratio, and we therefore restrict our radial analysis to the two lowest redshift bins.

#### 4.3.1. GALEX/NUV versus W1

As discussed in detail by A21 (see their Section 4.1.2), comparisons between radial profile measurements made at different wavelengths are biased by differing sky noise subtraction techniques, centroiding uncertainties, and differences in each instrument’s point-spread function. To mitigate these uncertainties, we begin by comparing GALEX/NUV, which traces the unobscured star formation, against W1 and W2, tracers of stellar mass. The FWHM of the GALEX/NUV beam is 4\"9, which is comparable to WISE (6\"1–6\"4); moreover, the sky is subtracted on the same scales in all three wavelength stacks.

Figure 2 shows the radial profiles of differential and cumulative flux (\(F_{\text{NUV}}\)) from the GALEX stacks in the first two redshift bins, compared against W1. Note that the radial profile of W2 is nearly indistinguishable from that of W1 within 1\sigma errors in both cases (see Figure 4 of A21). At both redshifts, the W1 and NUV radial profiles are similar at larger radii, but we observe a deficiency in UV light in the innermost \(\sim 15\"–30\"\) relative to the W1 profile when normalized at 1 Mpc. The ratio in the cumulative flux profile rises from the innermost region out to \(\sim 80\"\), reminiscent of the evidence for suppressed \(F_{250}/F_{25}\sim \text{SFR}_{\text{IR}}/M_\odot\) in the cluster centers reported by A21 for all of the redshift bins. This trend is more pronounced at \(z \sim 0.86\), which could be indicative of evolving quenching scenarios. In summary, there is evidence of suppressed obscured and unobscured star formation in the center of our \(z < 1\) cluster stacks relative to the stellar mass.
4.3.2. GALEX/NUV versus SPIRE

To test for differences or similarities in the structure of dust-obscured versus unobscured star formation across the clusters, we compare the NUV to SPIRE 250 μm radial profiles at z ∼ 0.57 and z ∼ 0.86. First, we convolve the NUV stack maps with the SPIRE 250 μm beam and measure both mean and median radial profiles at a spatial resolution of FWHM = 18″; however, the following conclusions remain the same if we use the native NUV mean-weighted radial profiles.

To quantitatively test for differences in the radial distribution between unobscured and obscured star formation, we devise a nonparametric test of the relative contribution from a central and extended emission component to the total differential flux profile. First, we fit a single Gaussian (1G) to the SPIRE beam-convolved NUV profile and the SPIRE 250 μm profile. As shown in Table 3, these fits have σ widths between ∼30″ and 40″. Next, we add another Gaussian component to the fit, which we restrict to σ < 30″ and find the best fit for this two-component Gaussian model (2G). By calculating Bayesian information criteria (BICs), and the change in BIC between model fits (|ΔBIC|), we can test which of a single or two-component Gaussian model is preferred, accounting for the overall fit to the data while penalizing models with more free parameters. The results from each set of fits are shown in Table 3. While a given |ΔBIC|

Table 3

Results from Radial Profile Fits to GALEX/NUV and SPIRE 250 μm Maps

| Band  | z    | σ₁G [arcsec] | σ₂G [arcsec] | |ΔBIC| | Preferred |
|-------|------|--------------|--------------|-----|----------------|-------------|
| UVmean| 0.57 | 34           | (15, 48)     | 72  | Double Gaussian|
| UVmed | 0.57 | 34           | (20, 50)     | 113 | Double Gaussian|
| SPIRE | 0.57 | 41           | (1, 41)      | 6.4 | Single Gaussian|
| UVmean| 0.86 | 31           | (28, 62)     | 1.3 | Single Gaussian|
| UVmed | 0.86 | 33           | (25, 61)     | 133 | Double Gaussian|
| SPIRE | 0.86 | 37           | (3, 37)      | 6   | Single Gaussian|

Note. σ widths for the Double Gaussian model.

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To quantitatively test for differences in the radial distribution between unobscured and obscured star formation, we devise a nonparametric test of the relative contribution from a central and extended emission component to the total differential flux profile. First, we fit a single Gaussian (1G) to the SPIRE beam-convolved NUV profile and the SPIRE 250 μm profile. As shown in Table 3, these fits have σ widths between ∼30″ and 40″. Next, we add another Gaussian component to the fit, which we restrict to σ < 30″ and find the best fit for this two-component Gaussian model (2G). By calculating Bayesian information criteria (BICs), and the change in BIC between model fits (|ΔBIC|), we can test which of a single or two-component Gaussian model is preferred, accounting for the overall fit to the data while penalizing models with more free parameters. The results from each set of fits are shown in Table 3. While a given |ΔBIC|
star formation is more extended than the unobscured component. Figure 3.

The mean halo mass of stacked clusters is $10^{13.9}$ $M_\odot$, corresponding to a virial radius of $R_{200} \sim 1$ Mpc. We find that the total star formation rate per $z \sim 0.5$–1.4 cluster, on average, is predominantly dust-obsured and ranges from $\sim 100$ to $600 M_\odot$ yr$^{-1}$, rising steeply with redshift. The GALEX/NUV measurements also place strong constraints on derived stellar masses at $z < 1$.

5.1. Dust-obscured Star Formation in Low-mass Galaxies

By comparing the Herschel total light stacks to stacks of individually identified massive ($\log(M/M_\odot) > 10.1$) cluster galaxies and analyzing their near- to far-IR SEDs, A21 argued that the total IR light in clusters is dominated by low-mass galaxies, which, in the field, have more unobscured SF on average than higher-mass galaxies (Whitaker et al. 2017). From this conclusion, one may expect the GALEX/NUV data to reveal a substantial amount of SFR$_{\text{UV}}$ originating from low-mass, low-dust galaxies, if low-mass cluster galaxies have similar $f_{\text{obs}}$ to field galaxies.

To test whether or not the amount of unobscured SF we observe is consistent with A21 and $f_{\text{obs}}(M_\ast)$ measured in the field, we compare measured SFR$_{\text{UV}}$ with predicted values. We begin by assuming that the fraction of SFR$_{\text{IR}}$ arising from the low-mass galaxies is the same as in the field, and that the obscured star formation is more extended than the unobserved component.

5. Discussion

In this work, we report the first complete census of star formation in high-$z$ galaxy clusters accounting for both the obscured and unobscured components through combined UV and IR stacks. The mean halo mass of stacked clusters is $10^{13.9}$ $M_\odot$, corresponding to a virial radius of $R_{200} \sim 1$ Mpc. We find that the total star formation rate per $z \sim 0.5$–1.4 cluster, on average, is predominantly dust-
formulation arising from low-mass galaxies in our cluster stacks assuming field-like conditions. These values do not change if we adopt stellar mass functions derived from clusters because the stellar mass function of star-forming galaxies does not depend on environment (e.g., van der Burg et al. 2018). From the uncertainties on the stellar mass functions, $f_{\text{obs}}(M_*)$, and the SFR calibrations, we estimate a systematic uncertainty on our predicted SFR$_{\text{UV}}$ of 30%. As shown in Figure 4, our cluster measurements of SFR$_{\text{UV}}$ are broadly consistent with what is expected to arise from low-mass $z \sim 0.8$--1.1 field galaxies. At $z \sim 0.57$, the total SFR$_{\text{UV}}$ we measure is a factor of 2.5 below the predictions, but within the 1σ uncertainties on both measured and predicted quantities. If significant, this deficit could reflect the rapid increase in quenching efficiency for $9 < \log(M/M_*) < 10$ galaxies from $z \sim 2$ to $z \sim 0.5$ (De Lucia et al. 2004; Stott et al. 2007; Kawinwanichakij et al. 2017), which is plausible given that such low-mass galaxies are easily perturbed in clusters (Boselli et al. 2008; Boselli & Gavazzi 2014) and because they exhibit low obscured fractions (Whitaker et al. 2017). At all redshifts, high-mass galaxies have $f_{\text{obs}} \sim 1$ and likely do not contribute significantly to SFR$_{\text{UV}}$.

Adding this unobserved star formation component to the previous measured obscured component reveals that the total specific star formation rate (sSFR) in galaxy clusters from $z \sim 0.57$--1.1 is declining below that of the field population (see Figure 12 in A21; see also Alberts et al. 2014; Brodwin et al. 2013). In other words, the GALEX data did not reveal a significant missing component of star formation from the IR analysis. This is consistent with the high environmental quenching efficiencies of low-mass galaxies reported at $z < 1.5$ (Kawinwanichakij et al. 2017; Papovich et al. 2018; McNab et al. 2021), which as a population must therefore play an important role in setting the evolution of clusters (A21, van der Burg et al. 2018). There is tentative evidence for low gas reservoirs and short depletion timescales in $\log(M/M_*) > 9.5$ cluster star-forming galaxies at $z \sim 0.75$ (Betti et al. 2019) and at $z \sim 1.4$ (Alberts et al. 2022), which supports the idea that gas removal is driving a “delayed then rapid” quenching scenario (i.e., Wetzel et al. 2013); however, future observations of the gas content in lower-mass cluster galaxies are necessary to further test this scenario.

5.2. Stripping of Dusty Envelopes in Galaxy Clusters at $z \sim 0.57$

As outlined in Section 4.3.2, we find evidence that the unobscured SF traced by the GALEX/NUV data includes a centrally concentrated component not found for the dust-obscured SF measured by Herschel in the $z \sim 0.57$ cluster stack. One mechanism that could affect the obscured SF fraction at different radii is hydrodynamic gas stripping by the intracluster medium (ram pressure stripping, Boselli et al. 2021), a common feature observed in infalling cluster galaxies at low redshift (e.g., Poggianti et al. 2017; Longobardi et al. 2020) and at high redshift (Boselli et al. 2019; Noble et al. 2019). As galaxies fall into the inner regions of clusters, they experience progressively more gas stripping in the outer disk regions, while simultaneously processing denser gas within the plane of the disk into stars. In particular, simulations show that most of a star-forming galaxy’s halo gas is stripped before arriving at the virial radius of the host cluster, but that star-forming disks remain unperturbed until $<0.5R_{\text{vir}}$ (Zinger et al. 2018). These galaxies also tend to be preferentially found on radial orbits (Lotz et al. 2019). One could plausibly expect more unobscured SF in the inner projected 2D radial profiles where the averaged galaxy population has preferentially had dusty envelopes removed by interactions with the intracluster medium. This could produce the centrally concentrated component of unobscured SF at $z \sim 0.57$ but not at $z \sim 0.86$ because galaxies have had more time to evolve toward the cluster centers at lower redshifts.

5.3. Stellar to Halo Mass Ratios

The ratio of total stellar mass to halo mass in cluster members is representative of the efficiency of stellar mass assembly in dense environments, itself a function of competing feedback mechanisms on galaxy and halo scales. Star formation and feedback from active galactic nuclei in galaxy/group and cluster-scale halos, respectively, have been invoked to explain the small $M_*/M_{\text{halo}}$ ratios that can be implemented in analytic and numerical models to test theories of galaxy formation within the framework of dark matter. By measuring the total cluster light from UV to IR wavelengths, we place a constraint on empirical trends in $M_*/M_{\text{halo}}$ for cluster galaxies, which can be used to test theoretical predictions.

Clusters in the full ISCS sample have a mean halo mass of $\log(M_{\text{halo}}/M_*) = 13.8$, independent of redshift (Brodwin et al. 2007; Lin et al. 2013; Alberts et al. 2014). In Figure 5, we show $M_*/M_{\text{halo}}$ versus $M_{\text{halo}}$ in our $z < 1$ stacked cluster sample, where the GALEX data improve the constraint on $M_*$ (Table 2), compared with observations of more massive cluster samples at $z \sim 0$--1.5 (Gonzalez et al. 2013; Hilton et al. 2013; van der Burg et al. 2014; Chiu et al. 2018; Decker et al. 2019), and simulations (Henriques et al. 2015). Note that we compare
against semianalytical galaxy formation models as opposed to more common $M_\ast/M_{\text{halo}}$ relations for central galaxies (e.g., Moster et al. 2010) because our method measures all of the light from the cluster. The model of Henriques et al. (2015) predicts little correlation between $M_\ast/M_{\text{halo}}$ and $M_{\text{halo}}$ at $z=0$, whereas empirical results from X-ray-selected $z\sim0$ clusters suggest a sharp anticorrelation between the two quantities (Gonzalez et al. 2013). Results from our previous work (A21) could not distinguish between the two scenarios owing to large uncertainties on $M_\ast$; however, the added GALEX/NUV data improve the constraint on derived stellar masses at $z<1$ (Table 2). We fit a trend line to our data and the $z<1$ literature, and find an anticorrelation between $M_\ast/M_{\text{halo}}$ and $M_{\text{halo}}$. The slope of this trend (blue line, Figure 5) is shallower than for $z\sim0$ clusters (Gonzalez et al. 2013) but steeper than what is observed in the semianalytic models. Our results support a stellar-mass-dependent star formation efficiency in clusters, with more massive systems exhibiting lower efficiencies. Further observations of $z\sim0.5$–$1$ clusters with $M_{\text{halo}}<10^{14} M_\odot$ will provide a more detailed constraint on the redshift evolution. Nevertheless, our results stress the importance of placing strong constraints at rest-frame UV wavelengths to elucidate how star formation proceeded in cluster environments.

5.4. Contaminants to the UV Emission

The hot gas in clusters is a source of UV photons in addition to the emission produced by massive, hot stars. Electrons at the virial temperature of halos emit free–free radiation extending into the UV (Sarazin 1999, 2005), which can also be contaminated by inverse Compton (IC) scattering of electrons that are accelerated to relativistic velocities in shocked gas during mergers within the cluster environment. Welch et al. (2020) rule out both mechanisms as likely contributors to the UV emission detected in GALEX FUV stacks of Planck cluster galaxies selected according to the Sunyaev–Zeldovich effect at $z<0.3$. Following their argument, we also rule out these sources of nonstellar UV photons as significant contributors to the measured flux densities in our cluster stacks. The typical spectral luminosity of free–free emission by halo electrons is $\sim10^{27}$ erg s$^{-1}$ Hz$^{-1}$, and $\sim10^{28}$ erg s$^{-1}$ Hz$^{-1}$ for IC scattering from shocked gas (Sarazin 2005), corresponding to flux densities of the order of $10^{-5}$ mJy and $10^{-3}$ mJy respectively in the GALEX NUV filter profiles at $z\sim0.5$–$1$. The flux densities of UV photons from IC scattering and free–free emission are 3–5 orders of magnitude less than the measured flux in our weighted mean cluster stacks.

Another source of contaminant flux is the UV upturn, which manifests as a rise in the SED of quiescent galaxies at rest-frame UV wavelengths (Burstein et al. 1988; O’Connell 1999). The UV upturn is generally attributed to hot horizontal branch stars, and is less prevalent at earlier times when stars have had less time to evolve. For this reason, we expect the UV upturn to contribute negligibly to the stacked GALEX flux measured in our highest redshift bins (e.g., Ali et al. 2018; Dantas et al. 2020). To quantify the contribution from the UV upturn to the measured flux in our $z\sim0.57$ bin, we estimate the UV flux arising from horizontal branch stars in quiescent cluster members based on the typical UV–optical color of UV-upturn galaxies. At this redshift, the GALEX NUV band corresponds to the GALEX NUV spectral luminosity of free emission by halo electrons (e.g., Ali et al. 2018; Dantas et al. 2020).

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6. Conclusion

In this work, we stack GALEX/NUV maps of galaxy clusters at $z\sim0.5$–$1.6$ to constrain the total UV emission from cluster-member galaxies, including those which go undetected in individual observations. We measure aperture-integrated photometry and radial flux profiles from the stacked maps in four redshift bins, $z = 0.5$–$0.7$, 0.7–$1.0$, 1.0–$1.4$, and $z = 1.4$–$1.6$, which we combine with near- to far-IR stacks of...
the same clusters from A21. From fits to the UV through IR SEDs, we measure total stellar masses, and the ratio of obscured to total star formation in clusters \(f_{\text{obs}} > 0.8\). Previous work found the IR light to be dominated by \(log(M_*/M_\odot) < 10\) galaxies, which also dominate the UV and therefore the total star formation in clusters. The predicted SFR\(_{\text{UV}}\) from this low-mass population could explain all of the unobscured SF we measure at \(z < 1\) if low-mass galaxies have as much dust-obscured star formation as their field counterparts.

2. Adding in the UV confirms that the total \(s\)SFR in galaxy clusters follows a declining trend from \(\sim 1\) to \(\sim 0.5\) relative to the field. Because low-mass galaxies dominate both the IR and UV, and therefore dominate the total star formation in \(\sim 0.5\)–1.4 clusters, environmental quenching of low-mass galaxies must be an important driver of cluster evolution.

3. The UV radial profile of \(\sim 0.57\) clusters has a centrally concentrated component not found in the IR radial profile. This could arise from gas stripping via interactions between infalling cluster galaxies and the intracluster medium, which can strip the obscuring material from the outer envelopes of star-forming galaxies as they make their way into the cluster center.

4. Improved stellar mass estimates favor an anticorrelation between \(M_*/M_{\text{halo}}\) and \(M_{\text{halo}}\) consistent with trends found in \(z \sim 0\) clusters (Gonzalez et al. 2013). This is in conflict with some semianalytic models that predict a flatter stellar-to-halo mass function of \(M_{\text{halo}}\).

Total light stacking of galaxy clusters allows for the full accounting of galaxies in wavelength and redshift regimes that are otherwise limited by observational depth. In the future, this technique may be applied to other wavelengths, such as the millimeter regime using the upcoming ToTEC camera on the Large Millimeter Telescope, in order to measure the evolution of the total dust mass in clusters. With other large-area samples that have different mass selection functions (e.g., MaDCoWS; Gonzalez et al. 2019), this technique may also be used to test for halo mass-dependent evolution in the panchromatic SED of galaxy clusters out to high \(z\) and to place further constraints on models for galaxy formation within the context of large-scale structure.

We thank the referee for their insightful comments that strengthened this work. J.M. and A.P. thank M. Weinberg for helpful discussion on nonparametric statistical tests. The authors acknowledge financial support from NASA through the Astrophysics Data Analysis Program, grant number 80NSSC19K0582. GALEX is a NASA Small Explorer, and we gratefully acknowledge NASA’s support for construction, operation, and science analysis for the GALEX mission, developed in cooperation with the Centre National d’Etudes Spatiales of France and the Korean Ministry of Science and Technology.

References

Alberts, S., Adams, J., & Gregg, B. 2022, arXiv:2201.01307
Albers, S., Lee, K.-S., Pope, A., et al. 2021, MNRAS, 501, 1970
Alberts, S., Pope, A., Brodwin, M., et al. 2014, MNRAS, 437, 437
Alberts, S., Pope, A., Brodwin, M., et al. 2016, ApJ, 825, 72
Ali, S. S., Bremer, M. N.,Phillips, S., & De Propris, R. 2018, MNRAS, 480, 2236
Baldry, I. K., Balogh, M. L., Bower, R. G., et al. 2006, MNRAS, 373, 469
Bertin, E., & Arnouts, S. 1996, A&AS, 117, 393
Betti, S. K., Pope, A., Scoville, N., et al. 2019, ApJ, 874, 53
Bianchi, L. 2009, Ap&SS, 320, 11
Boissier, S., Cucciati, O., Boselli, A., Mei, S., & Ferrarese, L. 2018, A&A, 611, A42
Boquien, M., Burgarella, D., Roehlly, Y., et al. 2019, A&A, 622, A103
Boselli, A., Boissier, S., Cortese, L., & Gavazzi, G. 2008, A&A, 489, 1015
Boselli, A., Boissier, S., Heinis, S., et al. 2011, A&A, 528, A107
Boselli, A., Epinat, B., Contini, T., et al. 2019, A&A, 631, A114
Boselli, A., Fossati, M., & Sun, M. 2021, arXiv:2109.13614
Boselli, A., & Gavazzi, G. 2014, A&ARv, 22, 74
Boselli, A., Voyer, E., Boissier, S., et al. 2014, A&A, 570, A69
Brodwin, M., Eisenhardt, P. R., Gonzalez, A. H., et al. 2006, AAS Meeting, 208, 27.07
Brodwin, M., Gonzalez, A. H., Moustakas, L. A., et al. 2007, ApJL, 671, L93
Brodwin, M., Stanford, S. A., Gonzalez, A. H., et al. 2013, ApJ, 779, 138
Brodwin, M., Stern, D., Vikhlinin, A., et al. 2011, ApJ, 732, 33
Buat, V., Heinis, S., Boquien, M., et al. 2014, A&A, 561, A39
Burgarella, D., Buat, V., & Iglesias-Páramo, J. 2005, MNRAS, 360, 1413
Burstein, D., Bertola, F., Buson, L. M., Faber, S. M., & Lauer, T. R. 1988, ApJ, 328, 440
Casey, C. M. 2012, MNRAS, 425, 3094
Chiu, I., Mohr, J. J., McDonald, M., et al. 2018, MNRAS, 478, 3072
Dantas, M. L. L., Coelho, P. R. T., de Souza, R. S., & Gonçalves, T. S. 2020, MNRAS, 492, 2996
De Lucia, G., Poggianti, B. M., Aragón-Salamanca, A., et al. 2004, ApJL, 610, L77
Deckers, B., Brodwin, M., Abdulla, Z., et al. 2019, ApJ, 878, 72
Desai, V., Dalcanton, J. J., Aragón-Salamanca, A., et al. 2007, ApJ, 660, 1151
Dressler, A., Oemler, Augustus, J., Couch, W. J., et al. 1997, ApJ, 490, 577
Eisenhardt, P. R. M., Brodwin, M., Gonzalez, A. H., et al. 2008, ApJ, 684, 905
Gómez, P. L., Nichol, R. C., Miller, C. J., et al. 2003, ApJ, 584, 210
Gonzalez, A. H., Gettings, D. P., Brodwin, M., et al. 2019, ApJS, 240, 33
Gonzalez, A. H., Sivanandam, S., Zabludoff, A. I., & Zaritsky, D. 2013, ApJ, 778, 14
Haines, C. P., Busarello, G., Merluzzi, P., et al. 2011, MNRAS, 412, 127
Henriques, B. M. B., White, S. D. M., Thomas, P. A., et al. 2015, MNRAS, 451, 2663
Hilton, M., Hasselfield, M., Sifón, C., et al. 2013, MNRAS, 435, 3469
Jian, H.-Y., Lin, L., Oguri, M., et al. 2018, PASJ, 70, S23
Kass, R. E., & Rafferty, A. E. 1995, J. Am. Stat. Assoc., 90, 773
Kawinwanichakij, L., Papovich, C., Quadri, R. F., et al. 2017, ApJ, 847, 134
Kirkpatrick, A., Pope, A., Sajina, A., et al. 2015, ApJ, 814, 9
Lin, L., Jian, H.-Y., Fucarla, S., et al. 2014, ApJ, 782, 33
Lin, Y.-T., Brodwin, M., Gonzalez, A. H., et al. 2013, ApJ, 771, 61
Longobardi, A., Boselli, A., Fossati, M., et al. 2020, A&A, 644, A161
Lotz, M., Remus, R.-S., Dolag, K., Biviano, A., & Burkert, A. 2019, MNRAS, 488, 5370
Marchesini, D., van Dokkum, P. G., Förster Schreiber, N. M., et al. 2009, ApJ, 701, 1765
Martini, P., Miller, E. D., Brodwin, M., et al. 2013, ApJ, 768, 1
McKab, N., Balogh, M. L., van der Burg, R. F. J., et al. 2021, MNRAS, 508, 157
Morrissey, P., Conrow, T., Barlow, T. A., et al. 2007, ApJS, 173, 682
Moster, B. P., Somerville, R. S., Mailbetsch, C., et al. 2010, ApJ, 710, 903
Murphy, E. J., Condon, J. J., Schinnerer, E., et al. 2011, ApJ, 737, 67

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