STAR FORMATION ACTIVITY IN CLASH BRIGHTEST CLUSTER GALAXIES*

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Received 2015 August 3; accepted 2015 October 4; published 2015 November 4

ABSTRACT

The CLASH X-ray selected sample of 20 galaxy clusters contains 10 brightest cluster galaxies (BCGs) that exhibit significant (>5σ) extinction-corrected star formation rates (SFRs). Star formation activity is inferred from photometric estimates of UV and Hα+[N ii] emission in knots and filaments detected in CLASH Hubble Space Telescope ACS and WFC3 observations. UV-derived SFRs in these BCGs span two orders of magnitude, including two with a SFR ≥ 100 M⊙ yr−1. These measurements are supplemented with [O ii], [O iii], and Hβ fluxes measured from spectra obtained with the SOAR telescope. We confirm that photoionization from ongoing star formation powers the line emission nebulae in these BCGs, although in many BCGs there is also evidence of a LINER-like contribution to the line emission. Coupling these data with Chandra X-ray measurements, we infer that the star formation occurs exclusively in low-entropy cluster cores and exhibits a correlation with gas properties related to cooling. We also perform an in-depth study of the starburst history of the BCG in the cluster RXJ1532.9 +3021, and create 2D maps of stellar properties on scales down to ~350 pc. These maps reveal evidence for an ongoing burst occurring in elongated filaments, generally on ~0.5–1.0 Gyr timescales, although some filaments are consistent with much younger (≤100 Myr) burst timescales and may be correlated with recent activity from the active galactic nucleus. The relationship between BCG SFRs and the surrounding intracluster medium gas properties provide new support for the process of feedback-regulated cooling in galaxy clusters and is consistent with recent theoretical predictions.

Key words: galaxies: clusters: general – galaxies: clusters: intracluster medium – galaxies: starburst

1. INTRODUCTION

Brightest cluster galaxies (BCGs) in cool core galaxy clusters exhibit nebular emission features that are thought to be related to the intracluster medium (ICM) in the centers of these objects (e.g., Heckman et al. 1989; Fabian 1994; Crawford et al. 1999). Observations of substantial continuum UV and FIR fluxes have been recorded in many of these nominally early-type galaxies as well (Hicks et al. 2010; Rawle et al. 2012). Resolved images of low-redshift (z ≤ 0.1) BCGs suggest that while some of this activity is triggered by active galactic nuclei (AGNs), most of the emission appears to be powered by recent star formation, located in knots and filaments (Conselice et al. 2001; O’Dea et al. 2004, 2010; McDonald & Veilleux 2009; Tremblay et al. 2012, 2015; McDonald et al. 2014a). Similar structures have also been observed in the Phoenix cluster (z = 0.596), which hosts a massive starbursting BCG producing new stars at a rate of nearly 1000 M⊙ yr−1 (McDonald et al. 2012, 2013).

The most plausible candidate for the source of the gas being converted into stars in these galaxies is radiatively cooled ICM plasma (Fabian 1994). In a cool core cluster, the cooling time below a critical radius is less than the Hubble time at the redshift of the cluster, and plasma initially at this radius ought to have cooled. The ICM that manages to cool descends into the gravitational well in order to maintain pressure equilibrium, ultimately condensing into star-forming gas inside the virial radius of the BCG (Fabian 1994). However, the cooling inferred from a simple cooling flow model is far more rapid than the star formation rates (SFRs) in these systems (e.g., Heckman et al. 1989; McNamara & O’Connell 1989).

Activity in BCGs in the form of recent star formation and AGN outbursts are important components of feedback mechanisms proposed to reconcile the tension between the predicted and observed ICM cooling in cool core clusters (McNamara & Nulsen 2007; Voit et al. 2015b). Specifically, the hot, X-ray emitting ICM of a relaxed galaxy cluster is predicted to radiatively cool more rapidly than is typically observed, and this manifests in SFRs in BCGs which are roughly an order of magnitude lower than what would be predicted if all the available gas did indeed condense into cold gas (O’Dea et al. 2008). However, in the presence of a feedback mechanism, such as energy injection from an AGN, the ICM is partially reheated and prevented from cooling catastrophically. Instead, residual cooling or cooling during an off-mode in the feedback duty cycle can account for the extended star-forming structures observed. Studying the residual cooling using observations of BCGs spanning a wide range of activity will allow us to learn about different phases of cooling and feedback, and help us to determine whether a single feedback mechanism accounts for the variety of BCG features we observe.

The high-resolution, multi-band Hubble Space Telescope (HST) observations available from the Cluster Lensing And Supernova survey with Hubble (Postman et al. 2012; hereafter referred to as CLASH) are ideal for examining the star-forming structures in BCGs. In Donahue et al. (2015), we examined UV photometry for the entire CLASH sample of 25 galaxy clusters, and found evidence for significant, extended emission
attributable to recent star formation in 10 of them. Two BCGs in this sample, RXJ1532.9+3021 and MACS J1931.8–2635, stand out due to their strikingly large and luminous UV filaments.

In the present study, we examine BCGs in the subset of CLASH clusters that were X-ray selected. This subsample includes 20 of the 25 CLASH clusters and includes all of the star-forming BCGs as identified by UV features. Using the CLASH HST photometry, along with spectra from the Southern Astrophysical Research (SOAR) telescope and archival Chandra data, we investigate the nature of star formation in these BCGs, and provide new constraints on the source of the star formation activity in the structures we observe.

This paper consists of two parts. First, we derive SFRs for all BCGs using HST photometry and characterize the source of nebular line-emission in UV-bright BCGs using a combination of the HST photometry and SOAR-Goodman spectra. Second, we analyze the connection between the star formation and the properties of the ICM. This second part includes a detailed star formation history (SFH) analysis of the BCG in RXJ1532.9+3021 derived from spectral energy distribution (SED) fitting of the CLASH photometry to create maps of stellar population parameters. RXJ1532.9+3021 was chosen for more detailed study because of the spectacular nature of its UV and Hα structure (see Figure 1).

We report on the incidence and distribution of reddening-corrected SFRs in our sample, and demonstrate that structures qualitatively comparable with those in the massive outburst in the Phoenix cluster are the sites of BCG activity in these “intermediate” starbursts as well. Structures observed in CLASH clusters also bear similarities to BCGs analyzed in Tremblay et al. (2015). These SFRs are compared with Chandra derived ICM core entropies and predicted cooling rates in the low-entropy core ICM in order to test the hypothesis that star formation is being fed by ICM cooling.

For RXJ1532.9+3021 we are able to compare the properties of BCG filaments with the properties of X-ray cavities in the ICM, which we use to assess recent AGN jet-mode activity. We compare our results to previous analysis of the morphology of the cluster ICM (Hlavacek-Larrondo et al. 2013). The maps produced for this BCG allow us to examine the SFH in individual knots and filaments, down to ~350 pc scales. These data allow us to investigate the source of the gas that condenses into the star-forming regions and, for the case of RXJ1532.9+3021, to examine this condensation in significant detail.

Our paper is organized as follows. We describe the observational data in Section 2. In Section 3, we present the analysis of these data. Results are presented in Section 4, and the astrophysical implications are discussed in Section 5. We summarize our main conclusions in Section 6. We adopt the following cosmological parameters throughout this work: $H_0 = 70.0 \text{ km s}^{-1} \text{Mpc}^{-1}$, $\Omega_m = 0.30$, and $\Omega_\Lambda = 0.70$. We assume a Salpeter (1955) IMF throughout.

2. OBSERVATIONS

2.1. CLASH HST Observations

The CLASH program is detailed in Postman et al. (2012). The 20 X-ray selected clusters were each observed for 15–20 orbits (for a total of at least 20 orbits including archival data) divided among 16 bands of photometry spanning an observer-frame wavelength range of ~2000–17000 Å. We use multi-band mosaics drizzled to a common 0.20 arcsec frame wavelength range of ~2000–17000 Å. All flux measurements are corrected for foreground reddening using the (Schlegel et al. 1998) dust maps. A single reddening correction due to dust in the Milky Way was calculated for each BCG in each filter. Additionally, we perform a background subtraction using a combination of iterative 3-σ clipping on large scales along with a local median flux measurement in an annulus around each BCG in the UV.

Early CLASH WFC3/UVIS observations are affected by non-uniform flat-fielding on scales of hundreds to thousands of pixels. We accounted for this in observations of BCGs with faint or possibly no significant detection of UV by extracting...
photometry from multiple identical apertures in WFC3/UVIS images placed on empty patches of sky, and adding the scatter in these apertures to our error budget. For all CLASH observations, we apply a 3% floor to the total photometric uncertainty to account for all sources of systematic error and absolute flux calibration uncertainty.

2.2. Chandra X-Ray Observations

All the clusters in the CLASH X-ray sample have archival Chandra data. For this work, we use the ICM parameters published in the Archive of Chandra Cluster Entropy Profile Tables (ACCEPT) (Cavagnolo et al. 2009). Gas density and temperature profiles were measured in ACCEPT, and the core entropies and cooling times used in the present study are calculated using these profiles. Gas density profiles were measured in concentric annuli 5″ wide. Temperature profiles, which were used in combination with the gas density profiles to derive both cooling time and entropy profiles, were measured in concentric annuli containing at least 2500 counts per bin.

2.3. Spectra

Optical spectra of the BCGs were obtained for 15 of the 20 CLASH X-ray selected clusters. Objects were observed with the Goodman High Throughput Spectrograph on the SOAR 4.1 meter telescope using either the KOSI 600 grating or the SYZY 400 grating. The KOSI grating’s dispersion is approximately 0.65 Å pix⁻¹, while the SYZY grating’s is approximately 1.0 Å pix⁻¹. Their spectral ranges are roughly 2670 Å and 4000 Å, respectively (see Table 1). Central wavelengths were selected to best include the [O III] doublet (λ5007, λ5067), the [O II] doublet (λ3727, λ3729), and Hβ at their redshifted positions. Position angles were chosen to sample observed filamentary structures or other objects of interest. For all observations, the 1°68 long slit was used.

Observations were reduced following Werner et al. (2014). Bias correction and trimming were performed with the IRAF task CCDPROC. Quartz lamp frames, taken before and after observation images, were used to flat-field the images. Wavelength calibration was performed with FeAr arc lamp exposures, with distortion along the spatial direction corrected for by tracing the position of standard stars. Sensitivity functions were produced from same-night observations of standard stars with the 10.6″ long slit that, along with an extinction correction based on IRAF’s extinction file ctioextinct.dat and a correction for airmass, were used to flux calibrate observations. After background subtraction to minimize the contribution of night sky lines, observations were then median combined using IMCOMBINE.

3. ANALYSIS

3.1. Mean UV Luminosities

We calculate the UV luminosity of CLASH BCGs in order to estimate SFRs using the Kennicutt (1998) relation. To do this, we extract the flux from those CLASH filters whose pivot wavelengths fall in the range 1500–2800 Å in the cluster rest frame, corresponding to the wavelength range used by Kennicutt (1998) to calculate the $L_{UV}$–SFR relation. Since the continuum $L_{UV}$ due to young stars is flat for a Salpeter (1955) IMF and continuous star formation, we use fluxes extracted from the relevant UV filters to calculate the average luminosity ($L_{UV}$). This quantity is one of two SFR proxies we are able to calculate from the HST photometry alone, the other being $L_{H\alpha+[N II]}$, which we discuss in Section 3.2.

For the majority of the BCGs, we extract fluxes from a subset of the CLASH WFC3/UVIS filters, F225W, F275W, F336W, and F390W. For the highest redshift clusters ($z > 0.542$), we use ACS filters F435W and sometimes F475W as well. Filter selections are shown in Table 2.

Since we are interested in the UV flux from young stars, we must remove the contribution from the UV-upturn in the quiescent stellar population in the BCGs. The UV-upturn has been well-studied and is due to post AGB stars and extreme blue horizontal branch stars (e.g., Ferguson & Davidsen 1993; Yi et al. 1998; Brown 2004; Yi 2008). This component of the

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Table 1

| Cluster   | Obs Date (YYYY-MM-DD) | Exposure Times (s) | Grating (l/mm) | Range Å | PA° | Airmass | Standard Star |
|-----------|-----------------------|--------------------|----------------|---------|------|---------|----------------|
| Abell 209 | 2012 Sep 24           | 1 × 1200, 1 × 1800 | 400            | 4514–7555 | 135 | 1.2     | LTT 7379      |
| Abell 383 | 2012 Oct 09           | 2 × 1200, 1 × 600  | 400            | 4126–7568 | 0   | 1.3     | LTT 1020      |
| MACS J0329.7–0211 | 2012 Nov 09 | 3 × 1200          | 400            | 4612–7555 | 125 | 1.1     | LTT 7379      |
| MACS J0429.6–0253 | 2012 Nov 19   | 2 × 1200, 1 × 900  | 400            | 4566–7556 | 167 | 1.3     | LTT 1020      |
| MACS J1115.9+0219 | 2013 May 11  | 4 × 900           | 400            | 4401–8462 | 130 | 1.2     | LTT 4364      |
| MACS J1206.2–0847 | 2013 May 11  | 4 × 900           | 400            | 4398–8457 | 100 | 1.1     | LTT 4364      |
| MACS J1311.0–0310 | 2013 May 11  | 1 × 1500, 1 × 900  | 400            | 4412–8470 | 40  | 1.5     | LTT 4364      |
| MACS J1423.8+2404 | 2015 Feb 26  | 3 × 1200          | 600            | 5049–7724 | 0   | 1.8     | LTT 4364      |
| MACS J1720.3+3536 | 2015 Jun 13  | 3 × 1200          | 600            | 4570–7235 | 160 | 2.2     | LTT 6248      |
| MACS J1931.8–2635 | 2012 Apr 17  | 1 × 1800          | 600            | 4271–6938 | 252 | 1.0     | LTT 7379      |
| MS2137–2353 | 2015 Jun 13  | 4 × 1200          | 600            | 4570–7235 | 145 | 1.1     | LTT 6248      |
| RXJ1347.5–1145 | 2012 Jul 15 | 1 × 1200, 1 × 900  | 600            | 4556–7223 | 125 | 1.6     | LTT 9491      |
| RXJ1532.9+3021 | 2012 Apr 17  | 2 × 1200          | 600            | 4811–7471 | 187 | 2.1     | LTT 3864      |
| RXJ2129.7+0005 | 2012 Jul 15  | 4 × 1200          | 600            | 4560–7228 | 201 | 1.2     | LTT 3864      |
| RXJ2248.7–4431 | 2013 Sep 08  | 4 × 1200          | 600            | 4299–6969 | 352 | 1.1     | LTT 1020      |

Note.

° Position Angle measured east of north.

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5 IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA) under a cooperative agreement with the National Science Foundation.
UV flux mimics low-level star formation and would, if left uncorrected, bias our SFR estimates in UV-faint BCGs.

A template SED of the UV-upturn population is derived by averaging the normalized ACS-WFC3IR rest-frame photometry of 5 satellite galaxies in each of 20 CLASH clusters (for a total of 100 satellite galaxies). We do not include WFC3/UVIS in the satellite galaxy photometry to avoid complications in estimating the sensitivity to weak UV sources, and instead opt to use the GALEX-MASS J colors in Hicks et al. (2010) to extend the range of our data below 2000 Å rest. These data are fit to a fifth order spline, and the uncertainty in the fit is estimated using a Monte Carlo distribution of spline fits.

We estimate the UV contribution from old stars by subtracting out a model of the underlying early-type galaxy. A 2D non-parametric model of each BCG was fit to the F160W image, which is dominated by the BCG’s old stellar population. The model is scaled according to the template SED shown in Figure 2 and subtracted from the UV images. The residual UV flux measured after the subtraction is our UV-upturn-corrected estimate due to ongoing star formation activity.

### 3.2. Hα+[N II] Maps

The CLASH data allow us to estimate Hα emission in the BCGs using a broadband subtraction technique in cases where the emission is strong relative to the stellar continuum. For each BCG, a “line” and “continuum” filter is chosen based on the cluster redshift (see Table 2). One or more satellite early-type galaxies are chosen based on having an IR—optical color similar to the BCG, and the mean ratio of the satellite galaxy fluxes between the line and continuum filters is used to scale the continuum filter to the line filter. We subtract the scaled continuum filter image from the line filter image, leaving a residual flux that is primarily due to Hα+[N II] emission. The Hα nebulae of clusters with significant UV emission are shown in Figure 3.

### Table 2

| Cluster       | z*   | UV Filters | E(B - V) Filters | Hα “continuum” | Hα “line” |
|---------------|------|------------|------------------|---------------|-----------|
| Abell 209     | 0.209| F225W, F275W, F336W | ... | F850LP | F775W |
| Abell 383     | 0.187| F225W, F275W | ... | F850LP | F775W |
| Abell 611     | 0.288| F225W, F275W | F225w, F275w | F775W | F850LP |
| Abell 1423    | 0.213| F225W, F275W | ... | F850LP | F775W |
| Abell 2261    | 0.224| F225W, F275W, F336W | ... | F625W | F775W |
| MACS J0329.7−0211 | 0.450 | F225W, F275W, F336W, F390W | F275W, F390W | F775W | F850LP |
| MACS J0429.6−0253 | 0.399 | F225W, F275W, F336W | F275W, F390W, F336W | F775W | F850LP |
| MACS 0744.9+3927 | 0.686 | F275W, F336W, F390W, F435W | F275W, F275W, F336W | F140W | F105W |
| MACS J1115.9+0129 | 0.352 | F275W, F336W, F390W, F435W | F275W, F336W, F390W | F775W | F850LP |
| MACS J1206.2−0847 | 0.440 | F225W, F275W, F336W, F390W | F275W, F390W | F775W | F850LP |
| MACS J1423.8+2404 | 0.545 | F225W, F275W, F336W, F390W | F275W, F390W | F125W | F105W |
| MACS J1720.3+3536 | 0.391 | F225W, F275W, F336W | ... | F775W | F850LP |
| MACS J1931.8−2635 | 0.352 | F225W, F275W, F336W | F275W, F390W, F336W | F775W | F850LP |
| MS2137−2353 | 0.313 | F225W, F275W, F336W | F275W, F390W, F336W | F775W | F850LP |
| RXJ1347.5−1145 | 0.451 | F225W, F275W, F336W, F390W | F275W, F275W, F336W | F775W | F850LP |
| RXJ1532.9+3021 | 0.363b | F225W, F275W, F336W, F390W | ... | F775W | F850LP |
| RXJ2129.7+0005 | 0.235 | F225W, F275W, F336W | F275W, F336W, F390W | F775W | F850LP |
| RXJ2248.7−4431 | 0.348 | F225W, F275W | F275W, F336W, F390W | F775W | F850LP |
| CLJ1226.9+3332 | 0.890 | F336W,F390W, F435W, F475W | ... | F105W | F125W |
| MACS J1311.0-0310 | 0.499 | F225W, F275W, F336W, F390W | ... | F125W | F105W |

Notes.

* Redshifts are the same as those quoted in Postman et al. (2012), unless otherwise stated.

b Crawford et al. (1999).
This method for estimating Hα+[N ii] is reliable only for line emission with a large equivalent width (EW). Hα+[N ii] EWs may be approximated by

\[
EW = \int \frac{f_\lambda - f_{\text{cont}}}{f_{\text{cont}}} d\lambda \approx B_{\text{line}} \frac{f_{\text{line}} - f_{\text{cont}}}{f_{\text{cont}},}
\]

where \( f_{\text{line}} \) and \( f_{\text{cont}} \) are the fluxes through the line and continuum filters, and \( B_{\text{line}} \) is the photometric bandwidth of the line filter. If we assume a 3% uncertainty for the surface photometry in both the “line” and “continuum” filters, we can reliably recover features with Hα+[N ii] EWs that are 0.044 \( \times B_{\text{line}} \). Because the BCGs are very bright in both the “line” and “continuum” filters, so the dominant source of uncertainty on our photometry will be the absolute flux calibration. For BCGs where we adopt ACS filters (either F775W or F850LP) as the line filters, we can recover Hα + [N ii] features with EWs \( \gtrsim 20 \) Å in the observer frame. For BCGs where we adopt WFC3IR filters (either F105W or F125W), we can recover features with EWs \( \gtrsim 40 \) Å in the observer frame.

### 3.3. Other Emission Lines

Longslit spectra provide coverage of the [O ii], [O iii] \( \lambda, \lambda4959, 5007 \), and Hβ emission lines. We measure line luminosities by fitting a Gaussian line profile and a continuum to reduced, 1D longslit spectra using the IRAF task splot. Continuum levels in splot are identified by averaging regions of continuum emission adjacent to emission lines, and continuum-subtracted Gaussian line profiles are fit using the default iterative Levenberg–Marquardt algorithm. An [O ii] luminosity could not be calculated for Abell 383, owing to contamination of the spectrum at \( \sim4424 \) Å. [O iii] \( \lambda5007 \) is unavailable for RXJ1347.5–1145 since the available spectrum does include this line.

[O ii] luminosities are an independent check on the SFR derived from our UV and Hα luminosities. While [O ii] luminosities are usually considered to be a less reliable estimator of SFRs due to their dependence on ionization and metallicity, they can provide extra constraining power when used in conjunction with other SFR estimators (Charlot & Longhetti 2001; Rosa-González et al. 2002; Kewley et al. 2004; Moustakas et al. 2006). We can use Hβ luminosities in a similar fashion. Assuming case B recombination, we can derive an SFR from Hβ, using the relation Hα/Hβ = 2.85 (Veilleux 2002).

[O iii] \( \lambda5007 \) is useful for constructing diagnostic diagrams to separate regions heated by normal stars versus other sources of ionization like AGN and shocks. The classic diagram for distinguishing star-forming regions from AGNs is the BPT diagram (Baldwin et al. 1981; Kewley et al. 2001; Kauffmann et al. 2003a). We construct a modified version of the BPT diagram based on a combination of spectral and broadband data. We use an additional diagnostic, when possible, that is nearly insensitive to extinction, and only uses our spectroscopic data. The so-called “blue-line” diagram barely depends on the accuracy of the reddening correction because it is derived solely from equivalent width values. In this work, we use the “blue-line” diagram derived from the [O ii], [O iii], and Hβ lines (Lamareille et al. 2004; Lamareille 2010). Specifically, this diagram compares the ratios of equivalent widths [O ii] \( \lambda5007/H\beta \) to [O ii]/Hβ and we can measure these ratios directly from the SOAR spectra.

### 3.4. Reddening Correction

HST and SOAR observations (when stated explicitly) are corrected for intrinsic dust reddening in a manner similar to McDonald et al. (2013). Assuming continuous star formation, the young-stellar continuum \( L_*(\nu) \) in the rest wavelengths 1500–2800 Å is flat, and we can thus construct reddening maps for the CLASH BCGs by assuming the gradual slope in flux we observe between pairs of UV images is due to mild dust extinction. In most cases we select the F275W and F336W filter to calculate the reddening. Filter selections for individual BCGs are given in Table 2. Even though this procedure assumes continuous star formation, the effect of SFH is relatively small — a starburst with a finite burst duration above 10 Myr will have a slope that differs from a model with continuous star formation by \( \lesssim 5\% \).

We construct spatially resolved reddening estimates by covering the UV emission features in each BCG with grid squares \( 0''195 \) on a side, corresponding to 3 \( \times \) 3 pixels in the drizzled images. Grid squares of this size are a compromise between sensitivity and spatial resolution, and make our corrections directly comparable to the reddening correction employed in McDonald et al. (2013). Squares which do not have a minimum of 5σ of UV flux in the two filters used to calculate \( E(B-V) \) are rejected, leaving behind a grid covering just the significant UV emission, like the example given in Figure 4.

We calculate two reddening maps for each BCG, one using a Calzetti et al. (2000) extinction curve, and one using the Milky Way dust curve parameterized in O’Donnell (1994). When
using the Milky Way dust model, we avoid the effect of the 2175 Å bump by both subtracting the best-fit model of the bump in Fitzpatrick & Massa (1986) and by choosing UV filters that minimize coverage of the bump. In each grid square, $E(B - V)$ is calculated by solving for the dust extinction necessary to flatten the slope between the UV-upturn-corrected fluxes in the two filters. The resulting reddening maps are Gaussian smoothed with a 0$''$195 kernel, in order to blur out the effects of binning.

Out of the 20 clusters examined from the CLASH sample, 11 have sufficient UV flux to estimate intrinsic reddening over at least part of the BCG. Images of the estimated intrinsic reddening maps are shown in the rightmost panel for each of these clusters in Figure 3. We find that, with few exceptions, $E(B - V) \lesssim 0.5$, which is consistent with the dust content typical of cluster BCGs (Crawford et al. 1999; McDonald et al. 2011).

Non-resolved dust extinctions for UV-faint BCGs and faint regions in UV-bright BCGs are calculated using $F140W$-IRAC colors assuming an underlying early-type stellar population. These bands are suitable for estimating extinction in these galaxies and regions since the $F140W$ band is slightly extinguished at the rest wavelengths of CLASH BCGs while the IRAC bands are essentially reddening free. Furthermore, the $F140W$-IRAC color at these redshifts is insensitive to the SFH, so the assumed underlying population does not affect the
Figure 3. (Continued.)
Figure 3. (Continued.)
resulting dust estimate. Spitzer/IRAC 3.6 and 4.5 μm fluxes are available for all CLASH clusters except Abell 1423 (L. Moustakas et al. 2015, in preparation). We use fluxes measured in 3″0 diameter apertures and apply the aperture corrections used in Sanders et al. (2007), selecting either the 3.6 and 4.5 μm band for each BCG separately in order to avoid the polycyclic aromatic hydrocarbon feature at 3.3 μm rest-frame.

Detections of H2 vibrational modes are also prevalent in the IR between 5 and 25 μm in star-forming BCGs (Donahue et al. 2011). We note that the presence of these lines in IRAC filters may affect our estimate of the dust reddening; however, we are mostly relying on this estimate of the reddening in BCGs with little evidence of ongoing star formation where we would not expect there to be wide vibrational H2 lines.

We use the spatially resolved extinctions to correct observed fluxes in UV-bright structures and the non-resolved extinctions to correct fluxes outside these structures and in UV-faint BCGs. To correct line luminosities, we adopt the relation $E(B - V)_0 = 0.44E(B - V)_{ext}$ reported in Calzetti et al. (2000). While this is the empirically observed relation between the extinction of nebular and stellar emission in starburst galaxies, our choice of extinction model will introduce a systematic uncertainty, since starburst BCGs may differ from the starburst galaxies used to calibrate this relationship.

The reddening correction multiplies our values for $L_{UV}$ in UV luminous BCGs by a factor of $\sim 2$–5, which is consistent with what Donahue et al. (2015) expected, given the typical dust content of an active cool core BCG. For example, Donahue et al. (2015) reports an unobscured SFR for RXJ1532 of $\sim 40 M_\odot \text{yr}^{-1}$, which is less than the Herschel-estimated value of $\sim 100 M_\odot \text{yr}^{-1}$. The reddening corrected UV SFR for RXJ1532 we find is $97 \pm 4 M_\odot \text{yr}^{-1}$ (only accounting for statistical uncertainty). For this BCG, the reddening corrected UV SFR yields a rate comparable to the IR estimate.

3.5. Broadband Aperture Photometry

To extract photometry for estimating the mean UV luminosities ($L_{\text{UV}}$) in UV-bright BCGs, we chose regions that contain all of the substantial UV flux with the aid of the ds96 contour tool (see Figure 3). These regions trace surface brightness contours of $7.14 \times 10^{24} \text{erg s}^{-1} \text{Hz}^{-1} \text{pix}^{-2}$, corresponding to a SFR surface density of $10^{-3} M_\odot \text{yr}^{-1} \text{pix}^{-2}$. For the ten UV-faint BCGs (those lacking sufficient UV flux to make a spatially resolved estimate of reddening), we measured fluxes inside circular apertures that were as large as possible but still excluded satellite galaxies. We opted for this strategy for measuring photometry because it makes it straightforward to capture the flux in the highly irregular morphologies present in the CLASH BCGs. We calculated Hα+[N ii] luminosities using the same apertures selected for significant UV flux.

Line luminosities measured in our spectra were measured in rectangular apertures that, while similar in area in most cases to the apertures we used to measure broadband luminosities, nonetheless do not cover the same regions of the BCGs that were included in our calculations of $L_{UV}$ and $L_{H\alpha+[N \text{ ii}]}$. Therefore, when comparing line luminosities obtained from SOAR spectroscopy with broadband luminosities, it was necessary to measure the broadband luminosities in the apertures corresponding to the position and shape of the slit. Since our reduced spectra are 1D, we used the mean value of $E(B - V)$ in each rectangular aperture to estimate the extinction correction for both the spectral line luminosities and the UV and Hα+[N ii] luminosities we compare them to.

3.6. Stellar Population Properties

We use iSEDfit to calculate the probability distributions for model approximations of the SED in RXJ1532.9+3021, either in single apertures or in individual pixels to create stellar parameter maps. See Moustakas et al. (2013) for details on iSEDfit. SEDs are composed of fluxes extracted from identical apertures (or individual pixels), in each of the 16 bands of CLASH HST photometry. We do not correct for fluxes for intrinsic reddening, since iSEDfit allows for local extinction to be treated as a fit parameter.

When creating parameter maps using SEDs fit on individual pixels, we point-spread function (PSF)-match each image to the F160W PSF and extract SED for each pixel using the PSF-matched photometry. For approximately normally distributed parameters, we assigned the mean values for the posterior probability density functions (PDF) for model SED parameters for each pixel SED to the locations of pixels in order to create maps of the BCG. The model predicted rest-frame flux for Hα+[N ii] provides a sanity check on the physical parameter maps for the 16 band SED, since we can compare its morphology to the $L_{H\alpha+[N \text{ ii}]}$ map described in Section 3.2. The two images are shown in Figure 5 with matching coordinates, where it can be seen that the filamentary features in the $L_{H\alpha+[N \text{ ii}]}$ map correspond to the features derived from the SED. The two images depict the same pair of Hα “bulges” in the center of the BCG as well.

4. RESULTS

4.1. Broadband Luminosities and SFRs

Mean UV and Hα+[N ii] luminosities are given in Table 3. We present the reddening corrected ($L_{\text{UV}}$) both for a Calzetti reddening law and for Milky Way-type dust. Luminosities are converted to SFRs using the Kennicutt SFR calibrations. There are several sources of potential scatter in this estimate, including contamination of the UV luminosity by AGN activity, and variations in the IMF and SFH of the stellar population (Kennicutt 1998, assumes a continuous SFH and a
Salpeter 1955, IMF). For the $L_{UV}$ based SFR estimates, we have not attempted to correct for these effects. However, the UV features we observe are not likely to be due to AGN activity, which is ruled out by the complicated UV morphology reported in Donahue et al. (2015).

In order to estimate H$_o$ based SFRs using Kennicutt (1998), we need to estimate the ratio [N ii]/H$_o$. The line ratio of [N ii] to H$_o$ can vary between BCGs, and within filamentary structures in BCGs, so whatever choice we adopt will add scatter to our estimate of the H$_o$ based SFR (Crawford et al. 1999; McDonald & Veilleux 2009; McDonald et al. 2014a). This ratio is typically 0.5 for optical galaxies (Kennicutt 1992; Kewley et al. 2001, 2004). However, the ratio [N ii]/H$_o$ is often larger than 0.5 in BCGs (Heckman et al. 1989; Crawford et al. 1999). For H$_o$ luminous BCGs in the X-ray selected sample of clusters in Crawford et al. (1999), the typical [N ii]/H$_o$ $\lambda$6584/H$_o$ is 1.1 $\pm$ 0.4. We adopt this value in order to calculate SFRs using $L_{H_o+[N\,ii]}$, bearing in mind that this is a rough approximation with considerable scatter. Nonetheless, we believe that variation in [N ii]/H$_o$ is a secondary consideration for the purposes of estimating SFRs, given the scatter in the Kennicutt (1998) calibrations between $L_{H_o}$ and SFR and between $L_{UV}$ and SFR.

The correlation between UV and H$_o$+[N ii] luminosities is shown in Figure 6. The two luminosities are broadly consistent with the ratio expected from Kennicutt (1998), in that the SFR estimates derived from the UV and H$_o$+[N ii] luminosities are consistent with each other. This result is differs from the findings of McDonald et al. (2010, 2011), since they find on average the UV/H$_o$ ratio is slightly lower than that predicted from the Kennicutt relationships. This is most likely because they do not correct for extinction due to dust in the BCG. Indeed, they propose adding a correction of $E(B-V)$ = 0.2 to their data, which would make their results consistent with continuous star formation, and this value is typical for the dust extinction we observe in CLASH BCGs.

UV SFRs are correlated with the areas of the star-forming region in CLASH BCGs (Figure 7). CLASH BCGs have an average SFR surface density ($\Sigma SFR$) of $\sim$0.3 $M_{\odot}$ yr$^{-1}$ kpc$^{-2}$, with typical values ranging between $\sim$0.1–0.4 $M_{\odot}$ yr$^{-1}$ kpc$^{-2}$. Areas of the UV flux emitting regions were measured using the F336W filter. In order to calculate the uncertainty, we sampled the distribution of fluxes in each pixel in the regions shown in Figure 3 using a Monte Carlo method, which we used to create a distribution of flux-emitting areas. The exception to this is MACS 1931.8–2635, which exhibits a $\langle \Sigma SFR \rangle$ of 0.83 $\pm$ 0.06 $M_{\odot}$ yr$^{-1}$ kpc$^{-2}$.

4.2. SOAR Spectra Results

The CLASH BCG UV and [O iii] luminosities, displayed in Figure 8, scale with each other, but produce divergent SFR estimates. However, UV and H$_\beta$ luminosities (Figure 9) have a tight correspondence and produce consistent estimates of the SFR in CLASH BCGs. The agreement between UV and H$_\beta$ based SFRs is tighter than the agreement between UV and H$_o$+[N ii] derived SFRs, which is to be expected considering the limited precision of SFRs estimated using broadband H$_o$+[N ii].

The SFR–$L_{[O\,iii]}$ relation we use is calculated in Kewley et al. (2004) by using a sample mean [O iii]/H$_\alpha$ to convert from the Kennicutt (1998) SFR–$L_{H\alpha}$ relation to an SFR–$L_{[O\,iii]}$ relation. However, the theoretical value of $L_{[O\,iii]}$/SFR depends on the metallicity of the nebular region (peaking near $Z \sim 0.5 Z_\odot$) as well as ionization parameter (peaking near $q \sim 1 \times 10^7$ cm$^{-s^{-1}}$) (Kewley et al. 2004). CLASH BCG reddening corrected flux ratios [O iii]/[O ii] are typically $\sim$0.1, implying an ionization parameter near $q \sim 1 \times 10^7$ cm$^{-s^{-1}}$ for solar and sub-solar metallicities (Kewley & Dopita 2002). The combination of these two parameter dependencies may explain the systematic tension between UV and [O iii] SFRs. Furthermore, the offset between UV and [O iii] SFRs we observe in CLASH clusters is consistent with the observation in Kennicutt (1998) that $L_{[O\,iii]}$/SFR is typically boosted in starbursts relative to galaxies undergoing continuous star formation by a factor of $\geq 2$.

SOAR spectra were also used to constrain the source of the photoionizing emission we observe. We place active CLASH BCGs on the blue-line diagnostic diagram for distinguishing starbursting galaxies from AGN, described in Lamer et al. (2004) and Lamareille (2010), as well as on the BPT diagram, in Figure 10. We cannot directly separate H$_\alpha$ from [N ii] in our broadband H$_o$+[N ii] fluxes, so when available, we use line fluxes from the SDSS Data Release 127 to determine the locations of CLASH BCGs on the BPT diagram (Alam et al. 2015). In order to place the remaining active BCGs on the BPT diagram, instead of comparing [O iii]/H$\beta$ to [N ii]/H$_\alpha$, we compare [O iii]/H$\beta$ to $X \equiv 0.75 \left( \frac{H_\alpha + [N\,ii]}{2.85 \, H_\beta} \right)$. Our expression for $X$ assumes case B recombination. Regardless of the presence of AGN emission, case B recombination allows us to derive a reasonable estimate of the ratio of H$_\alpha$ to H$_\beta$, since for systems with hydrogen densities in the range $10^3$–$10^6$ cm$^{-3}$, H$_\alpha$/H$_\beta$ $\sim$ 2.7–3.2 (Netzer 2013). Because AGN often produce harder photoionizing spectra than young stellar populations, our assumption will tend to bias $X$ slighter higher than [N ii]/H$_\alpha$ in the presence of an AGN. However, such a bias will cause the estimated line ratios to appear more “AGN-like,” so the resulting BPT diagram is a conservative estimate of the contribution of ongoing star formation to the line ratios we observe. The positions of BCGs on the BPT diagram determined using $X$ depend on both the accuracy of our reddening corrections and broadband H$_o$+[N ii] estimates. Therefore, their value is primarily as a consistency check of the blue-line diagram.

\footnote{http://dr12.sdss3.org/}
For the blue-line diagram, we use equivalent widths observed with SOAR for all CLASH BCGs except Abell 383 and MACS 1423.8+2404. Since these BCGs have incomplete line flux data from the SOAR spectra (Abell 383 does not have an [O III] measurement and MACS 1423 has an upper limit for [O III] $\lambda$5007 estimated from an upper limit of [O III] $\lambda$4959) but were observed in Data Release 12, we use SDSS equivalent widths for these lines instead. In general, our SOAR spectra are better suited to observing extended nebular emission in CLASH BCGs because we were able to place the slit to maximize coverage of the nebulae. We overplot our results on the SDSS galSpec\footnote{http://www.sdss.org/dr12/spectro/galaxy_mpajha/} galaxy sample (Kauffmann et al. 2003b; Kauffmann et al. 2010 November 10).
Brinchmann et al. 2004; Tremonti et al. 2004). CLASH BCGs tend to lie in a particular region of this diagram, with low [O iii]/Hβ and high [O iii]/Hβ relative to the SDSS dataset. Our results imply that most of the BCGs lie in the composite star-forming-LINER region described in Lamareille (2010), with the exception of MACS J1931.8–2635.

The BPT diagram shows the Kewley et al. (2001) line in blue and Kauffmann et al. (2003a) line in green. CLASH BCGs are distributed in the star-forming and composite star-forming regions of the diagram. The CLASH BCGs cluster around log ([O iii]/Hβ) ~ −0.3, which puts them below the BPT discriminating boundary between star-forming galaxies and AGN (Kauffmann et al. 2003a). The exception to this is MACS 1931, which is consistent with emission powered predominantly by star formation. We observe an X-ray AGN in the Chandra image of MACS 1931; however, given the extent of the UV emission region it makes sense to classify the BCG as starbursting. For the most part, the blue-line and BPT indicate consistent sources powering line emission in CLASH BCGs.

Based on these diagnostics, we conclude that the line emission in most of the BCGs is either predominantly due to ongoing star formation, or to a composite star-forming-LINER-like source. In particular, the two most UV luminous BCG in our sample, MACS 1931 and RXJ1532, are consistent with star formation being the main photoionization mechanism when taking into account both diagnostic diagrams. MACS 1720, MS2137 and possibly Abell 383 may be LINERS, although much of their UV and Hα+[N ii] flux is not in a nuclear emission region. Likewise, the majority of the composite galaxies fall into the composite star-forming-LINER classification. This is consistent with previous results finding LINER-like emission in cool-core BCGs (Véron-Cetty & Véron 2000; Edwards et al. 2007). However, while the emission line diagnostics in these BCGs are LINER-like, they cannot be LINERs since they cannot be powered by a central black hole (Heckman et al. 1989). Several hypotheses have been proposed for the source of this extended LINER-like emission. Stellar populations may be responsible for this emission, which could be due to photoionization from O-stars and young starbursts, shocks, and old stars (Shields 1992; Ilison et al. 2010; Loubser & Soechting 2013). Emission lines may also be due to nebular gas being heated by the surrounding medium (e.g., Donahue & Voit 1991; Werner & Oonk 2013), or collisional heating (Sparks et al. 1989; Ferland et al. 2009).

### 4.3. Correlation with ICM X-Ray Properties

#### 4.3.1. Core Entropies

SFRs derived from $L_{UV}$ in our sample are correlated with the X-ray properties of the ICM. Figure 11 shows the relationship between CLASH BCG SFRs and ICM core entropies. The core entropy $K_0$ used in the present study is defined to be the innermost bin of the entropy profile in ACCEPT, and is a proxy for the existence of a cool core in a galaxy cluster (Hudson et al. 2010). Entropy as measured by X-rays is defined to be

$$K \equiv k T_e n_e^{-2/3},$$

where $T_e$ is the X-ray temperature in keV, $n_e$ electron density in cm$^{-3}$, and $k$ is the Boltzmann constant.

Low values of $K_0$ typically accompany activity in BCGs. BCG activity, such as elevated NUV flux relative to the predicted quiescent UV emission, is observed to occur only in clusters where $K_0 \lesssim 30$ KeV cm$^2$ (Cavagnolo et al. 2008; Hoffer et al. 2012). McDonald et al. (2010) reported on this phenomenon as well with resolved Hα emission maps in low-redshift BCGs. In Donahue et al. (2015), a similar entropy threshold was found for the UV-NIR color of CLASH BCGs, indicating the threshold does not change substantially out to $z \sim 0.5$.

Here, we demonstrate that a tight correlation exists between reddening corrected SFRs and $K_0$. Specifically, all of the BCGs with an SFR $> 10 M_\odot$ yr$^{-1}$ have a core entropy consistent with a value $\lesssim 30$ KeV cm$^2$ (see Figure 11). Meanwhile, BCGs that
is the averaged X-ray cooling time at radius $r$. $n_kT$ is the azimuthally average X-ray gas density, and $n_k$ is the gas mass enclosed in the radius $r$. We use

$$n_k = \frac{3}{2} \frac{M_{\text{enc}}(r)}{r_{\text{cool}}(r)}$$

where $M_{\text{enc}}(r)$ is the gas mass enclosed in the radius $r$. We use

$$t_{\text{cool}} = \frac{3}{2} \frac{n_k T}{n_H} \Lambda(Z, T)$$

to define the cooling time, and use the assumption in Cavagnolo et al. (2009) that $n \approx 2.3 n_H$. The cooling curve $\Lambda(Z, T)$ is estimated by interpolating the Sutherland & Dopita (1993) cooling function at solar metallicity.

We choose to measure $M_{\tilde{\text{r}}}(r)$ at $r = 35$ kpc ($M_{\text{r},35}$), and at the radius in each cluster where the ratio between the cooling time and free-fall time is $t_{\text{cool}}/t_{\text{ff}} = 20$ ($M_{\text{r},20}$). We calculate lack significant UV or $H_\alpha + [N\,\!k]$ luminosities occupy a range of core entropies that extends up to $\sim 200$ keV cm$^2$. Considering the difference between the two observables, the tight correspondence between SFR and core entropy is compelling.

4.3.2. Core $M_{\text{r}}$ Estimates

ICM cooling rates inferred by Chandra observations of clusters bear little relation to the actual cooling rate in cool-core clusters (e.g., McNamara & O’Connell 1989). However, we may to be able to find a relationship between star formation and a simple proxy for cooling at radii where we hypothesize ICM cooling actually occurs. The quantity we examine, $M_{\text{r}}(r)$, is analogous to the predicted cooling rate as a function of radius, and is defined by

$$M_{\text{r}}(r) = \frac{4\pi}{t_{\text{cool}}(r)} \int_0^r \rho_g(r) r^2 dr$$

$$= \frac{M_{\text{enc}}(r)}{t_{\text{cool}}(r)}$$

where $\rho_g(r)$ is the azimuthally average X-ray gas density, and $t_{\text{cool}}(r)$ is the averaged X-ray cooling time at radius $r$. $M_{\text{enc}}(r)$ is the gas mass enclosed in the radius $r$. We use

$$t_{\text{cool}} = \frac{3}{2} \frac{n_k T}{n_H} \Lambda(Z, T)$$

to define the cooling time, and use the assumption in Cavagnolo et al. (2009) that $n \approx 2.3 n_H$. The cooling curve $\Lambda(Z, T)$ is estimated by interpolating the Sutherland & Dopita (1993) cooling function at solar metallicity.

We choose to measure $M_{\text{r}}(r)$ at $r = 35$ kpc ($M_{\text{r},35}$), and at the radius in each cluster where the ratio between the cooling time and free-fall time is $t_{\text{cool}}/t_{\text{ff}} = 20$ ($M_{\text{r},20}$). We calculate free-fall times by estimating cluster density profiles as the sum of NFW profiles derived from lensing in Merten et al. (2015) and singular isothermal sphere profiles of BCG stellar density derived from stellar mass estimates in Burke et al. (2015). The impact of the stellar mass component on our overall result is not substantial; however, we include it for completeness. $M_{\text{r},35}$ is useful to measure because 35 kpc is typical of the maximum radius we observe $H_\alpha + [N\,\!k]$ and UV structures in CLASH clusters, and because this radius maximizes the correlation between UV SFR and $M_{\text{r}}(r)$ (see Figure 12). This quantity can be calculated for all the CLASH clusters using ACCEPT data.
The choice of $M_{r,20}$ reflects the finding that BCG activity occurs in clusters with a minimum $t_{\text{cool}}/t_{\text{ff}}$ between 4 and 20 (Voit et al. 2015b). Since BCG activity is associated with potentially cooling ICM gas where $t_{\text{cool}}/t_{\text{ff}} \leq 20$, $M_{r,20}$ measures the predicted cooling rate in gas that we suspect is directly involved in cooling. Radii where $t_{\text{cool}}/t_{\text{ff}} = 20$ are listed for each cluster in Table 4. Clusters where $t_{\text{cool}}/t_{\text{ff}} > 20$ in the innermost bin of the cooling time profile calculated from ACCEPT data are not included.

We show the relationship between the UV SFR and both $M_{r,35}$ and $M_{r,20}$ in Figure 13. The dashed lines denote, from right to left, where the BCG is forming stars at 100%, 10%, 1%, and 0.1% of the cooling rate implied by $M_{r}$. If we interpret the SFR as a proxy for the actual cooling rate in this system, and interpret $M_{r}$ as the “potential” cooling rate in the absence of feedback, then the larger starbursts are cooling much more efficiently than smaller starbursts, and these lines indicate where the “efficiency” is 100%, 10%, 1%, and 0.1%.

We fit trend lines to the data for both the SFR–$M_{r,35}$ and SFR–$M_{r,20}$ relations using orthogonal least squares regression. We find that the slope on the trends fit to the two datasets ($0.35 \pm 0.05$ for SFR–$M_{r,35}$ and $0.27 \pm 0.06$ SFR–$M_{r,20}$) are nearly consistent, leading to the conclusion that the two definitions of $M_{r}$ measure a similar quantity.

Several limitations impacting our measurements may affect how tightly correlated SFR–$M_{r}$ (both $M_{r,35}$ and $M_{r,20}$) appear to be in our data. Gas density profiles in ACCEPT have a limited resolution (between 10 and 30 kpc per bin depending on the CLASH cluster), so values for $M_{\text{enc}}$ are typically calculated by interpolating on the central few bins of each profile. Temperature profiles are less well resolved than $\rho_{g}$ profiles, which adds scatter to our estimate of $t_{\text{cool}}(r)$ profiles. Deeper X-ray observations will beat down the systematics in $M_{r}$, and a larger sample of cool core clusters will allow us to more precisely constrain the SFR–$M_{r}$ relationship and examine the effects of sample selection. With our current data, we establish that a relationship exists between these two quantities, and that this relationship implies that as the BCG SFR increases, there is a steady increase in the ratio of ongoing star formation relative to the predicted cooling time in the reservoir of hot gas.

**4.4. Model Fitting to RXJ1532.9+3021**

We adopt RXJ1532.9+3021 as a case study and use its HST SED to delve into the SFH of the BCG in this galaxy cluster. RXJ1532 exhibits the second highest star formation in our...
Figure 14. We show the two-dimensional posterior probability distributions for $\Delta_{\text{tot}} \times \text{SFR}$, $\Delta_{\text{tot}} \times \text{Burst Mass}$, $\Delta_{\text{tot}} \times \text{Total Mass}$, SFR $\times \text{Burst Mass}$, SFR $\times \text{Total Mass}$, and Burst Mass $\times$ Total Mass. Black points denote the individual Monte Carlo draws used to construct the posterior probability distribution, and contours are the 68%–95%–99.7% contours calculated from the kernel density estimate smoothed distribution. The marginal distributions for individual parameters are shown by the histograms on the diagonal.

The histograms on the diagonal.

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- star-forming galaxy in our sample, MACS J1931.8

sample and is replete with UV and H$\alpha$ bright filaments and knots. This BCG makes a better case study than the strongest star-forming galaxy in our sample, MACS J1931.8–2635, because the latter exhibits a strong X-ray AGN which could complicate pixel-scale SED fitting. RXJ1532 also has detailed auxiliary data including an SDSS spectrum covering H$\alpha$ and [N II] and a deep Chandra observation (Hlavacek-Larrondo et al. 2013). RXJ1532 is therefore an excellent prototype for exploring the characteristics of the star-forming regions in CLASH BCGs.

We both fit a single-aperture SED from the region used to calculate $L_{\text{UV}}$ and constructed stellar parameter maps. The best-fit SFR in the single-aperture SED is $118^{+25}_{-15} M_\odot$ yr$^{-1}$. The average extinction is $E(B-V) = 0.27 \pm 0.07$. Since the posterior probability distribution of the SFR is close to log-normal, the best-fit value we report is the mode of the distribution and the uncertainty we report is the 68.3% confidence interval. The best-fit starburst is relatively long-lived, with a burst duration $\log \Delta t_{\text{b}}$ [Gyr] = $-0.16 \pm 0.47$, and massive, with a total burst mass $\log M_{\text{b}}$ [M$_\odot$] = $11.03 \pm 0.36$. The burst parameters in the fit have degeneracies (see Figure 14), although the peaks in the probability distribution suggest that we are constraining the parameters.

We show stellar parameter maps in Figure 15, including $\Delta t_{\text{b}}$, the SFR, and the spatial distribution of the total mass of the BCG. Star formation is concentrated in knots in the center of the BCG, along with a network of six bright filaments and several dimmer filaments. The SFR morphology is consistent with the H$\alpha$ and UV morphology. The sum of the pixel SFR modes in the single-aperture SED region is $119 M_\odot$ yr$^{-1}$, which matches the single-aperture value remarkably well.

Two filaments point south (A in Figure 15), two point northwest (B, C1), one points southeast (C2), and one extends northward before bending to the east (D). The filament pointing southeast and the brighter northwest pointing filament (C1 and C2) appear to lie along a single axis. The clumps in the core and the filaments in the north account for the bulk of the ongoing star formation. The starbursts in these structures are long-lived, on the order of $10^8$–$10^9$ years, which is consistent with the results of the single aperture SED. The filaments to the south, and the two that lie along a single southeast–northwest axis passing through the center of the BCG, are more an order of magnitude younger than the rest of the burst system.

The peak and western “bulge” in the total mass corresponds to the central knot morphology in the BCG. Meanwhile, two roughly conical “drop-offs” appear to the east and west, and both of them extend outward from the positions of star-forming filaments. Similar drop-offs are visible at the positions of the young, southern filaments. These drop-offs may reflect real deficits in the stellar surface density of the BCG, but may also be a consequence of the dust geometry in this system. Since dusty filaments in the BCG screen the elliptical stellar populations behind them, it is possible that the drop-offs are regions where the mass estimate is biased low due to the positions of filaments along the line of sight.

In the Appendix, we demonstrate that the iSEDfit derived values for SFR and $E(B - V)$ agree with the broadband values.
Δ roughly along the positions of bright NW features in the parameter maps. The SFR map is in units of \(M_\odot\) yr\(^{-1}\), \(\Delta t_b\) in log Gyr, and the total mass in units of \(M_\odot\) pix\(^{-2}\). All values are expectation values. \(\log \Delta t_b\) is masked to only depict regions where the likelihood of a starburst is \(\geq 1\sigma\). The pair of filaments to the south of the center of the BCG, and the filament along the NW/SE are noteworthy for being by \(\geq 1\) order of magnitude younger than the average age of the starburst in this system. Possible conical shaped underdensities are roughly along the positions of bright filaments. At the redshift of the cluster, \(z = 0.363\), the 3′ reference scale in the figures corresponds to about 15.2 kpc.

Figure 15. Two-dimensional maps of SFR, \(\log \Delta t_b\), and the total mass surface density for RXJ1532. The bottom right panel provides labels for the morphological features in the parameter maps. The SFR map is in units of \(M_\odot\) yr\(^{-1}\), \(\log \Delta t_b\) in log Gyr, and the total mass in units of \(M_\odot\) pix\(^{-2}\). All values are expectation values. \(\log \Delta t_b\) is masked to only depict regions where the likelihood of a starburst is \(\geq 1\sigma\). The pair of filaments to the south of the center of the BCG, and the filament along the NW/SE are noteworthy for being by \(\geq 1\) order of magnitude younger than the average age of the starburst in this system. Possible conical shaped underdensities are roughly along the positions of bright filaments. At the redshift of the cluster, \(z = 0.363\), the 3′ reference scale in the figures corresponds to about 15.2 kpc.

and show that the SED predicted \(H_\alpha+[\text{N} \text{II}]\) line emission feature matches the SDSS spectrum. We also discuss the importance of the \(H_\alpha\) feature to characterizing the SFH using SED fitting. The particulars of the SFH model (a uniform starburst superimposed on an exponentially decaying SFH) and our choice of parameter space are documented in the Appendix as well.

5. DISCUSSION

Half (10 out of 20) of the X-ray selected sample of CLASH clusters show evidence for significant (>5 \(\sigma\)) rates of reddening-corrected star formation using both UV and \(H_\alpha\) indicators. CLASH BCGs occupy regions of line diagnostic diagrams that are typical of composite star-forming-LINER galaxies, and in several cases line emission may be primarily powered by star formation. This rate of incidence is substantially higher than previous published rates of incidence of star formation or line emission in X-ray selected cluster BCGs, which are in general closer to 20%–30% (e.g., Crawford et al. 1999; Edwards et al. 2007). However, the CLASH X-ray selected sample differs from these populations of galaxy clusters, since it is comprised of high gas temperature (\(kT_x \gtrsim 5\) keV) clusters chosen according to a relaxation criterion based on X-ray morphology. The CLASH sample of BCGs has an incidence of line emission similar to the incidence of line emission in REXCESS cool core clusters (70%) (Donahue et al. 2010). Our sample characteristics differ from REXCESS in that it is at higher redshift (\(z = 0.2–0.7\) compared to \(z = 0.06–0.18\) and along with being X-ray selected, CLASH clusters were selected for exhibiting relatively condensed, round X-ray isophotes.

The trends between \(L_{\text{UV}}\) and \(L_{H_\alpha+[\text{N} \text{II}]\text{,}\ \sigma}\) and between \(L_{\text{UV}}\) and \(L_{\text{H} \beta}\) suggest applying the Kennicutt SFR calibrations produces consistent SFRs. However, SFRs predicted using \(L_{[\text{O} \text{II}]\text{,}\ \sigma}\) are systematically elevated relative to UV based SFRs. This is in contrast to our findings using \(L_{\text{H} \alpha+[\text{N} \text{II}]\text{,}\ \sigma}\) and \(L_{\text{H} \beta}\) both of which predict SFRs consistent with \(L_{\text{UV}}\). These results may not be unusual for starburst galaxies, although they may also indicate that the \([\text{O} \text{II}]\) emission line is being partially powered by an additional source heating the ionized gas.

The SFRs in several BCGs are very large. In particular, two galaxies exhibit SFRs >100 \(M_\odot\) yr\(^{-1}\), and an additional five have SFRs > 10 \(M_\odot\) yr\(^{-1}\). The strongest star formers (MACHS 1931, RXJ1532) are forming stars several times more slowly than the Phoenix cluster, which to date exhibits the largest known SFR of a BCG (McDonald et al. 2013, 2014b). However, MACHS 1931 is noteworthy because its UV SFR (280 \(M_\odot\) yr\(^{-1}\)) is \(~40%\) of the cooling rate in the absence of heating (\(~700 \ M_\odot\) yr\(^{-1}\)) measured in Ehlerl et al. (2011). The Phoenix SFR is \(~30\%\) of the cooling rate in the absence of heating measured in McDonald et al. (2014b), so it is plausible that MACHS 1931 and the Phoenix cluster harbor BCGs undergoing similar feedback events. The presence of an X-ray AGN in each BCG also suggests that the AGN is undergoing a similar evolutionary phase. Furthermore, MACHS 1931 is forming stars more densely than the rest of the CLASH sample, which suggests it is an outlier relative to other star-forming BCGs.
5.1. BCG–ICM Interactions

Examination of core entropies implies that the extended star-forming features in CLASH BCGs are likely due to an interaction between the BCG and the enveloping ICM. Reddening corrected SFRs obey the 30 keV cm\(^2\) core entropy threshold reported in e.g., Hoffer et al. (2012)—all the strong star formers (SFR > 10 \(M_\odot\) yr\(^{-1}\)) fall at or below the threshold. From these results we conclude that ongoing star formation in the BCGs is correlated with the thermodynamics of the surrounding ICM. It is plausible that a low ICM core entropy is necessary for the onset of star formation in these BCGs. However, it does not directly trigger star formation, as evidenced by the existence of low-SFR BCGs with core entropies below 30 keV cm\(^2\).

We also analyze observables related to cooling in the low-entropy ICM surrounding BCGs, in order to better understand the interaction between the low-entropy ICM and BCG starbursts. We define two quantities, \(M_{\ast, r, 35}\) and \(M_{\ast, r, 20}\), which approximate the cooling rate of ICM gas in the vicinity of the BCG. For both definitions of the cooling rate, we observe a similar trend between SFR and \(M_{\ast}\). The positive correlations between SFR and both \(M_{\ast, r, 35}\) and \(M_{\ast, r, 20}\) are reasonable since the low-entropy gas near the BCG is a prime candidate for the reservoir of gas that cools to become star-forming molecular gas. Since the correlation between SFR and \(M_{\ast, c}(r)\) drops as \(M_{\ast, c}(r)\) is measured at larger radii, these findings are consistent with the tension between observed ICM cooling rates those predicted by measuring ICM gas masses with \(t_{\text{cool}}\) less than a Hubble time.

Recent theoretical work has made significant progress in identifying some of the key elements of the AGN feedback processes in clusters of galaxies. Simulations in which cold gas drives the accretion onto an AGN have been done by Gaspari et al. (2012), Li & Bryan (2014a, 2014b), Li et al. (2015). Gaspari et al. (2012) modeled bi-polar AGN jets heating an ICM atmosphere, following up on the work of McCourt et al. (2012) and Sharma et al. (2012), who found that circumbulgalactic gas in which heating balances cooling globally becomes thermally unstable when \(t_{\text{cool}} / t_{\text{ff}} \lesssim 10\). Gaspari et al. (2012) found that this criterion also demarcated the transition to a multiphase medium in simulations relying on AGN jet heating fueled by cold gas. Gaspari et al. (2013, 2015) extended this work by focusing on the sub-pc scale behavior and demonstrated that chaotic cold accretion could significantly increase the accretion rate onto the central black hole, relative to the Bondi rate one would infer from the thermal state of the hot phase alone. Li & Bryan (2014a) examined a mechanism similar to that in Gaspari et al. (2012), implementing bi-polar AGN jet feedback, fueled by cold gas, in an ENZO adaptive mesh simulation. They found that AGN feedback balanced cooling robustly, and generated episodic behavior on timescales of a Gyr, in alignment with the work of Gaspari et al. (2012). The scale and filamentary nature of the cold filaments in Li & Bryan simulations resemble those we observe, and the ages of star-forming filaments we recover in RXJ1532 are consistent with a Gyr duty cycle.

Star formation in the context of bi-polar AGN feedback triggered by cold gas was first tracked in Li et al. (2015), and that simulation exhibits episodic outbursts of star formation on Gyr time scales, as well as filamentary structures of cold star-forming gas tens of kpc long, while the minimum threshold of \(t_{\text{cool}} / t_{\text{ff}}\) varies from 5 to 20 over the course of any single outburst. These simulations reproduce UV morphologies similar to those of cool-core BCGs in CLASH, shown in Donahue et al. (2015), and of lower-redshift BCGs studied in Tremblay et al. (2015). The earlier simulation work described here inspired the analytic precipitation model framework described in Voit et al. (2015a) and Voit & Donahue (2015), which compared the implications of a minimum cooling time to free fall time to the bimodal entropy profiles seen in X-ray observations of clusters from the ACCEPT database (Cavagnolo et al. 2008). Voit et al. (2015b) extends this precipitation framework to lower-mass galaxies and derives interesting implications for the connections between galaxy mass, mass of the central black hole, star formation efficiency, and chemical composition.

Since jet-triggered precipitation ought to have a morphological relationship with the jet and a characteristic timescale set by the AGN duty cycle, we can look for evidence that may support or contradict this prediction by comparing the SED-derived stellar parameter maps in RXJ1532 to X-ray measurements of recent AGN activity. In the single-aperture SED of RXJ1532, the starburst lifetime is \(\Delta t_{\ast} \approx 8 \pm 0.5 \times 10^7\) years, so the bulk of the starburst has a lifetime on the order of \(\sim 1\) Gyr. However, the southern filaments and the northwest–southeast filaments are \(10^7–10^8\) years old. The Chandra X-ray image reveals two well-defined cavities to the east and west of the BCG, and possible evidence of ghost cavities to the north and south (Hlavacek-Larrondo et al. 2013). The cavity refill times, which are the largest estimates of the cavity ages provided by Hlavacek-Larrondo et al. (2013), are \(6.3 \pm 0.7\) and \(8.2 \pm 0.7 \times 10^7\) years. The cavities appear to be young relative to the timescale of the starburst we recover in our analysis, but match the ages of the young filaments. Our results in RXJ1532 are consistent with an ongoing process of clumps and filaments precipitating out of the ICM when pushed out of equilibrium by jets. Application of the SED fitting techniques developed in this paper to other BCGs in the CLASH sample will determine if this narrative is consistent for all of the star-forming BCGs.
The cavities in RXJ1532 also appear to be aligned with the northwest–southeast oriented young filament, and anti-aligned with the shape of the BCG filament network more generally. This morphological relationship is depicted in Figure 16. The young filament traces one of the bright Hα filaments as well. The most prominent X-ray cavity corresponds to the brighter (western) end of this filament, suggesting a system with the western edge inclined toward us. Given the available data, we do not rule out a coincidence; however, the corresponding ages and morphologies suggest jet-triggered formation of the young filaments. We hypothesize that the northwest–southeast filament may have been the result of positive feedback triggered by compression from a jet infalling the X-ray cavities.

The narrative we propose for RXJ1532 may be typical for other BCGs in cool core clusters. The SFH of RXJ1532 agrees with a study of line emitting BCGs in the SDSS survey produced by Liu et al. (2012). While their interpretation of the burst history differs from ours (they assume a stellar population divided into three components—a recent starburst, young stars, and old stars), they find that the majority of the flux they observe in that sample of BCGs is due to stars forming within ~2.5 Gyr. Furthermore, estimates of molecular gas masses imply that BCG starbursts typically have fuel to last ~1 Gyr (O’Dea et al. 2008). While the case of RXJ1532 may be extreme in terms of SFR, its burst history may be the norm for star-forming BCGs. The sum of the results described here, taken in addition to the evidence provided by Donahue et al. (2015), shows agreement between the resolved star structures we observe in the CLASH BCGs and recent theoretical work on feedback in cool core clusters.

If gas is condensing out of the ICM and feeding star formation, then we expect a general trend between the SFR and our $M_d$. The idea of an AGN jet-driven mechanism for ICM condensation could also account for our finding that as the SFR increases in the BCG, the SFR accounts for a larger fraction of the total cooling implied by $M_d$, $M_{e,r,75}$ and $M_{e,r,20}$ can be interpreted as the cooling rate of gas in these radii in the absence of reheating. Based on this interpretation, we suspect that larger starbursts occur in BCGs where gas is cooling more efficiently. The correlation between cool core BCG SFRs and “efficiency” can be explained neatly if cooling is localized around AGN jets and cavities, or if in systems with stronger cooling a larger fraction of the gas with $t_{cool}/t_{ff} < 20$ is at $t_{cool}/t_{ff} \lesssim 10$. If larger SFRs occur in BCGs exhibiting AGN feedback in larger areas, a larger fraction of unstable ICM gas inside a given radius may be triggered into condensing by feedback. This scenario is consistent with our finding that SFR is correlated with the area of the star-forming regions in BCGs.

In the feedback cycle modeled in Li et al. (2015), a large amount of gas is cooled quickly with the initial onset of jet feedback (on the order of 10s of Myr), and is slowly consumed by star formation (on the order of a Gyr). Larger SFRs tend to occur earlier in the feedback cycle, when proportionally more of the ICM is precipitating. If this concern dominates the SFR–$M_d$ relationship, then we expect to see evidence that larger BCG starbursts are younger on average. In RXJ1532, we see evidence connecting the durations of star-forming knots and filaments to the duration of AGN activity (as evidenced by estimates of the ages of X-ray cavities in this system), although a more detailed study of multiple systems will be necessary to establish whether or not there is a relationship between burst age, SFR, and low-entropy ICM gas.

6. CONCLUSION

We have conducted a detailed analysis of the star-forming structure in the BCGs in the CLASH X-ray selected sample of galaxy clusters. Using the rich set of CLASH photometry, we estimated the dust reddening in BCGs with significant UV emission and calculated reddening corrected mean UV luminosities and Hα+[N ii] luminosities. We compared these measurements to observations of [O iii] and Hβ taken using the Goodman spectrograph. Additionally, we compared the UV derived SFR to X-ray properties calculated using the ACCEPT catalog, including the core entropy, $K_0$, and predicted cooling rates for low entropy gas inside $r = 35$ kpc ($M_{e,r,35}$) and inside radii where $t_{cool}/t_{ff} = 20$ ($M_{e,r,20}$). We concluded our analysis by creating a resolved map of the starburst in RXJ1532.9+3021, for which we also have a SDSS spectrum and detailed X-ray data from Hlavacek-Larrondo et al. (2013).

Using measurements of [O ii], [O iii], and Hβ lines in conjunction with broadband Hα+[N ii] estimates, we constructed diagnostic diagrams for the CLASH BCGs in order to constrain the line-emission power source in these galaxies. Line emission in CLASH BCGs are powered by a combination of star formation and a LINER-like source (possibly the signature of hot, young stars or interaction between the ICM and nebular gas), while the biggest starburst (MACS 1931) has a line emission spectrum dominated by ongoing star formation.

CLASH SFRs span a range of magnitudes up to \(\geq 100 M_\odot yr^{-1}\), and significant, extended star formation occurs in 10 out of 20 BCGs in our sample. Based on comparisons with $K_0$ and $M_d$, we establish a link between the star formation in the BCG and the state of the surrounding ICM. All of the star-forming BCGs with an SFR > $10 M_\odot yr^{-1}$ are consistent with a ~30 keV cm$^{-2}$ entropy threshold, and a trend exists between SFR and $M_d$. These findings imply SFR is fueled by a reservoir of low entropy gas.

SED analysis of RXJ1532.9+3021 reveals a long-lived starburst, with a log lifetime of $8.8 \pm 0.5$ log$_{10}$ years, and a total SFR of $118^{+42}_{-21} M_\odot yr^{-1}$, which is consistent with our estimates from UV and Hα luminosities. The overall burst timescale is much longer than the AGN on-cycle as inferred by
the ages of AGN cavities in the ICM of this cluster, although several of the individual filaments are consistent with the \( \sim 60-80 \) Myr cavity refill times. These results are consistent with recent jet-triggered filaments super-imposed on an older long-lived starburst, which may have been the result of jets from previous AGN on-cycles. The burst history in RXJ1532 is also consistent with another study of stellar populations by Liu et al. (2012) conducted on SDSS BCGs, so we hypothesize that in upcoming work we will find similar evidence for sporadic starbursts corresponding to episodes of AGN activity.

The SFH of knots and filaments in RXJ1532 suggest a jet-induced precipitation scenario such as Li et al. (2015) is responsible for converting the ICM into cold, star-forming gas. If true for all CLASH BCGs, this mechanism would explain the relationship between the thermodynamic state of the ICM surrounding CLASH BCGs and the SFRs in the BCGs. The increasing “efficiency” of BCG SFRs relative to the cooling rates implied by \( M_b \) as a function of SFR is plausibly explained by this scenario, as well.

APPENDIX

This appendix includes the details of the parameter space chosen to fit the photometry of RXJ1532.9+3021 to a distribution of model SEDs. We describe the parameterization of the SFH, along with the parameter space we defined. Finally, we describe the consistency tests performed on fitting the CLASH SED.

For the 16 band SEDs we construct using all the available bands of CLASH photometry, we used the Salpeter (1955) IMF and Bruzual & Charlot (2003) SSP. The SFH we fit consists of a uniform starburst imposed on a background population with an exponentially decaying SFR, thus the SFH is modeled by

\[
\psi_e(t) = \frac{M_{\text{early}}}{\tau} e^{-t/\tau}
\]

\[
\psi_b(t) = \begin{cases} 
F_b M_{\text{early}} \frac{1 - e^{-t/(t_{\text{age}} - \Delta t_b)}}{(t_{\text{age}} - t) \le \Delta t_b} \\
0 \quad (t_{\text{age}} - t) > \Delta t_b 
\end{cases}
\]

\[
\psi_{\text{tot}}(t) = \psi_e(t) + \psi_b(t),
\]

which is a variant of the SFH described in Moustakas et al. (2013). \( \psi_e \) is the SFH for the background early-type population of stars, which is parameterized by the time constant \( \tau \). \( \psi_b \) is the burst SFH, and it is parameterized by the burst lifetime \( \Delta t_b \) and the fractional burst amplitude \( F_b \). Our SFH consists of one burst for simplicity.

We allowed the age of the galaxy to vary between 6 and 9.5 Gyr, and we allowed \( \tau \) to vary between \( \frac{1}{20} \) and \( \frac{1}{10} \) the age of the BCG, thereby ensuring that the background population corresponds to a quiescent, early-type galaxy. We allowed the metallicity of the stellar population to vary between 0.04 \( Z_\odot \) and 1.6 \( Z_\odot \), and the dust attenuation \( A_V \) to vary between 0 and 5 mag. In order to sample a wide range of possible burst histories, we sampled burst parameters logarithmically, selecting \( \Delta t_b \) in the range \( -3 \leq \log \Delta t_b \) [Gyr] \( \leq 0.8 \), and \( F_b \) in the range \( -2 \leq \log F_b \leq 1.0 \). This parameter space is summarized in Table 5. We drew \( 10^4 \) models from this parameter space for each SED we fit to.

### Table 5

| Parameter | Range | Units |
|-----------|-------|-------|
| SSP       | BC03<sup>a</sup> | ...   |
| IMF       | Salpeter<sup>b</sup> | ...   |
| Model Draws |        | ...   |
| \( \tau \) | [6, 9.5] | Gyr   |
| Metallicity | [0.05, 0.2] | \( t_{\text{age}} \) |
| \( A_V \) | [0.0, 5.0] | mag   |
| \log \([\text{O m}] / H\beta\) | [−0.5, 0.5] | dex   |
| \log \( \Delta t_b \) | [−3.0, 0.8] | log Gyr |
| \log \( F_b \) | [−2.0, 1.0] | dex   |

Notes.

<sup>a</sup> Bruzual & Charlot (2003).

<sup>b</sup> Salpeter (1955).

![Figure 17](image_url)

**Figure 17.** We plot the distribution in \( \Delta t_b \) and \( \text{EW}([\text{N II}] + H\alpha) \) for all the models gridded in the parameter space summarized in Table 5. Each point corresponds to the values of these two parameters for each individual model, and the vertical line denotes 269.3 \( \text{Å}_{\text{rest}} \), the SDSS measured EW. This plot reveals a densely populated trend tracing out a curve of decreasing burst lifetimes as a function of EW, with a wider, more sparsely populated envelope.

### A.1. SED Fitting Consistency Checks

The equivalent width of \([\text{N II}] + H\alpha\), \( \text{EW}([\text{N II}] + H\alpha) \), is exquisitely sensitive to the SFH of a galaxy, since it is a measure of the ratio of an SFR indicator to the red continuum (Kennicutt 1998; Leitherer 2005). Since this value was measured directly by SDSS, and our model SEDs predict line strengths, we can compare the best fit \( \text{EW}([\text{N II}] + H\alpha) \) for the CLASH SED with the SDSS measured value. This in turn indicates how reliable our estimate of the burst duration is.

We perform this comparison by fitting the SED of fluxes extracted in a 3" diameter aperture centered on the coordinates of the SDSS fiber used to take spectra of RXJ1532. Our predicted \( \text{EW}([\text{N II}] + H\alpha) = 269 \pm 120 \text{ Å}_{\text{rest}} \), which matches the SDSS measurement of 269.3 \( \pm 2.4 \text{ Å}_{\text{rest}} \). The probability distribution we recover also shows that the burst duration \( (\Delta t_b) \) is \( \log \Delta t_b = 8.8 \pm 0.5 \text{[yr]} \), and burst mass \( (M_b) \) is \( M_b = 10.83 \pm 0.35 \text{[M}_\odot] \). The overlap between the SDSS fiber and the observable UV structure in RXJ1532 is substantial, so it is not surprising that we recover the same burst history and burst mass for this SED as the SED fit in the Results.
As shown in Figure 17, $\Delta t_b$ is highly dependent upon the equivalent width. The sensitivity of the equivalent width to the burst history makes it straightforward to constrain a relatively narrow range of burst durations for the model SED. The agreement between the spectral equivalent width and our SED fit value is important because it shows that the Hα+[N II] feature is detected strongly enough in the CLASH photometry that a meaningful constraint on the burst history can be made with it.

We used iSEDfit to fit only the three bands of WFC3/UVISIS photometry that were used to estimate $L_{UV}$, and show that the results agree with our broadband estimates. We fit photometry extracted from the region used to calculate $L_{UV}$ and assumed fit parameter constraints that are consistent with Kennicutt (1998). For this step, we assume the metallicity in the stellar population is 1 $Z_\odot$, that the observed age of the BCG, $t_{\text{age}}$, is at least 6 Gyr, and that the decay timescale for the SFH, $\tau$, is 100 Gyr in order to force a continuous SFR model. We also assume a Salpeter (1955) IMF. Bruzual & Charlot (2003) SSP, and a Calzetti et al. (2000) reddening law.

Using this method, we calculated an SFR of 99 ± 24 $M_\odot$ yr$^{-1}$, and an average reddening of $(E(B-V) = 0.26 ± 0.04$. As before, the SFR PDF is log-normal and we report the mode of the distribution. This result is consistent with the UV photometry results. The agreement implies that while taking a single-aperture SED fit washes out the correlation seen between the spatial distribution of the dust and the SFR, this effect is not a strong source of systematic variation in our fits.

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