DETECTING STAR FORMATION IN BRIGHTEST CLUSTER GALAXIES WITH GALEX∗

A. K. Hicks1, R. Mushotzky2,3, and M. Donahue1

1 Department of Physics & Astronomy, Michigan State University, East Lansing, MI 48824-2320, USA; ahicks@alum.mit.edu, donahue@pa.msu.edu
2 Goddard Space Flight Center, Code 662, Greenbelt, MD, 20771, USA; richard@astro.umd.edu
3 Department of Astronomy, University of Maryland, College Park, MD 20742-2421, USA

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ABSTRACT

We present the results of GALEX observations of 17 cool core (CC) clusters of galaxies. We show that GALEX is easily capable of detecting star formation in brightest cluster galaxies (BCGs) out to z ≥ 0.45 and 50–100 kpc. In most of the CC clusters studied, we find significant UV luminosity excesses and colors that strongly suggest recent and/or current star formation. The BCGs are found to have blue UV colors in the center which become increasingly redder with radius, indicating that the UV signature of star formation is most easily detected in the central regions. Our findings show good agreement between UV star formation rates and estimates based on Hα observations. IR observations coupled with our data indicate moderate-to-high dust attenuation. Comparisons between our UV results and the X-ray properties of our sample suggest clear correlations between UV excess, cluster entropy, and central cooling time, confirming that star formation is directly and incontrovertibly related to the cooling gas.

Key words: galaxies: clusters: general – galaxies: clusters: intracluster medium – galaxies: elliptical and lenticular, cD – galaxies: stellar content – stars: formation – ultraviolet: galaxies – X-rays: galaxies: clusters

Online-only material: color figure

1. INTRODUCTION

The existence of star formation in “cooling flow” (hereafter referred to as cool core, or CC) clusters has been a contentious issue for over 25 years (Fabian et al. 1986). A class of clusters with high central gas densities and theoretically short cooling times was discovered with the Einstein Observatory (e.g., Fabian & Nulsen 1977; Cowie & Binney 1977; Mathews & Bregman 1978; Canizares et al. 1979; Mushotzky et al. 1981) via X-ray imaging and low resolution X-ray spectroscopy. These objects were also associated with Hα filaments (e.g., Cowie et al. 1983; Heckman et al. 1989), extra radio sources (e.g., Ge & Owen 1994), blue light (e.g., McNamara & O’Connell 1989; Cardiel et al. 1998), and spatial coincidence of the X-ray peak with the central radio source (e.g., Burns et al. 1981). The simplest physical model was the one in which the gas in the center cooled by radiating away its thermal energy, gradually losing pressure support, resulting in a flow (e.g., Cowie & Binney 1977; Fabian & Nulsen 1977; Mathews & Bregman 1978). Cool cores are inferred to be present in more than half of all clusters at low-redshift (Peres et al. 1998), and nearly as prevalent at moderate- z (30%–50% at 0.15 < z < 0.4; Bauer et al. 2005).

It has become clear with the advent of XMM-Newton and Chandra data that almost every such cluster also shows a temperature drop in the center (e.g., Cavagnolo 2008). However, measurements with the high spectral resolution XMM-Newton RGS spectrometer (e.g., Peterson et al. 2003; Kaastra et al. 2004; Piffaretti & Kaastra 2006) show that the X-ray spectra of the cooler gas has major differences from the theoretical cooling flow model, with a marked absence of gas at temperatures below ~1/3 of the average cluster temperature. Thus what happens to the cool gas remains a mystery. The combination of Chandra imaging and radio data (McNamara et al. 2000; Blanton et al. 2001) has shown that in many of these objects holes exist in the X-ray surface brightness which are filled in by radio emitting plasma, thus lending credence to ideas that feedback from active galactic nuclei (AGNs) in brightest cluster galaxies (BCGs) strongly modifies the cooling and thus reduces the net amount of material available for star formation.

Despite past evidence of star formation in these systems (e.g., McNamara & O’Connell 1989; Cardiel et al. 1998; Crawford et al. 1999) and the apparent preference for emission-line systems to inhabit the cores of high-central density, short cooling time clusters (Hu et al. 1985), the fact that star formation rate (SFR) estimates often differed by factors of ~10 or more from inferred X-ray cooling rates led to the doubt that the two phenomena were related. However, recent UV investigations (Mittaz et al. 2001; Hicks & Mushotzky 2005), Spitzer data (Quillen et al. 2008; O’Dea et al. 2008), and precision optical photometry (Bildfell et al. 2008) have definitively shown that CC clusters are indeed the sites of star formation, and that there is an indisputable relationship between X-ray properties and SFRs.

Previous studies have shown a connection between activity, such as star formation and radio AGNs, in BCGs and the thermodynamic state (traced by entropy, cooling time, etc.) of the intracluster medium in the cluster core (e.g., Cavagnolo 2008). The physical explanation for a connection between the state of the hot gas in the core inside 100 kpc and star formation in the inner 10 kpc in the BCG is not at all obvious. However, the situation in nearby BCGs might be similar to what models predict is happening in massive galaxies at high redshift. Models such as Ostriker & Ciotti (2005) suggest that almost all star formation in the high-redshift universe derives from accretion of gas that fell into potential wells, shocked, heated, then cooled (White & Frenk 1991; Fabian et al. 1986). More recent simulations (e.g., Kereš et al. 2009) show that this “hot mode” of accretion might be the dominant mode of star formation for massive galaxies, but this verdict is far from final owing to the unknown effects of feedback.

In either steady-state or bursty star formation scenarios, the dominant contribution to the UV flux comes from short-lived
main-sequence stars, therefore the UV band constitutes one of the prime routes for understanding star formation. Despite this fact, while CC clusters have been well observed in the radio (e.g., McNamara et al. 2000; Blanton et al. 2001), IR (e.g., Quillen et al. 2008; O’Dea et al. 2008), and with emission line studies (e.g., Heckman et al. 1989), there have been comparatively few published studies of UV observations of CC clusters (O’Dea et al. 2004; Hicks & Mushotzky 2005; Sparks et al. 2009; Donahue et al. 2010). Here we attempt to address and quantify the connection between X-ray properties and star formation,
using recent Galaxy Evolution Explorer (GALEX) observations of a sample of 16 CC clusters. Unless otherwise noted, this paper assumes a cosmology of $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.3$, and $\Omega_{\Lambda} = 0.7$.

### 2. OBSERVATIONS

GALEX is an orbiting space telescope possessing both imaging and spectroscopic capabilities in two ultraviolet wavebands, far-UV (FUV) 1350–1780 Å and near-UV (NUV) 1770–2730 Å, and therefore has NUV data only. Figure 1 shows the far-UV (FUV) and NUV, respectively (GALEX Technical Documentation$^4$).

Our GALEX targets consist of 17 clusters of galaxies that exhibit evidence of central cooling based on the indicators discussed in the introduction. These objects were chosen to sample a wide range of redshifts ($0.02 < z < 0.45$) and central cooling times ($0.5 < t_{cool} < 4.6$ Gyr at $R = 20$ kpc), be safely observable by GALEX (i.e., no bright nearby UV sources), and have low attenuations ($A_v < 0.5$); therefore they do not constitute a complete sample. One of our targets (A644) was observed after the loss of the GALEX FUV detector and therefore has NUV data only. Figure 1 shows the GALEX NUV images of a representative sample of our targets with Chandra X-ray contours overlaid. Table 1 lists the objects in our sample, their redshifts, and GALEX exposure times. These exposure times were based on our previous work with XMM-Newton Optical Monitor UV data (Hicks & Mushotzky 2005).

### 3. PHOTOMETRY

All photometry was performed on pipeline-processed GALEX intensity maps. FUV data were convolved with a gaussian to match the NUV point-spread-function (PSF), and the sizes of point sources in the resulting images were checked against those in the NUV data with the IRAF tool imexam. Photon counts were corrected for background using large ($\sim 40^\prime\prime$ radius) source-free regions taken from nearby areas of the camera in the same observation. Our photometric measurements were compared to those obtained with the background-subtracted intensity images provided in the GALEX pipeline, as an added check.

Final fluxes were determined by employing GALEX counts-to-flux conversions, and correcting for average Galactic extinction in the line of sight to each cluster (Cardelli et al. 1989). Errors were assessed by adding Poisson (root N) photon statistics in quadrature to a conservative 5% fixed systematic error (Morrissey et al. 2007). All of our targets were easily detected in both GALEX wavebands, with an average SNR of 40 (21) in the NUV (FUV), and minimum SNRs of $\sim 6$ in each band (for a fixed $7^\prime\prime$ radius aperture). Photometric results are presented in Table 2.

### 4. SPATIAL ANALYSIS

To investigate the spatial distribution of UV emission in our targets, radial flux profiles were produced for each band from point source subtracted intensity maps (convolved to produce matching PSFs, as above). Profiles were constructed using concentric annuli of at least 5$^\prime\prime$ width and binned to achieve signal-to-noise ratio (S/N) $>3$. These profiles are shown in Figure 2. With GALEX, we are able to detect UV emission out to large radii in many of the CC clusters.

The surface brightness profiles were then background subtracted and combined to create radial color profiles for each cluster (Figure 3). Overall, the central colors of most of the BCGs indicate the presence of a very young stellar population, and imply active star formation. We also see positive color gradients in nearly all of our targets, in keeping with the results of Rafferty et al. (2008) and Wang et al. (2010) for CC clusters.

Greater than 82% of elliptical galaxies have FUV–NUV colors of $>0.9$ (Gil de Paz et al. 2007), much redder than the central regions of all of our objects (Figure 3). However, presumably due to variations in the UV upturn (thought to be caused by horizontal branch stars) there is still a broad distribution of UV color among passive ellipticals, therefore we have not attempted to determine a definitive extent of star formation in individual targets.

### 5. FIXED APERTURE ANALYSIS

To determine the amount of “excess” UV light present in our targets, we first need an estimate of their “expected” UV emission. We empirically obtain this by examining the UV emission of non-star forming ellipticals and BCGs, using Two Micron All Sky Survey (2MASS) $J$-band flux as a proxy for the old stellar population. We avail ourselves of existing 2MASS photometric measurements by adopting their fixed $7^\prime\prime$ radius aperture in this portion of our analysis. We note that this aperture contains the majority of excess UV emission (Figures 2 and 3).

#### 5.1. Control Sample

Our non-star forming control sample is composed of 17 cluster ellipticals and 22 BCGs in non-CC clusters, all drawn from archival GALEX observations. The clusters used in our calibration analysis are listed in Table 3 along with their redshifts and GALEX exposure times.

Elliptical galaxies were gathered from four clusters spanning a redshift range of $0.08 < z < 0.15$. We used FUV-$K$ colors as a proxy for galaxy type (Gil de Paz et al. 2007), adopting a liberal cutoff of FUV-$K = 7.5$.

#### Table 1

| Cluster | $z$ | Exposure (NUV/FUV) (s) |
|---------|-----|------------------------|
| A85     | 0.0557 | 2494/2494 |
| A644    | 0.0705 | 3520/09 |
| A1204   | 0.1706 | 3738/3738 |
| A2029   | 0.0779 | 1517/1517 |
| A2052   | 0.0345 | 2863/2863 |
| A2142   | 0.0904 | 1556/1556 |
| A2597   | 0.0830 | 2111/2111 |
| A3112   | 0.0761 | 4873/2618 |
| Hercules A | 0.1540 | 3870/3870 |
| Hydra A | 0.0549 | 2230/2230 |
| MKW3s   | 0.0453 | 2271/2271 |
| MKW4    | 0.0196 | 2194/2194 |
| MS0839.8+2938 | 0.1980 | 4729/4728 |
| MS1358.4+6245 | 0.3272 | 5614/5614 |
| MS1455.0+2232 | 0.2578 | 3385/3384 |
| RXJ1347.5–1145 | 0.4500 | 9120/9119 |
| ZwCl 3146 | 0.2906 | 3127/3127 |

Note: $^a$ Observation executed after loss of FUV detector.

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$^4$ http://www.galex.caltech.edu/researcher/techdocs.html
Table 2

Brightest Cluster Galaxy 7° Radius Photometry

| Cluster | Position | mAB | FUV | NUV | J |
|---------|----------|-----|-----|-----|---|
| A85     | 00 41 50.4 -09 18 11.0 | 20.86 ±0.07 | 20.31 ±0.03 | 13.71 ±0.01 |
| A644    | 08 17 25.6 -07 30 45.6 | ... | 20.94 ±0.08 | 14.10 ±0.00 |
| A1204   | 11 13 20.5 +17 35 41.5 | 21.32 ±0.07 | 21.47 ±0.05 | 15.53 ±0.07 |
| A2029   | 15 10 56.1 +05 44 40.3 | 20.88 ±0.10 | 20.34 ±0.04 | 13.49 ±0.01 |
| A2052   | 15 16 44.5 +07 01 17.8 | 20.65 ±0.06 | 19.98 ±0.03 | 13.35 ±0.01 |
| A2142   | 15 58 20.0 +27 14 00.2 | 22.01 ±0.2   | 21.50 ±0.09 | 14.50 ±0.04 |
| A2597   | 23 25 19.7 -12 07 27.2 | 19.21 ±0.03 | 19.03 ±0.02 | 14.60 ±0.04 |
| A3112   | 03 17 57.6 -44 14 17.2 | 20.74 ±0.06 | 20.43 ±0.02 | 13.95 ±0.02 |
| Hercules A | 16 51 08.2 +04 59 33.9 | 21.7 ±0.2   | 21.36 ±0.07 | 15.39 ±0.08 |
| Hydra A | 09 18 05.7 -12 05 44.2 | 18.29 ±0.02 | 18.00 ±0.01 | 13.71 ±0.02 |
| MKW3s   | 15 21 51.8 +07 42 32.5 | 21.01 ±0.08 | 20.57 ±0.04 | 13.66 ±0.02 |
| MKW4    | 12 04 27.1 +01 53 54.9 | 19.24 ±0.03 | 18.85 ±0.02 | 12.11 ±0.05 |
| MS0839.8+2938 | 08 42 56.0 +29 27 26.8 | 20.72 ±0.06 | 20.66 ±0.03 | 15.52 ±0.06 |
| MS1538.4+6245 | 13 59 50.5 +62 31 04.2 | 23.36 ±0.3   | 23.2 ±0.2  | 16.62 ±0.1 |
| MS1455.0+2232 | 14 57 15.1 +22 20 33.1 | 20.24 ±0.05 | 20.37 ±0.03 | 15.55 ±0.06 |
| RXJ3474.5−1145 | 13 47 30.7 −11 45 09.3 | 21.36 ±0.06 | 21.06 ±0.03 | 16.24 ±0.1 |
| ZwCl 3146 | 10 23 39.6 +04 11 11.6 | 19.24 ±0.03 | 19.53 ±0.02 | 16.2 ±0.2 |

Note. a From the 2MASS Database.

Correlations between luminosities and flux ratios are given in Table 5 and are shown in Figures 4 and 5. Clearly, the FUV shows a stronger correlation with the other filters than the NUV. This is expected because the FUV filter covers a spectral region which is very sensitive to variations in the magnitude of the UV upturn from object to object. High sensitivity to the UV upturn makes the NUV filter a more straightforward choice for investigating star formation in early-type galaxies, so our discussion will focus on the NUV results.

5.2. UV Excesses

The UV luminosity excesses of our 17 CC clusters were calculated by subtracting the expected UV luminosity from the old stellar population (based on the fit obtained in Section 5.1)
from the measured value. The majority of our sample exhibits clear UV excesses, indicating recent star formation. Figure 5 shows the $J$-band luminosity of each galaxy in our sample plotted against its UV/$J$ flux ratios (UV$-J$ colors). We have not attempted to estimate and correct for internal dust absorption, and thus these excesses provide a lower limit on the UV emission in these clusters. Our measured UV excesses are given in Table 6.

Starburst99 (Leitherer 1999) redshifted models corresponding to continuous Salpeter star formation over a 20 Myr period...
were used to estimate SFRs for our sample. The 20 Myr continuous model was chosen to grossly approximate episodic cooling timescales, during which the system undergoes feedback processes with alternating heating and cooling cycles; it is this model that we use in the figures to follow. We emphasize that there are too many unknowns (e.g., internal reddening, IMF, continuous versus burst star formation, age of star formation) to predict accurate SFRs, and that we estimate SFRs with this model purely to facilitate comparisons with previous work and with other wavebands. Resulting values are shown in Table 6.

SFRs estimated from the NUV and FUV bands show general agreement (Figure 6), though FUV-derived SFRs tend to be slightly lower, ostensibly due to the larger scatter in the FUV calibration relationship. Because of the overall agreement between SFR estimates in the two bands, and the tendency for NUV data to be less plagued by variations in the UV
5.3. UV Colors

Some of our targets have very blue FUV–NUV colors when compared to our control sample, but none of them are known to harbor a central AGN. It is possible that their dust is of the Milky Way variety, which preferentially absorbs NUV emission and therefore results in bluer observed colors (e.g., Witt & Gordon 2000).

In Figure 7, we show that the FUV–NUV colors of the central (7") of our sample are inversely correlated with excess UV luminosity (correlation coefficient = −0.74), such that the reddest UV colors are associated with the weakest UV excesses. Typical FUV–NUV colors for inactive BCGs are shaded gray on this plot, consistent with the colors of the BCGs with the smallest

Figure 2. (Continued)
Figure 3. UV color profiles (FUV–NUV), clearly showing bluer emission in the center. Star forming galaxies tend to have GALEX UV colors $\sim 0.4$, while the majority (82%) of elliptical galaxies have UV colors of $>0.9$ (Gil de Paz et al. 2007). Dotted lines are shown at FUV–NUV = 0.9 as a point of reference.

excesses. A couple of the BCGs' colors are undoubtedly affected by Ly$\alpha$ emission contributing to the FUV band (ZwCl 3146) or NUV band (RXJ1347.5−1145).

If extinction by Milky Way-type dust is the explanation for the color trend, then the conclusion from this plot is that the BCGs with the largest UV excesses have the largest intrinsic dust extinction. If the color differences are intrinsic to the stellar population, then the BCGs with the largest excesses have more hot main-sequence stars and therefore may host more recent bursts than galaxies with lower UV excesses.

Using our measured UV excesses, we can estimate the color of the young stellar population in our targets (ranging from
−0.7 to 0.5). All but two (MKW4 and MS1358.4+6245, which are bluer than −0.3) can be explained using either continuous or burst models for the star formation. Interestingly, objects with colors redder than ∼0.1 (about half of the sample) can only be explained by a burst of star formation occurring 30–200 Myr ago.

Figure 3. (Continued)

6. MULTIWAVELENGTH COMPARISONS

6.1. Hα

Hα measurements for our sample were taken from the literature (specific references are given in Table 7), and are
Figure 3. Calibration Relationships: UV vs. J-band relationships obtained from our 39 passive (non-star forming) calibration targets (17 cluster ellipticals, 22 BCGs). Cluster ellipticals are shown as circles, and BCGs as 4-pointed stars. Shaded areas represent 1σ errors on the relationship, while dot-dash lines indicate the scatter (∼20% in NUV and ∼30% in FUV).

Figure 4. Calibration Relationships: UV vs. J-band relationships obtained from our 39 passive (non-star forming) calibration targets (17 cluster ellipticals, 22 BCGs). Cluster ellipticals are shown as circles, and BCGs as 4-pointed stars. Shaded areas represent 1σ errors on the relationship, while dot-dash lines indicate the scatter (∼20% in NUV and ∼30% in FUV).

Figure 3. (Continued)

Figure 4. (Continued)

shown versus NUV inferred SFR in Figure 8. We note that Hα measurements are usually based on long-slit estimates, and may miss emission line flux outside of the slit. Overlaid on the plot is the Kennicutt (1998) Hα–SFR relationship. This relationship is based on an assumption of constant SFR at ages < 2×10^7 years. The fact that there is general agreement with UV SFRs estimated using similar assumptions suggests that a recent, constant SFR model provides an adequate description of our targets.

6.2. IR

Infrared fluxes were gathered from the literature for 12 of our targets: 8 from Spitzer data and 4 from IRAS (Table 7). Spitzer
Table 4
Control Targets 7° Radius Photometry

| Cluster | Position | R.A. | Decl. | FUV | NUV | J |
|---------|----------|------|-------|-----|-----|---|
| A239    |          | 02 51 27.1 | −24 57 17.0 | 23.8 ± 0.1 | 22.9 ± 0.02 | 0.02 ± 0.02 | 16.1 ± 0.02 |
|         |          | 02 51 22.2 | −24 55 17.0 | 23.4 ± 0.09 | 22.3 ± 0.02 | 0.02 ± 0.02 | 15.6 ± 0.01 |
|         |          | 02 51 23.2 | −24 57 44.0 | 23.6 ± 0.01 | 22.5 ± 0.02 | 0.02 ± 0.02 | 15.6 ± 0.09 |
|         |          | 02 51 33.0 | −24 59 09.3 | 23.06 ± 0.07 | 22.27 ± 0.02 | 0.02 ± 0.02 | 15.11 ± 0.06 |
| A795    | 09 24 15.4 | 09 30 47.0 | 23.8 ± 0.02 | 22.5 ± 0.02 | 0.02 ± 0.02 | 15.26 ± 0.06 |
| A2100   | 15 36 22.0 | +37 37 43.0 | 24.5 ± 0.1 | 22.7 ± 0.02 | 0.02 ± 0.02 | 16.2 ± 0.1 |
|         | 15 36 22.1 | +37 39 34.0 | 24.1 ± 0.1 | 22.9 ± 0.02 | 0.02 ± 0.02 | 15.9 ± 0.1 |
| A2670   | 23 54 09.1 | −10 24 20.0 | 23.24 ± 0.09 | 22.49 ± 0.03 | 0.03 ± 0.03 | 15.37 ± 0.08 |
|         |          | 23 54 13.2 | −10 23 11.0 | 22.84 ± 0.07 | 21.86 ± 0.03 | 0.03 ± 0.03 | 14.78 ± 0.04 |
|         |          | 23 54 18.1 | −10 24 56.0 | 23.3 ± 0.1 | 22.4 ± 0.02 | 0.02 ± 0.02 | 15.59 ± 0.09 |
|         |          | 23 54 18.4 | −10 25 09.0 | 22.71 ± 0.07 | 21.95 ± 0.03 | 0.03 ± 0.03 | 15.1 ± 0.06 |
|         |          | 23 54 18.9 | −10 23 19.0 | 23.82 ± 0.07 | 22.86 ± 0.07 | 0.07 ± 0.07 | 16.32 ± 0.2 |
|         |          | 23 54 15.7 | −10 26 30.0 | 23.06 ± 0.05 | 21.96 ± 0.03 | 0.03 ± 0.03 | 15.26 ± 0.07 |
|         |          | 23 54 21.5 | −10 25 11.0 | 21.98 ± 0.04 | 21.66 ± 0.03 | 0.03 ± 0.03 | 14.71 ± 0.04 |
|         |          | 23 54 14.3 | −10 21 28.0 | 23.20 ± 0.09 | 22.31 ± 0.04 | 0.04 ± 0.04 | 15.05 ± 0.06 |
|         |          | 23 54 00.3 | −10 21 45.0 | 22.63 ± 0.06 | 22.11 ± 0.04 | 0.04 ± 0.04 | 15.32 ± 0.07 |
|         |          | 23 54 03.5 | −10 20 57.0 | 23.17 ± 0.09 | 22.52 ± 0.05 | 0.05 ± 0.05 | 15.61 ± 0.09 |

Note: From the 2MASS Database.

Table 5
Control Sample Fitting Parameters

| Fit          | FUV        | NUV        |
|--------------|------------|------------|
|              | C1         | C2         | Scatter |                  | C1         | C2         | Scatter |
| LUV − L1     | −1.16 ± 0.023 | 1.00 ± 0.062 | 0.10    | −0.85 ± 0.016 | 0.89 ± 0.045 | 0.08 |
| f_v,UV/f_v,J − L4 | −3.05 ± 0.028 | −0.08 ± 0.075 | 0.13    | −2.77 ± 0.016 | −0.14 ± 0.046 | 0.08 |

Notes. Fits are described as Y = X (see Equation (1)). UV luminosity is in units of 10^33 erg s⁻¹ and J band luminosity is in units of 10^44 erg s⁻¹.
### Table 6

| Cluster       | L_{FUV} Excess (10^{33} \text{ erg s}^{-1}) | Cont. SFR^{a} (M_{\odot} \text{ yr}^{-1}) | Burst Stellar Mass^{b} (10^{6} M_{\odot}) | L_{NUV} Excess (10^{33} \text{ erg s}^{-1}) | Cont. SFR^{a} (M_{\odot} \text{ yr}^{-1}) | Burst Stellar Mass^{b} (10^{6} M_{\odot}) |
|---------------|---------------------------------------------|------------------------------------------|------------------------------------------|---------------------------------------------|------------------------------------------|------------------------------------------|
| A85           | 0.026 ± 0.006                              | 0.031                                    | 1.2                                      | 0.037 ± 0.008                               | 0.05                                     | 1.7                                      |
| A644          |                                            |                                          |                                          |                                             |                                          |                                          |
| A1204         | 0.39 ± 0.04                                | 0.41                                      | 15.9                                     | 0.31 ± 0.03                                | 0.34                                     | 12.7                                     |
| A2029         | 0.03 ± 0.01                                | 0.03                                      | 1.3                                      | 0.05 ± 0.02                                | 0.06                                     | 2.1                                      |
| A2052         | 0.009 ± 0.003                              | 0.011                                     | 0.4                                      | 0.013 ± 0.005                              | 0.017                                    | 0.6                                      |
| A2142         | 0.008 ± 0.01                               | 0.009                                     | 0.3                                      | <0.01                                      | <0.01                                    | <0.5                                     |
| A2597         | 0.69 ± 0.04                                | 0.81                                      | 31.2                                     | 0.88 ± 0.05                                | 1.07                                     | 38.7                                     |
| A3112         | 0.08 ± 0.01                                | 0.09                                      | 3.5                                      | 0.09 ± 0.01                                | 0.10                                     | 3.8                                      |
| Hercules A    | 0.20 ± 0.04                                | 0.22                                      | 8.4                                      | 0.27 ± 0.04                                | 0.30                                     | 11.1                                     |
| Hydra A       | 0.68 ± 0.04                                | 0.82                                      | 31.2                                     | 0.97 ± 0.05                                | 1.22                                     | 44.0                                     |
| MKW3s         | 0.009 ± 0.004                              | 0.011                                     | 0.4                                      | <0.005                                     | <0.007                                   | <0.2                                     |
| MKW4          | 0.013 ± 0.002                              | 0.016                                     | 0.6                                      | 0.007 ± 0.004                              | 0.009                                    | 0.3                                      |
| MS0839.8+2938 | 1.03 ± 0.08                                | 1.05                                      | 40.7                                     | 1.20 ± 0.09                                | 1.25                                     | 46.7                                     |
| MS1358.4+6245 | 0.21 ± 0.07                                | 0.19                                      | 7.8                                      | 0.14 ± 0.06                                | 0.13                                     | 4.8                                      |
| MS1455.0+2232 | 3.2 ± 0.2                                  | 3.0                                      | 119                                      | 3.0 ± 0.2                                  | 2.9                                      | 110                                     |
| RXJ1347.5−1145| 4.0 ± 0.3                                  | 3.5                                      | 157                                      | 5.9 ± 0.4^{c}                              | 4.6^{c}                                  | 177                                     |
| ZwCl 3146     | 11.3 ± 0.6^{c}                             | 10.4^{c}                                 | 413                                      | 9.4 ± 0.5                                  | 8.9                                      | 337                                     |

**Notes.**

^{a} Assuming continuous star formation over 20 Myr.

^{b} Lower limit of total star formation obtainable from the single burst assumption, set by a starburst occurring 10 Myr ago.

^{c} Some Lyα contamination is suspected.

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**Figure 5.** UV/J flux ratios for our CC sample. Lines show the fitted relationships for passively evolving galaxies from our correlations; shaded regions designate 1σ errors on the fits. Dot-dash lines indicate the scatter. Most of the objects in our sample exhibit signs of recent star formation.

**Figure 6.** Ratio of NUV to FUV inferred SFRs vs. FUV SFR. The average ratio is 1.2, suggesting that higher scatter in the FUV calibration relationship may result in a slight underestimation of SFRs.

**Figure 7.** Total 7″ FUV–NUV color vs. NUV luminosity excess. The dashed line shows the mean color of our control sample (0.73), while the shaded area designates the standard deviation (0.34). The object with high NUV excess at FUV–NUV ~ 0.3 is suspected of having some contaminating Lyα emission contributing to its NUV flux.
Table 7
Multiwavelength Comparison Data

| Cluster          | $L_{\text{Hα}}$ (Ref.) | $L_{\text{IR}}$ (Ref.) | IR SFR$^a$ | IRX$^b$ | Entropy$^c$ (keV cm$^{-2}$) | Cooling Time$^d$ (Gyr) |
|------------------|-------------------------|-------------------------|------------|---------|-----------------------------|------------------------|
|                  | (10$^{40}$ erg s$^{-1}$) | (10$^{44}$ erg s$^{-1}$) | ($M_\odot$ yr$^{-1}$) | Central | $R = 20$ (kpc) Central     | $R = 20$ (kpc) |
| A85              | < 0.43 (1)              | 0.28 ± 0.03 (7)         | 1.6 ± 0.2  | 1.1 ± 0.1 | 12.5 ± 0.5                  | 38 ± 1                 |
| A644             | ...                     | ...                     | ...        | ...      | 132 ± 9                     | 153 ± 21               |
| A1204            | 6.5 ± 0.8 (2)           | 1.7 ± 0.2 (7)           | 8.1 ± 0.8  | 1.1 ± 0.1 | 15 ± 1                      | 23 ± 1                 |
| A2029            | < 0.64 (3)              | ...                     | ...        | ...      | 10.5 ± 0.7                  | 50 ± 2                 |
| A2052            | 1.5 ± 0.1 (2)           | 0.24 ± 0.02 (7)         | 1.4 ± 0.1  | 1.4 ± 0.2 | 9.4 ± 0.7                   | 34 ± 1                 |
| A2142            | < 0.90 (4)              | ...                     | ...        | ...      | 68 ± 2                      | 84 ± 4                 |
| A2597            | 51 ± 7 (1)              | 0.93 ± 0.09 (8)         | 3.4 ± 0.3  | 0.60 ± 0.07 | 11 ± 2                       | 26 ± 2                 |
| A3112            | 3.8 ± 0.5 (1)           | 0.84 ± 0.08 (7)         | 4.2 ± 0.4  | 1.3 ± 0.2 | 11 ± 1                      | 37 ± 3                 |
| Hercules A       | 1.3 ± 0.2 (1)           | < 2.2 (9)               | < 7.56     | < 1.1    | 9 ± 1                       | 33 ± 1                 |
| Hydra A          | 10 ± 1 (1)              | 0.5 ± 0.2 (10)          | 2.1 ± 0.2  | 0.4 ± 0.1 | 13.3 ± 0.7                  | 34 ± 1                 |
| MKW3s            | 0.50 ± 0.07$^e$ (4)     | ...                     | ...        | ...      | 24 ± 2                      | 51 ± 2                 |
| MKW4             | ...                     | < 0.033 (11)            | < 0.21     | < 0.5    | 6.9 ± 0.3                   | 58 ± 4                 |
| MS0839.8+2938    | 67 ± 9 (5)              | ...                     | ...        | ...      | 19 ± 3                      | 32 ± 3                 |
| MS1358.4+6245    | 4.9 ± 0.4 (6)           | 1.4 ± 0.1 (12)          | 4.87 ± 0.5 | 1.1 ± 0.2 | 21 ± 3                      | 31 ± 3                 |
| MS1455.0+2232    | 33$^{+3}_{-2}$ (2)      | 2.0 ± 0.2 (12)          | 6.81 ± 0.7 | 0.26 ± 0.03 | 17 ± 2                      | 26 ± 2                 |
| RXJ1347.5–1145   | ...                     | < 84 (10)               | < 350      | < 1.8    | 12 ± 2                      | 46 ± 8                 |
| ZwCl 3146        | 458$^{+3}_{-2}$ (2)     | 15 ± 2 (12)             | 65 ± 6     | 0.62 ± 0.09 | 11 ± 2                      | 24 ± 2                 |

Note. Spitzer IR flux uncertainties are conservatively estimated at 10%.

$^a$ Calculated from total IR luminosities following the method of O’Dea et al. (2008).

$^b$ IR excess determined as in Johnson et al. (2006).

$^c$ Values from Cavagnolo et al. (2009)

$^d$ 15% errors are assumed.

References. (1) Cavagnolo et al. 2009; (2) Crawford et al. 1999; (3) Jaffe et al. 2005; (4) Salome & Combes 2003; (5) Donahue et al. 1992; (6) Lamareille et al. 2006; (7) O’Dea et al. 2008; (8) Donahue et al. 2007; (9) Golombek et al. 1988; (10) Edge 2001; (11) Knapp et al. 1989; (12) Egami et al. 2006.

Figure 8. NUV inferred SFR vs. Hα luminosity for a subset of our targets. The line indicates the $L_{\text{Hα}}$ vs SFR relationship of Kennicutt (1998). The general agreement between the line and our data suggests that a 20 Myr constant star formation model provides a reasonable description of our targets.

The X-ray properties of our sample are taken from the ACCEPT database$^5$ (Cavagnolo et al. 2009). As well as using central estimates based on a fit, both entropy ($K$) and cooling time profiles were interpolated to obtain values at $R = 20$ kpc from the center of each cluster. Interpolation enabled a more uniform comparison between objects with different redshifts and/or data quality.

NUV inferred SFR versus entropy is shown in Figure 10, and SFR is plotted versus cluster cooling time in Figure 11. The plots constructed with central ($R \rightarrow 0$) entropies and cooling times indicate thresholds comparable to those reported by Cavagnolo et al. (2008), Voit et al. (2008), and Rafferty et al. (2008). Comparisons with gas properties at $R = 20$ kpc from the cluster center, however, yield smoother trends in entropy and cooling time. These plots show a clear tendency for lower entropy, shorter cooling time objects to exhibit more star formation, providing convincing evidence that the star formation in these objects is directly related to cooling gas in the cluster cores. A bivariate correlated errors and intrinsic scatter regress fit between NUV inferred SFR and the $R = 20$ kpc cooling time data yields the relationship $\log_{10} SFR_{\text{NUV}} = a \log_{10} t_{\text{cool,20}} + b$, where $a = -3.9 \pm 0.7$ and $b = -0.6 \pm 0.1$.

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7. SUMMARY AND DISCUSSION

In our UV study of 17 CC clusters we find that GALEX easily detects star formation in cluster BCGs out to $z \geq 0.45$ and to unprecedented radii. The BCGs are found to be bluest in the center, with colors that become increasingly redder with radius, suggesting that star formation is most easily detected in the central regions.

We construct UV/\textit{J}-band calibration relationships from 17 cluster ellipticals and 22 quiescent BCGs that enable us to subtract the expected UV light from older populations. Our findings are corroborated by H\alpha observations, showing good agreement with Kennicutt (1998) models of recent, continuous star formation.

SFRs are estimated using Starburst99 templates for both continuous and burst models, for easy comparison to results in the literature. Comparisons with the SDSS sample of Johnson et al. (2007) indicate that our sample has moderate-to-high extinction and has NUV–FUV colors consistent with or bluer than other star-forming galaxies. These results emphasize a need for additional observations and detailed studies of cluster BCGs, as currently there are no adequately large samples of quiescent BCGs to provide a sufficient context for our findings.

We also compare our UV results to properties of the intra-galactic medium using X-ray observations. We find clear correlations between UV excess, cluster entropy, and central cooling time, demonstrating that the star formation is directly and incontrovertibly related to the cooling gas in these objects.

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