STAR FORMATION EFFICIENCY IN THE COOL CORES OF GALAXY CLUSTERS

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ABSTRACT

We have assembled a sample of high spatial resolution far-UV (Hubble Space Telescope Advanced Camera for Surveys/Solar Blind Channel) and Hα (Maryland-Magellan Tunable Filter) imaging for 15 cool core galaxy clusters. These data provide a detailed view of the thin, extended filaments in the cores of these clusters. Based on the ratio of the far-UV to Hα luminosity, the UV spectral energy distribution, and the far-UV and Hα morphology, we conclude that the warm, ionized gas in the cluster cores is photoionized by massive, young stars in all but a few (A1991, A2052, A2580) systems. We show that the extended filaments, when considered separately, appear to be star forming in the majority of cases, while the nuclei tend to have slightly lower far-UV luminosity for a given Hα luminosity, suggesting a harder ionization source or higher extinction. We observe a slight offset in the UV/Hα ratio from the expected value for continuous star formation which can be modeled by assuming intrinsic extinction by modest amounts of dust ($E(B-V) \sim 0.2$) or a top-heavy initial mass function in the extended filaments. The measured star formation rates vary from $\sim 0.05 M_\odot$ yr$^{-1}$ in the nuclei of non-cooling systems, consistent with passive, red ellipticals, to $\sim 5 M_\odot$ yr$^{-1}$ in systems with complex, extended, optical filaments. Comparing the estimates of the star formation rate based on UV, Hα, and infrared luminosities to the spectroscopically determined X-ray cooling rate suggests a star formation efficiency of $14\pm 18\%$. This value represents the time-averaged fraction, by mass, of gas cooling out of the intracluster medium, which turns into stars and agrees well with the global fraction of baryons in stars required by simulations to reproduce the stellar mass function for galaxies. This result provides a new constraint on the efficiency of star formation in accreting systems.

Key words: galaxies: active – galaxies: clusters: general – galaxies: clusters: intracluster medium – galaxies: elliptical and lenticular, cD – galaxies: star formation – ISM: jets and outflows

Online-only material: color figures

1. INTRODUCTION

The high densities and low temperatures of the intracluster medium (hereafter ICM) in the cores of some galaxy clusters suggests that massive amounts ($100–1000 M_\odot$ yr$^{-1}$) of cool gas should be deposited onto the central galaxy. The fact that this gas reservoir is not observed has been used as prime evidence for feedback-regulated cooling (see review by Fabian 1994). By invoking feedback, either by active galactic nuclei (hereafter AGNs; e.g., Guo et al. 2008; Rafferty et al. 2008; Conroy & Ostriker 2008), mergers (e.g., Gómez et al. 2002; ZuHone 2010), conduction (e.g., Fabian et al. 2002; Voigt & Fabian 2004), or some other mechanism, theoretical models can greatly reduce the efficiency of ICM cooling, producing a better match with what is observed in high-resolution X-ray grating spectra of cool cores ($0–100 M_\odot$ yr$^{-1}$; Peterson et al. 2003). However, these modest cooling flows had remained unaccounted for at low temperatures until only recently.

The presence of warm, ionized gas in the form of Hα emitting filaments has been observed in the cores of several cooling flow clusters to date (e.g., Hu et al. 1985, Heckman et al. 1989, Crawford et al. 1999, Jaffe et al. 2005, Hatch et al. 2007). More recently, it has been shown by McDonald et al. (2010, 2011, hereafter M+10 and M+11, respectively) that this emission is intimately linked to the cooling ICM and may be the result of cooling instabilities. However, while it is possible that the warm gas may be a byproduct of ICM cooling, the source of ionization in this gas remains a mystery. A wide variety of ionization mechanisms are viable in the cores of clusters (see Crawford et al. 2005 for a review), the least exotic of which may be photoionization by massive, young stars.

The identification of star-forming regions in cool core clusters has a rich history in the literature. Early on, it was noted by several groups that brightest cluster galaxies (hereafter BCGs) in cool core clusters have higher star formation rates than non-cool core BCGs (Johnstone et al. 1987; Romanishin 1987; McNamara & O’Connell 1989; Allen 1995; Cardiel et al. 1995). These studies all found evidence for significant amounts of star formation in cool cores, but the measured star formation rates were orders of magnitudes smaller than the X-ray cooling rates (e.g., McNamara & O’Connell 1989). In recent history, two separate advances have brought these measurements closer together. First, as mentioned earlier in this section, the X-ray spectroscopically determined cooling rates are roughly an order of magnitude lower than the classically determined values based on the soft X-ray luminosity. Second, large surveys in the UV (e.g., Rafferty et al. 2006; Hicks et al. 2010), optical (e.g., Crawford et al. 1999; Edwards et al. 2007; Bildfell et al. 2008; McDonald et al. 2010), mid-IR (hereafter MIR; e.g., Hansen et al. 2000; Egami et al. 2006; Quillen et al. 2008; O’Dea et al. 2008), and submillimeter (e.g., Edge 2001; Salomé & Combes 2003) have allowed a much more detailed picture of star formation in BCGs. The typical star formation rates of $1–10 M_\odot$ yr$^{-1}$ (O’Dea et al. 2008) imply that gas at temperatures of $10^6–10^7$ K is being continuously converted into stars with an efficiency on the order of $\sim 10\%$. The fact that most of these studies consider the integrated SF rates makes it difficult to determine the exact role of young stars in ionizing...
the extended warm gas observed at Hα, since the two may not be spatially coincident or the measurements may be contaminated by the inclusion of a central AGN.

In order to understand both the role of star formation in ionizing the warm gas and the efficiency with which the cooling ICM is converted into stars, we have conducted a high spatial resolution far-UV survey of BCGs in cooling and non-cooling clusters. We describe the collection and analysis of the data from this survey in Section 2. In Section 3 we describe the results of this survey, while in Section 4 we discuss the implications of these results in the context of our previous work (M+10, M+11).

Finally, in Section 5 we summarize our findings and discuss these results in the context of our previous work (M+10, M+11).

Due to the small bandpass, it is possible for line emission to dominate the observed flux—we investigate this possibility in a relatively small range in wavelength, from 1400 Å to 1500 Å. We can effectively remove the red leak and consider only a small amount of non-FUV flux. Following Cardelli et al. (1989) using reddening estimates from Schlegel et al. (1998). The final pixel scale for both the Hα/FUV image, allowing us to identify interesting morphological features. The final pixel scale for both the Hα and FUV images is 0.′′2.

All FUV and Hα fluxes were corrected for Galactic extinction following Cardelli et al. (1989) using reddening estimates from Schlegel et al. (1998).

3. RESULTS

In the Appendix, we show the stellar continuum, Hα, and FUV images for each of the 15 BCGs in our sample. At a glance there does not appear to be consistent agreement between the Hα and FUV morphologies. We observe systems having Hα emission in the field of view. Exposures with multiple filters are required to properly remove the known ACS/SBC red leak, which has a non-negligible contribution due to the fact that the underlying BCG is very luminous and red. Since the aforementioned filters are long-pass filters, they have nearly identical throughputs at longer wavelengths. Thus, by subtracting the F150LP exposure from the F140LP exposure we can effectively remove the red leak and consider only a relatively small range in wavelength, from 1400 Å to 1500 Å. Due to the small bandpass, it is possible for line emission to dominate the observed flux— we investigate this possibility in Section 4. We have carried out this subtraction for 13/15 of the BCGs in our sample which have both F140LP and F150LP imaging. For A1795 and A2597, we are unable to remove the red-leak contribution due to the lack of paired exposures, but we point out that, conveniently, these two systems have the brightest FUV flux in our sample and, thus, are largely unaffected by the inclusion of a small amount of non-FUV flux. Following the red-leak subtraction, we also bin the images 8 × 8 and smooth the images with a 1.5 pixel smoothing radius, yielding matching spatial resolution at FUV and Hα. This process is also necessary in order to increase the signal-to-noise of the FUV image, allowing us to identify interesting morphological features. The final pixel scale for both the Hα and FUV images is 0.′′2.

All FUV and Hα fluxes were corrected for Galactic extinction following Cardelli et al. (1989) using reddening estimates from Schlegel et al. (1998).

Table 1

| Name      | R.A.    | Decl.  | z     | E(B−V) | M     | F14   | Proposal Number |
|-----------|---------|--------|-------|--------|-------|-------|-----------------|
| A0970a    | 10h17m25.7 | −10h41m20.3 | 0.0587 | 0.055  | ...   | <2.5 | 11980           |
| A1644     | 12h57m11.6 | −17h24m33.9 | 0.0475 | 0.069  | 3.2   | 98.4 | 11980           |
| A1650     | 12h58m41.4 | −01h45m41.1 | 0.0846 | 0.017  | 0.0   | <2.5 | 11980           |
| A1795     | 13h48m52.5 | −26h35m33.9 | 0.0625 | 0.013  | 7.8   | 924.5 | 11980, 11681    |
| A1837     | 14h01m36.4 | −11h07m43.2 | 0.0691 | 0.058  | 0.0   | 4.8  | 11980           |
| A1991     | 14h54m31.5 | +18h38m32.4 | 0.0587 | 0.025  | 14.6  | 39.0 | 11980           |
| A2029     | 15h10m56.1 | +05h46m41.8 | 0.0773 | 0.040  | 3.4   | 527.8 | 11980           |
| A2052     | 15h16m44.5 | +07h21m18.2 | 0.0345 | 0.037  | 2.6   | 5499.3 | 11980          |
| A2142     | 15h58m20.0 | +27h14m00.4 | 0.0904 | 0.044  | 1.2   | <2.5 | 11980           |
| A2151     | 16h04m35.8 | +37h43m17.8 | 0.0352 | 0.043  | 8.4   | 2.4  | 11980           |
| A2580b    | 23h21m26.3 | −23h12m27.8 | 0.0890 | 0.024  | ...   | 46.4 | 11980           |
| A2597     | 23h25m19.7 | −12h07m27.1 | 0.0830 | 0.030  | 9.5   | 1874.6 | 11131          |
| A4059     | 23h57m00.7 | −34h45m32.7 | 0.0475 | 0.015  | 0.7   | 1284.7 | 11980           |
| Ophiuchus | 17h12m27.7 | −23h22m10.4 | 0.0285 | 0.588  | 0.0   | 28.8 | 11980           |
| WBL 360−03 | 11h39m35.4 | −03h29m17.0 | 0.0274 | 0.028  | ...   | <2.5 | 11980           |

Notes. Column 1: cluster name; Columns 2–4: NED R.A., decl., redshift of BCG (http://nedwww.ipac.caltech.edu); Column 5: reddening due to Galactic extinction from Schlegel et al. (1998); Column 6: spectroscopically determined X-ray cooling rates (M yr−1) from McDonald et al. (2010); Column 7: 1.4 GHz radio flux (mJy) from NVSS (http://www.cv.nrao.edu/nvss/); Column 8: HST proposal number for FUV data. Proposal PIs are W. Jaffe (11131), W. Sparks (11681), and S. Veilleux (11980).

a No available Chandra data.
Figure 1. (a) FUV vs. Hα luminosity for 15 BCGs in our sample. For systems with extended FUV or Hα emission, we separate the emission into extended, nuclear (inner 3″), and entire systems (see the Appendix). The dashed line represents the relation between Hα and FUV luminosity for SF regions, as defined by Kennicutt (1998), the shaded blue region represents the expected FUV/Hα ratio for continuous SF covering the full range of IMFs and metallicities from Starburst99 (Leitherer et al. 1999), while the shaded red region defines the expected FUV/Hα ratio for fast shocks (Dopita & Sutherland 1996). The legend in the lower right describes the different point type/colours. (b) FUV vs. K′-band luminosity in the central 3″ of the BCG. The solid line represents our estimate of the contribution to the FUV luminosity from old, horizontal branch stars. (c) Similar to panel (a), but with the contribution from old stars removed from the nuclear and total regions. The correlation between FUV and Hα luminosity is much more significant, suggesting that the majority of the observed Hα emission may be due to photoionization by young stars.

Extended emission (A1644, A1795). Thus, it is obvious that a single explanation (e.g., star formation) is unable to account for the variety of FUV and Hα emission that we observe.

As we did with the Hα emission in M+10, the FUV morphology can be classified as either nuclear or extended. We find, in the FUV, 7/15 systems have extended emission, 5/15 have nuclear emission, while 3/15 have no emission at all. In order to quantitatively examine both the nuclear and extended emission, we extract FUV and Hα fluxes in several regions, as shown in the Appendix.

In Figure 1(a), we show the correlation between the FUV and Hα luminosity for the regions identified in the Appendix. We find a significant amount of FUV emission in all five of the systems for which we do not detect any Hα emission. Additionally, we see that at least three systems are consistent with being shock heated (Dopita & Sutherland 1996)—a point we will return to later in this section.

As discussed by Hicks et al. (2010), a significant fraction of the FUV emission may be due to old stellar populations (e.g., horizontal branch stars) in the BCG. To proceed, we must isolate the FUV excess due to young, star-forming regions. In order to remove the contribution from old stars, we consider the inner 3″ and plot the K band (from 2MASS; Skrutskie et al. 2006) versus the FUV luminosity (Figure 1(b)). Hicks et al. (2010) show that the FUV luminosity from old stars is highly concentrated in the central region, thus removing this contribution in the inner region will act as a suitable first-order correction. In order to calibrate this correction for our sample, which lacks a control sample of confirmed non-star-forming galaxies, we opt to fit a line which is chosen to pass through the four points with the lowest $L_{\text{FUV}}/L_{K'}$ ratio. We make the assumption that these four galaxies with the lowest $L_{\text{FUV}}/L_{K'}$ ratio are non-star-forming, which is supported by non-detections at Hα. The equation for this relation is: $\log_{10}(L_{\text{FUV,3'}}) = 2.35\log_{10}(L_{K',3'}) - 42.98$. The fact that four points with non-detections at Hα lie neatly along the same line suggests that this correction is meaningful.

Figure 1(c) shows the FUV excess due to young stars versus the Hα luminosity for the total, nuclear, and extended regions in our complete sample of BCGs. With the contribution from old stellar populations removed, we find a tight correlation between...
The majority of systems in our sample are consistent with the continuous star formation scenario (Kennicutt 1998; Leitherer et al. 1999), suggesting that much of the warm gas found in cluster cores may be photoionized by young stars. Two systems, A0970 and A2029, have anomalously high FUV/Hα ratios, suggesting that star formation may be proceeding in bursts. As a starburst ages, the UV/Hα ratio will climb quickly due to the massive stars dying first. This means that, by 10 Myr after the burst, the UV/Hα ratio can already be an order of magnitude higher than the expected value for continuous star formation (see M+10 for further discussion). We find that the filaments in A1991 and A2052 are consistent with being heated by fast shocks, along with the nuclei of A2052 and A2580. In the case of A2052, there exist high-quality radio and X-ray maps which show that the observed Hα emission is coincident with the inner edge of a radio-blow bubble. In A1991, the Hα morphology is reminiscent of a bow shock and is spatially coincident with a soft X-ray blob which is offset from the cluster core. Much of the FUV and Hα data are clustered between the regions depicting continuous star formation and shock heating, as shown in the zoomed-in portion of Figure 1. These regions may indeed be heated by a combination of processes or they may simply be reddened due to intrinsic extinction. Based on their FUV/Hα ratios, Hα morphology, disrupted X-ray morphology, and high radio luminosity, we propose that the optical emission in A1991, A2052, and A2580 is the product of shock heating, while the remaining 12 systems are experiencing continuous or burst-like star formation. We will return to this classification in the remaining 12 systems are experiencing continuous or burst-like star formation.

In Figure 2, we present the distribution of the FUV/Hα ratio in various regions for the 10 systems with detections (>1σ) at either Hα or FUV. In the innermost region (r < 0′.8), the warm gas appears to be shock heated in 60% of systems—these shocked nuclei may be associated with AGN-driven outflows. Due to the small radial extent of this bin, the 2MASS data are of insufficient spatial resolution to remove any contribution from old stars. Thus, these FUV/Hα ratios are upper limits. Of the remaining four systems, two are consistent with continuous star formation or a young starburst, while the remaining two are consistent with an aged starburst. At larger radius (0′.8 < r < 3′0) the FUV/Hα ratio is slightly larger, with the distribution peaking in between the regions describing shocks and star formation (see the inset in Figure 3). These data have had the contribution from old stellar populations removed, as described earlier in this section. The FUV/Hα ratio at this radius is similar to what we observe in the filaments, as is seen in the third panel of Figure 2. The fact that the distribution of FUV/Hα peaks between the values for shocks and star formation supports a number of scenarios, including a mixture of the two processes, dusty star formation and star formation with an IMF skewed toward high-mass stars (see the rightmost panel of Figure 2). We will investigate these scenarios in Section 4.

In M+10 and M+11, we showed that the Hα emission observed in the cool cores of galaxy clusters is intimately linked to the cooling ICM. In general, the thin, extended filaments observed in many of these clusters are found in regions where the ICM is cooling most rapidly, suggesting that this warm gas may be a byproduct of the ongoing cooling. If this is the case, it is relevant to ask what fraction of the cooling ICM is turning into stars. We address this question in Figure 3 by comparing the star formation rate with the X-ray cooling rate (dM/dt) for 32 galaxy clusters. In order to compute the star formation rate, we use the prescriptions in Kennicutt (1998). For the systems observed with HST, we use the average of the FUV- and Hα-determined star formation rates (filled blue circles). For an additional 10 clusters from M+10 and M+11 we make use of archival Galaxy Evolution Explorer (GALEX) data for five clusters (open blue
We assume that the Hα emission is the result of photoionization by young stars and convert the Hα luminosity into a continuous star formation rate (green triangles). For the three shock-heated systems (red crosses) mentioned above, we determine the SF rate based on their FUV luminosities. While not shown here, we also investigated the distribution of star formation efficiencies (SFEs) with the central entropy, $K_0$, from Cavagnolo et al. (2009) and, similar to $T_X$, find no correlation. In the following section we will discuss possible interpretations of this efficiency measure.

4. DISCUSSION

4.1. Star Formation as an Ionization Source

In Crawford et al. (2005), a variety of ionization sources are discussed which could produce the observed Hα emission in the cool cores of galaxy clusters. The purpose of this HST survey was to investigate one of the most plausible ionization sources: photoionization by young stars. In Figures 1 and 2 we showed that, once the contribution to the FUV emission from old stellar populations is removed, the majority of the Hα and FUV emission that we observe in cluster cores is roughly consistent with the star formation scenario. Based on the FUV/Hα ratios, we identify three different types of system.

1. FUV/Hα $\gtrsim 10^{-12}$ Hz$^{-1}$. Suggests a starburst that has aged by at least 10 Myr. Two systems, A0970 and A2029, fulfill this criteria, while several others may fall into this category if their Hα luminosity is significantly less than the measured upper limits.

2. FUV/Hα $\sim 10^{-13}$ Hz$^{-1}$. The FUV/Hα ratios of these systems are consistent with continuous star formation or a recent (0–5 Gyr ago) burst of star formation. The filaments in A1644, A1795, A2597, and part of A2052, along with the nuclei of A1795, A1991, A2151, and A2597 appear to be star forming.

3. FUV/Hα $\lesssim 10^{-14}$ Hz$^{-1}$. Suggests heating by fast shocks or some other source of hard ionization (e.g., cosmic rays, AGN). The filaments of A2052 and A1991, and the nuclei of A2052 and A2580 have FUV/Hα ratios which...
are consistent with this picture, in the absence of internal reddening.

Figures 1 (inset) and 2 show that a large fraction of the systems which we observe fall between the regions describing shock heating and star formation. However, these data have not been corrected for intrinsic reddening due to dust. Correcting for a very modest reddening ($E(B - V) \sim 0.2$) would boost the FUV luminosity of these systems such that the FUV/Hα ratio is consistent with star formation (see Figure 1(c) and the lower panel of Figure 2). Unfortunately, the amount of reddening in the filaments and nuclei of these systems is currently not well constrained for very many systems, but typical values of $E(B - V)$ can range from 0 to 0.4 in the cores of galaxy clusters (Crawford et al. 1999). In the case of A2052, for which we measure FUV/Hα ratios indicative of shock heating and have an estimate of the amount of intrinsic reddening from Crawford ($E(B - V) = 0.22^{+0.36}_{-0.22}$), we can investigate whether correcting for this extinction would provide FUV/Hα ratios consistent with star-forming regions. Assuming a simple dust-screen model, correcting for a reddening of $E(B - V) = 0.22$ would transform a FUV/Hα ratio of $4.4 \times 10^{-15}$ Hz$^{-1}$ in the filaments of A2052 to $1.2 \times 10^{-14}$ Hz$^{-1}$, which is consistent with the upper limit for shock-heated systems (see Figure 2). However, if contrary to expectations, the filaments have a slightly higher reddening than the nucleus, the FUV/Hα ratio may be even higher. Thus, it is certainly possible that the systems which we classify as shock heated, or those which have ambiguous FUV/Hα ratios, may in fact be highly obscured star-forming systems. We will address this possibility in significantly more detail in an upcoming paper which will include long-slit spectroscopy of the Hα filaments providing, for the first time, reddening estimates away from the nucleus in these systems.

An alternative explanation for the intermediate FUV/Hα ratios is that the IMF in the filaments is top heavy ($\alpha \ll 2.35$). Again, the lower panel of Figure 2 shows that the peak of the FUV/Hα distribution is consistent with the value expected for O8V stars. There is a substantial amount of literature providing evidence for a top-heavy IMF in various environments including the Galactic center (Maness et al. 2007) and disturbed galaxies (Habergham et al. 2010). Thus, regardless of whether there is a small amount of dust or a slightly altered IMF, we suspect that the majority of the systems with intermediate FUV/Hα ratios are in fact star forming, with the exception of A1991, A2052, and A2580, which have low FUV/Hα ratios and morphologies which resemble bow shocks and/or jets.

Due to our use of the F150LP filter to remove red-leak contamination, we are considering only a very small wavelength range from 1400 to 1500 Å. In this region, there may be line emission from [O IV] and various ionization states of sulfur due to gas cooling at $\sim 10^5$ K. In order to establish that we are indeed observing continuum emission from young stars, we have computed UV spectral energy distributions (SEDs) for six BCGs which have deep GALEX, XMM-OM, and HST UV data. These data are presented in the left panel of Figure 4. We see that, in general, the UV SED follows a power law over the range of 1500–3000 Å. The new HST data, depicted as colored stars in this plot, agree well with the extrapolation of the continuum to shorter wavelengths, suggesting that there is very little contamination from line emission. This also suggests that there is little contribution from a diffuse UV component. This is further emphasized in the right panel of Figure 4 where we show the residuals from the continuum fit for each of the six BCGs. Our measured FUV fluxes from these new HST data are consistent with the measurement of a UV continuum from archival GALEX and XMM-OM data.

The idea that massive, young stars may be responsible for heating the majority of the warm, ionized filaments observed in cool core clusters is certainly not a new one (see e.g., Hu et al. 1985; Heckman et al. 1989; McNamara & O’Connell 1989). Most recently, O’Dea et al. (2008), Hicks et al. (2010), and McDonald et al. (2010) conducted MIR, UV, and Hα surveys, respectively, of cool core clusters and found a strong correlation between the SF rate and the cooling properties of cluster cores. However, this work extends these findings to include spatially resolved SF rates, which the previous studies have been unable to provide. This allows us to say conclusively that the young stars...
and the warm, ionized gas are in close proximity ($\lesssim 1''$) in the vast majority of systems, offering a straightforward explanation for the heating of these filaments.

4.2. Star Formation Efficiencies in Cooling Flows

In Section 3, we provide estimates of the efficiency with which the cooling ICM is converted into stars, assuming that this is indeed the source of star formation. This assumption is based on the results of M+10 and M+11, which provided several strong links between the X-ray cooling properties and the warm, ionized gas. These estimates of SFE represent a constraint on the so-called accreting box model of star formation. The simplified model that we posit is that the ICM is allowed to cool rapidly in regions where cooling locally dominates over feedback (Sharma et al. 2010). Our estimates of the ICM cooling rate, based on medium-resolution Chandra spectra, are consistent with estimates based on high-resolution XMM grating spectroscopy by Peterson et al. (2003) for the five overlapping systems. Once the gas reaches temperatures of $\sim 10^{7.5}$ K, it can continue to cool rapidly via UV/optical/IR line emission without producing fluxes that are inconsistent with what are observed. In the standard way, star formation will proceed once the gas reaches low enough temperature and high enough density. Observations by Edge (2001) and Salomé & Combes (2003) show evidence for molecular gas in the cool cores of several galaxy clusters, consistent with this picture.

If the above scenario is correct, our estimate of the SFE provides a constraint on the fraction of hot gas that will be converted to stars, assuming a steady inflow of gas. In Figure 5 we provide a histogram of SF efficiencies for all of the systems in Figure 3 with non-zero X-ray cooling rates ($dM/dt$). The peak of this distribution is well defined at an efficiency of $14^{+18}_{-8}\%$, regardless of which SF indicator (UV, Hα, and MIR) is used. We note that, while the distribution for UV- and MIR-determined SF rates both peak at roughly the same value, the UV-determined SF histogram extends to much lower values. The low-efficiency tail of this distribution may be an artifact produced by intrinsic extinction due to dust, to which the UV will be most sensitive, or may be indicative of a selection bias in the MIR sample. If we measure the peak efficiency based on the subsamples excluding the MIR and MIR+Hα (with no accompanying UV) data, we get $10^{+25}_{-5}\%$ and $14^{+20}_{-8}\%$, respectively. Thus, the peak value of 14% is not solely driven by the inclusion of MIR data.

The average efficiency of $14^{+18}_{-8}\%$, based on MIR, Hα, and UV data, is consistent with the estimates of SFE over the lifetime of a typical molecular cloud (20%–50%; Kroupa 2001; Lada & Lada 2003). This large variance in SFE may be due to differences in the ICM cooling and star formation timescales. Naturally, one would expect that there is some delay between the ICM cooling and the formation of stars, so that a reservoir of cold gas can accumulate and the formation of stars can be triggered. If this is indeed the case, one would expect to observe cooling-dominated periods (low SFE) followed by periods of strong star formation (high SFE) once the cold gas reservoir has reached some critical mass. Over an ensemble of systems, the average SFE is then an estimate of the time-averaged efficiency of an accreting system in converting a steady stream of cooling gas into stars. An alternative explanation for the spread of observed efficiencies is that the source of feedback is episodic (e.g., AGN). In this scenario, an episode of strong feedback from the AGN would re-heat the reservoir of cool gas, severely reducing the potential for star formation. This may indeed be the case, since two of the three systems with the highest 1.4 GHz luminosity (A2052, A2597, and Perseus A) have SFE $\lesssim 0.1$.

The fact that Figure 5 shows a well-defined peak suggests that the fraction of stars formed in an accreting system is constant over long enough timescales. Our estimate of an average efficiency indicates that, for a steady-state system accreting hot gas which is then allowed to cool, roughly $4 M_\odot$ of gas will either be re-heated or expelled via winds for every $1 M_\odot$ of stars formed. This fraction of baryons in stars is consistent with the global fraction of $\sim 20\%–30\%$ required by simulations to reproduce the observed stellar mass function of galaxies (Somerville et al. 2008). Unlike measurements of SF efficiency for giant molecular clouds, this estimate does not require the use of a specific timescale, since we are assuming that stars are forming out of the inflow of hot gas and that the reservoir for this hot gas is inexhaustible.

5. SUMMARY AND FUTURE PROSPECTS

We have assembled a unique set of high spatial resolution far-UV and Hα images for 15 cool core galaxy clusters. These data provide an unprecedented view of the thin, extended filaments in the cores of galaxy clusters. Based on the ratio of the far-UV to Hα luminosity, the UV SED, and the far-UV and Hα morphology, we conclude that the warm, ionized gas in the cluster cores is photoionized by massive, young stars in all but a few (A1991, A2052, A2580) systems. We show that the extended filaments, when considered separately, appear to be forming stars in the majority of cases, while the nuclei tend to have slightly lower FUV/Hα ratios, suggesting either a harder ionization source or higher extinction. The slight deviation from expected FUV/Hα ratios for continuous star formation (Leitherer et al. 1999) may be due to the fact that we have made no attempt to correct for intrinsic extinction due to dust or due
Figure 6. Optical and FUV data for the 15 clusters in our sample. From left to right the panels are: (1) MMTF red continuum image, (2) MMTF continuum-subtracted Hα image, (3) ACS/SBC FUV red-leak-subtracted image (F150LP–F140LP), and (4) Hα image with extraction regions defined. The horizontal scale bar in the left two panels represents 20 kpc. The Hα and FUV images are zoomed-in relative to the red continuum image. The square region in the red continuum panels represents the field of view for the zoomed-in panels. The gray scale in all images is arbitrarily chosen in order to enhance any morphological features.
Figure 6. (Continued)
Figure 6. (Continued)
to a top-heavy ($\alpha \ll 2.35$) IMF. We note that modest amounts of dust ($E(B-V) \sim 0.2$) in the most dense regions of the ICM can account for this deviation. Ideally, one would like spatially resolved optical spectra of the filaments in order to constrain the heat source and intrinsic reddening of the filaments. We plan on addressing this issue in upcoming studies. Comparing the estimates of the star formation rates based on FUV, H\alpha, and MIR luminosities to the spectroscopically determined X-ray cooling rate suggests an SFE of $14^{+8}_{-6}$. This value represents the time-averaged fraction, by mass, of gas cooling out of the ICM which turns into stars and agrees well with the stars-to-gas fraction of $\sim 20\text{--}30\%$ required by simulations to reproduce the observed stellar mass function. This result provides a new constraint for studies of star formation in accreting systems. Many aspects of this simplified scenario are still not well understood, including the origin of the high low-ionization line ratios (e.g., [N II]/H\alpha, [O I]/H\alpha; Crawford et al. 1999; Ferland et al. 2009), the absence of star formation in many “normal” looking filaments (e.g., NGC 1275; Fabian et al. 2008), and whether the star formation is similar to that seen in nearby spirals or vastly different. We intend to investigate such differences in future work via deep, optical spectroscopy of the filaments along with an assortment of star formation indicators from the UV to radio.

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APPENDIX

Optical and FUV data for the 15 clusters in our sample are shown in Figure 6.

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