Mon. Not. R. Astron. Soc. **000**, 1–?? (2008) Printed 26 February 2013 (MN LaTeX style file v2.2)

Evidence for recent star formation in BCGs: a correspondence between blue cores and UV excess

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Accepted 2009 January 20. Received 2008 December 20; in original form 2008 July 17

ABSTRACT

We present a joint analysis of near-ultraviolet (NUV) data from the GALEX mission and (optical) colour profiles for a sample of 7 Brightest Cluster Galaxies (BCGs) in the Canadian Cluster Comparison Project. We find that every BCG which has a blue rest-frame UV colour also shows a blue-core in its optical colour profile. Conversely, BCGs that lack blue cores and show monotonic colour gradients typical of old elliptical galaxies, are red in the UV. We interpret this as evidence that the NUV enhancement in the blue BCGs is driven by *recent star formation* and not from old evolved stellar populations such as horizontal branch stars. Furthermore, the UV enhancement cannot be from an AGN because the spatial extent of the blue cores is significantly larger than the possible contamination region due to a massive black hole. The recent star formation in the blue BCGs typically has an age less than 200 Myrs and contributes mass fractions of less than a percent. Although the sample studied here is small, we demonstrate, *for the first time*, a one-to-one correspondence between blue cores in elliptical galaxies (in particular BCGs) and a NUV-enhancement observed using GALEX. The combination of this one-to-one correspondence and the consistently young age of recent star formation, coupled with additional correlations with the host cluster's X-ray properties, strongly suggests that the star formation is fueled by gas cooling out of the intracluster medium. In turn, this implies that any AGN heating of the intracluster medium in massive clusters only acts to reduce the magnitude of the cooling flow and that once this flow starts, it is nearly always active. Collectively, these results suggest that AGN feedback in present-day BCGs, while important, cannot be as efficient as suggested by the recent theoretical model by proposed by De Lucia et al. (2006).

Key words: galaxies: clusters: general – galaxies: elliptical and lenticular, cD – galaxies: evolution – cooling flows – X-rays: galaxies: clusters

1 INTRODUCTION

Elliptical galaxies provide a critical test bench for many scenarios of galaxy formation because they follow tight relations in their photometric (optical), chemical and dynamical properties. Within massive groups and clusters, elliptical galaxies populate a tight region of the colour-magnitude relation (CMR) (Bower et al. 1992) known as the red sequence, which is mainly driven by an underlying 'mass-metallicity' relation (e.g. Carollo et al. 1993). The lack of significant change in the slope and scatter of the CMR (e.g. Stanford et al., 1998), the slow evolution of colours (e.g. Saglia et al. 2000; Ellis et al., 1997), and line strength indices of cluster early-type galaxies out to $z \sim 1$ (e.g. Bernardi et al., 2003) indicate that the *bulk* of their stars that comprise these systems formed over a relatively short period of time at high redshifts ($z > 3$) (see Renzini, 2006 for a recent review), though the issue of where these stars formed and how they were assembled into the observed elliptical galaxies has yet to be conclusively resolved.

The simplest model for the formation of elliptical galaxies — especially the most massive ones — is the 'monolithic collapse' model (see e.g. Larson 1974, Matteucci & Tornambe 1987, Pipino & Matteucci 2004, Merlin & Chiosi, 2006). In this model, the elliptical galaxies are believed to

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have formed from homogeneous collapse of intergalactic material, followed by a rapid, massive starburst, during which nearly all of the available gas is converted into stars that comprise the observed stellar content of the elliptical galaxies today. In its simplest form, the monolithic model predicts that the vast majority of the present-day elliptical systems were already be in place by $z \sim 3$ and that once formed, have been evolving passively towards the present. Consequently, this model predicts that ellipticals galaxies should be largely *red and dead* today.

Detailed recent observations of elliptical galaxies, however, indicate a more complex formation history: Taylor et al. (2008), for example, find that at the most only 20% of the local red sequence galaxies with stellar mass $M_* > 10^{11}\ M_\odot$ were already in place by $z \sim 2$ (but see Whiley et al. 2008, who do not detect any significant change in the stellar mass of the BCG since $z \sim 1$). Kormendy et al. (2008) argue that the mass-dependent variations in the structural properties of elliptical galaxies is inconsistent with the idea of a uniform, synchronized formation history. And using rest-frame UV observations[1] to probe the finer details of the star formation histories in elliptical galaxies, Kaviraj et al. (2007a; 2008) find compelling evidence that while the bulk of the stars that comprise the elliptical galaxies are old, the galaxies continue to form stars at a reduced rate over the lifetime of the Universe. Specifically, using GALEX (UV) and SDSS (optical) photometry, Kaviraj et al. (2007a) find that *at least* 30% of nearby ($0 < z < 0.11$), massive ($M_{\rm r} < -21$) ellipticals show *unambiguous* signatures of star formation within the last Gyr, contributing up to a few percent of the stellar mass of the galaxy.

An alternative model for the formation and evolution of galaxies is the hierarchical clustering model in which the these systems are *assembled* via successive mergers of lower mass systems, with both the formation of the lower mass progenitors occurring at an earlier epoch and the merger rate being larger in regions of the Universe characterized by higher than average total mass density. The hierarchical model is an inescapable prediction of the currently favored cold dark matter models for the formation and evolution of large-scale structure in the Universe. Strictly speaking, the hierarchical model only speaks to how the mass is assembled, not to the details of star formation, which is what the observations are sensitive to. The latter depends on a series of complex, highly nonlinear baryonic physics, including the manner in which galaxies acquire their gas (Keres et al. 2005), the local environment where the galaxy and its progenitors reside, the details of the cooling and heating processes that the gas is subjected to (e.g. Silk 1977; White & Rees, 1978; Scannapieco et al. 2005; Kaviraj et al. 2005, 2007b), etc. The most recent detailed study of the formation history of elliptical galaxies by De Lucia et al. (2006) shows that while the bulk of the stars that make up the most massive ellipticals form rapidly and high redshifts, they do so in a number of different progenitor systems and typically, the assembly of the progenitors into a single massive elliptical galaxy occurs much later. Whether the observed structural, chemical and photometric properties of massive elliptical galaxies is compatible with hierarchical late-time assembly remains to be seen (see, for example, Cimatti et al. 2006; Ciotti et al. 2007; Pipino & Matteucci 2008; Pipino et al. 2009, Maiolino et al. 2008, and Whiley et al. 2008 for observational arguments against late-time assembly).

In the context of the hierarchical models, the most important of the recent innovations is the inclusion of AGN feedback. AGN feedback plays a central role in driving gas out of the progenitor systems, thereby both truncating the initial starburst in these systems and ensuring that any subsequent mergers involving these objects are gas-poor (i.e. "dry mergers"). AGN feedback is also critical for preventing the cooling of any gas that subsequently accumulates in the halos of the massive elliptical galaxies or the larger systems (e.g. groups and clusters) that they are embedded in. Prior to the inclusion of AGN feedback, the hierarchical model produced elliptical galaxies that were both much too luminous and much too blue compared to the present-day population of massive elliptical galaxies. Unfortunately, details of how AGN feedback actually works is not well understood and the properties of the elliptical galaxies in the hierarchical model depends sensitively on how AGN feedback is modeled.

In this paper, we will use recent observations of a special class of massive elliptical galaxies, the Brightest Cluster Galaxies (BCGs), to gain additional insights into processes shaping the formation of elliptical galaxies. We are especially interested knowing whether these systems show evidence of late-time star formation, the conditions that facilitate late-time star formation and in understanding the nature of AGN feedback in these systems, at least at the present-time. As the most massive, most luminous galaxies in their local environment,[2] these galaxies have long been of special interest. In spite of their special status, they have much in common with other massive early-type galaxies. For example, the mean stellar ages and metallicities of BCG galaxies are similar to those of non-BCG ellipticals of the same mass (Fisher et al., 2005; Brough et al. 2007, von der Linden et al., 2007). More importantly, within the context of the hierarchical model, the essential features of the formation history of the BCGs is predicted to be similar to those of massive non-BCG early-type systems. Specifically, while nearly 80% of the stars that comprise the BCGs form at $z > 3$, they form in several distinct systems. The BCGs themselves do not take on a distinct identity until after $z \sim 0.7$. (De Lucia & Blaizot 2007; Romeo et al. 2008).

The BCGs that emerge from the theoretical modeling by De Lucia & Blaizot (2007) are, for all intensive purposes, *red and dead*. They experience virtually no star formation after the initial burst because the modeling assumes an extremely efficient form of AGN feedback. However, several recent studies (non-UV based) have reported examples of ongoing star formation in the brightest cluster galaxies (Cardiel et al. 1998, Crawford et al. 1999, Edge 2001, Goto 2005, McNamara et al. 2006, Wilman et al. 2006, O'Dea et

[1] In contrast to the optical spectral ranges, the UV is highly sensitive to even small fractions of young stars (younger than about a Gyr), making it an excellent probe of the low-level recent star formation.

[2] It is often incorrectly assumed that BCGs always reside at the center of the cluster potential. As shown by Bildfell et al. (2008), this is not necessarily so.

al. 2008, Bildfell et al. 2008, Cavagnolo et al. 2008, Rafferty et al. 2008); most of these BCGs reside in cool core clusters. Additionally, Hicks & Mushotzky (2005) noted an excess in the UV flux — as determined from the XMM-Newton Optical Monitor — in many (but not all) the cooling flow clusters in their sample, which they interpreted as evidence for star formation. Most recently, Bildfell et al. (2008) undertook a comprehensive study of 48 clusters that span a wide range of X-ray characteristics. Specifically, they analyzed the surface brightness and color profiles of the BCGs hosted by these clusters, seeking to relate the resulting trends to the relative location of the BCGs within the clusters as well as to their global X-ray luminosity (L_x) and temperature (T_x). They found that 25% of their BCGs had bluer colors in their central regions, which they interpreted as evidence for ongoing star formation. They also found that these blue core systems only occurred in cool core clusters (see also Cavagnolo et al 2008) and then only if the BCG is located at the cluster center. For completeness, we note that cool core clusters are systems whose central gas density is sufficiently high that the corresponding radiative cooling timescale is < 5 Gyrs. (See McCarthy et al. 2004; 2008 for a detailed discussion of the diversity in the cluster population, including the distinction between cool core versus non-cool core clusters).

The mounting evidence for active star formation poses a challenge for models that invoke strong AGN feedback. Bildfell et al (2008) suggest that in the systems that they studied, heating by AGN feedback may be offsetting most of the radiative losses suffered by the hot gas surrounding the BCGs but not all. Therefore, the gas cools but at a significantly reduced rate. If this is indeed the case, it represents an important clue into how AGN feedback operates. Our long-term goal, therefore, is to understand that implications of ongoing star formation in BCGs within the broader context of galaxy formation. As a first step, we need to establish that the blue core phenomenon is indeed associated with star formation. As discussed below, we do so by demonstrating that the blue core are unambiguously linked to UV-enhancement. Next we quantify the extent of recent star formation. Specifically, we are interested in determining the age of the last star formation event and the fraction of the total stellar mass that it gave rise to. Finally, we review the conditions characterizing the environments of the BCGs in our sample and use the apparent correlations to identify the source(s) of the cold gas that is fueling the residual star formation.

In order to carry out our analysis, we start by cross-matching the 48 BCGs in the Bildfell et al. catalog with archival data from the GALEX GR3. We find 10 BCGs in common, of which we analyze 7. In Sec. 2, we briefly summarize the main characteristics of the Bildfell et al. sample and the data retrieved from the GALEX archive. In Sec. 3, we present the model set up used to estimate the characteristics of the recent star formation (ages and mass fraction) in each BCG. Finally, our results are discussed in Sec. 4, and the conclusions are presented in Sec. 5. The cosmological parameters used throughout this work are $H_0 = 70$ km s^{-1} Mpc^{-1}, $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$.

2 DATA

The galaxies studied by Bildfell et al. (2008) are drawn from the Canadian Cluster Comparison Project (CCCP) The CCCP is a study of an X-ray selected sample of 50 clusters from the Advanced Satellite for Cosmology and Astrophysics (ASCA) catalog of Horner (2001), with redshifts in the range $0.15 \leqslant z \leqslant 0.55$ and most clusters having X-ray temperatures $T_x > 5$ keV. Almost all clusters have also either Chandra or XMM-Newton high resolution data. The CCCP clusters span the observed range in scatter of cluster X-ray and S-Z scaling relations, and thus create maximal leverage for the investigation of baryonic feedback effects. The combination of X-ray and deep, multi-filter optical data makes the CCCP an excellent sample for studying the links between BCGs and their host cluster environments. The deep optical imaging data was obtained using the Canada-France-Hawaii Telescope (CFHT). The full sample comprises a set of 30 clusters observed in g' and r' filters using the MegaCam detector and 20 clusters observed in the B and R filters using the CFH12K detector which were taken from the CFHT data archive at the Canadian Astronomical Data Centre (CADC).

A quarter (13/53) of the BCGs in the CCCP show colour profiles that become increasingly blue in the core. These galaxies are displaced from their host-cluster optical red sequence by $\sim$ 0.5 to 1.0 *mag* in (g'-r'), which is important for optical cluster studies that may reject the BCGs based on colour. The blue cores in these systems cannot be explained by AGN point-sources because (a) they are at least twice the size of the seeing disk and (b) Type II AGN do not contaminate the optical spectrum at more than a few percent level (Zakamska et al. 2006a; 2006b). The above arguments also apply to the NUV, in that the contamination due to AGN is less than 15% in the UV (see Salim et al. 2007 for a more detailed discussion). Moreover, Kauffmann et al. (2007) examined a sample of nearby AGN hosts and find that their UV emission too is quite extended, thus unlikely to emanate from the central AGN, whereas it seems to be associated with star forming discs. For these reasons, we shall assume that all of the NUV flux is purely stellar in origin and compute star formation rates accordingly. Strictly speaking, however, the star formation rates that we derive represent upper limits.

The Bildfell et al. sample was cross-matched with publicly available *UV* photometry from the second data release of the GALEX mission (Martin et al. 2005). GALEX provides two *UV* filters: the far-ultraviolet (*FUV*), centered at $\sim 1530\AA$ and the near-ultraviolet (*NUV*), centered at $\sim 2310\AA$. Note that, since the bulk of our sample are at intermediate redshifts ($z > 0.15$) we only use the NUV filter in this study, since the NUV filter traces the spectrum between rest-frame NUV and FUV. The cross-matching produced 10 BCGs which have *at least* a detection in the *NUV* filter. The remainder of the galaxies are not observed partly because of a lack of sufficient spatial coverage in Galex data and, possibly, short exposure times in some Galex fields. The positional matching is performed within the GALEX fiducial angular resolution of 6". NUV magnitudes and exposure times for the GALEX fields are given in Table 1, along with other information related to the galaxies such as redshifts, J2000 coordinates, effective radii, and the type of

Table 1. Galaxies from Bildfell et al. (2008) present in GALEX DR2

BCG ref	Name	z_{sp}	α_{BCG} (J2000)	δ_{BCG} (J2000)	r',R mag	g',B mag	$r_e^{r'}$ kpc	Core colour	R_* kpc	NUV (2300Å) mag	exp ks
1	Abell 1835	0.25	14 01 02.10	+02 52 42.69	15.97	17.17	$66.4^{+0.6}_{-0.1}$	blue	19 ± 2	19.13 ± 0.02	1.7
2	Abell 1942	0.22	14 38 21.88	+03 40 13.34	16.35	17.38	$43.7^{+0.2}_{-0.2}$	red	-	22.68 ± 0.28	1.7
3	Abell 2111	0.23	15 39 40.52	+34 25 27.46	17.26	18.50	$26.4^{+0.3}_{-0.3}$	red	-	23.41 ± 0.35	7.3
4	CL0910+41	0.44	09 13 45.52	+40 56 28.54	18.93	18.81	$32.6^{+0.5}_{-0.4}$	blue	40 ± 8	19.58 ± 0.11	0.4
5*	MS0440+02	0.19	04 43 09.92	+02 10 19.33	15.06	-	$102.0^{+0.3}_{-0.3}$	red	-	21.84 ± 0.44	0.09
6*	MS0451-03	0.54	04 54 10.84	−03 00 51.39	19.38	20.75	$45.5^{+0.3}_{-0.6}$	blue	20 ± 2	20.65 ± 0.28	0.11
7	Abell 2219	0.2256	16 40 19.85	+46 42 41.30	15.98	18.40	$61.7^{+0.5}_{-0.5}$	red	-	22.66 ± 0.27	2.75
8	Abell 2390	0.2280	21 53 36.84	+17 41 44.10	17.33	19.22	$18.4^{+0.3}_{-0.2}$	blue	25 ± 5	20.94 ± 0.07	1.96
9*	CL0024+16	0.39	00 26 35.68	+17 09 43.48	17.45	-	$60.1^{+1.8}_{-0.8}$	red	-	21.91 ± 0.09	15.42
10	MS1512+36	0.3727	15 14 22.51	+36 36 21.30	17.66	19.94	$57.6^{+0.9}_{-0.9}$	blue	15 ± 2	21.40 ± 0.34	0.07

CCCP targets from Bildfell et al. (2008). The first group of six BCGs was observed with CFHT MegaCam, while the second group was observed with the CFH12K camera. The galaxies marked with a * have not been used for the analysis (see Section 2). Redshifts (z) listed are spectroscopic. The (r', g') and (R, B) apparent magnitudes are in AB and Vega system, respectively (see text). The associated errors are typically 0.03 mag. Note that for the reasons outlined in section 2 no g' or B magnitudes were obtained for CL0024+16 and MS0440+02. The r' best-fit surface brightness profile parameter $r_e^{r'}$ is given to be compared to the size of the blue region R_* - if a blue core is present. Core colour is given as 'red' or 'blue' based on the shape of the inner colour profile (see Bildfell et al., 2008). Galex NUV magnitudes are in AB system. Galex NUV exposure times (exp) in units of 1000s.

core (red or blue) as described in Bildfell et al. In each case the GALEX image with the longest exposure time was used.

We note that, in general, galaxies harbouring recent star formation are more likely to be detected than non recent star formation-galaxies (since their UV flux will be higher), especially at higher redshift. Thus at any redshift the chances of detecting a UV blue BCG is higher than its UV red counterparts. However, since the goal of this work is to verify if a strong *NUV* flux is unambiguously linked to blue-core galaxies (and vice versa) the incompleteness in the detection of UV red BCGs does not affect our results.

Out of the 10 BCGs that are detected by GALEX, 5 have blue cores and 5 have normal (red) cores. However, this sample reduces to 7 objects because we have to exclude the BCGs in MS0440, CL0024 and MS0451 for the reasons outlined below. The MS0440 and CL0024 BCGs are excluded because there are systematics due to crowding in both of these systems. Moreover, the MS0440 BCG lies right at the edge of a very bright stellar reflection artifact, which causes problems for proper background subtraction.

In the case of the MS0451, there is a large foreground spiral that overlaps with its BCG. To minimize contamination, Bildfell et al. were required to mask a significant fraction of the BCG before measuring a total magnitude from its optical image. The central regions of the BCG are more heavily masked than the outer regions, which leads the colour to be dominated by that of the outer regions making the galaxy optically red. Since we extract the UV photometry directly from the GALEX GR3 database (without any masking) and given the large PSF of GALEX ($\sim$ 6 arc seconds) it is likely that the star formation in the overlapping spiral contributes to the UV signal we measure. This results in the MS0451 BCG having a very red $(g' - r')$ colour and an extremely blue UV-optical colour, rendering it difficult to perform accurate parameter estimation using realistic models.

3 MODELLING THE SPECTRUM: QUANTIFYING THE AGE AND MASS FRACTION IN YOUNG STARS

We estimate parameters governing the star formation history (SFH) of each galaxy by comparing its GALEX *NUV* and CFHT optical photometry to a library of synthetic photometry, generated using a large collection of model star formation histories. Specifically, we follow Kaviraj et al. (2007b) and make use of g'-r' & (NUV-r) colours, with the near-UV constraining the amount of recent star formation and the red optical light providing the normalization.

Each model SFH is constructed by assuming that a burst of star formation at high redshift ($z \sim 3$) is followed by a second burst, which is allowed to vary in age between 0.001 Gyrs and the look-back time corresponding to $z = 3$ in the rest-frame of the galaxy, and mass fraction between 0 and 1. Both bursts are assumed to be instantaneous. A Salpeter (1955) initial mass function is adopted for each burst. Figure 1 shows a schematic representation of the model SFHs. As an alternative, we could have modeled the second star formation event as extended in time (or even, continuous). We are unable to do so, however, because this approach requires more wavelength coverage than currently available in order to break the degeneracies between age, metallicity and dust content.

To build the library of synthetic photometry, each model SFH is combined with a single metallicity in the range 0.1Z$_\odot$ to 2.5Z$_\odot$ and a value of dust extinction parametrised by E_{B-V} in the range 0 to 0.5. Photometric predictions are generated by combining each model SFH with the chosen metallicity and E_{B-V} values and convolving with the stellar models of Yi (2003) through the GALEX *NUV* and CFHT optical filters. The model library contains $\sim 750,000$ individual models. Finally, since our galaxy sample spans a range of redshifts, equivalent libraries are constructed at the redshift of every galaxy.

The primary free parameters in this analysis are the age

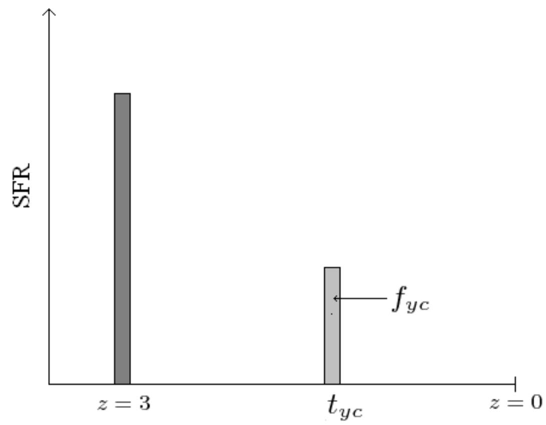

Figure 1. Model SFHs (see Section 3) are constructed by assuming that an instantaneous burst of star formation at high redshift ($z = 3$) is followed by a second instantaneous burst which is allowed to vary in age and mass fraction. The main free parameters are the age (t_{yc}), mass fraction (f_{yc}) of the second burst. t_{yc} is allowed to vary from 0.001 Gyrs to the look-back time corresponding to $z = 3$ in the rest-frame of each galaxy. f_{yc} varies between 0 and 1.

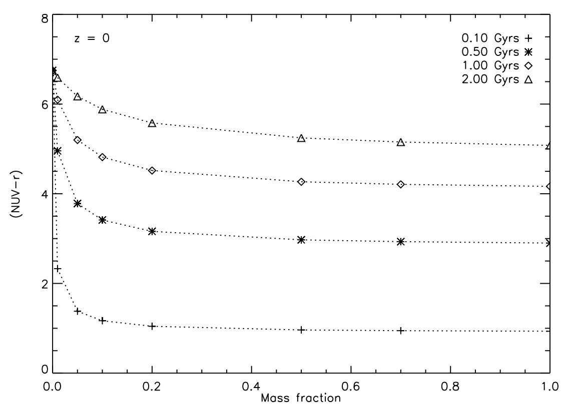

Figure 2. The sensitivity of the UV to young stars. We assume two instantaneous bursts of star formation, where the first burst is fixed at $z = 3$ and the second burst is allowed to vary in age and mass fraction. The near-UV (NUV) colour of the composite stellar population is plotted as a function of the age (symbol type) and mass fraction (x-axis) of the second burst. It is apparent that even a small mass fraction (∼1%) of young stars (∼ 0.1 Gyrs old) causes a dramatic change in the $NUV - r$ colour compared to what might be expected from a purely old stellar population ($NUV - r \sim 6.8$).

(t_{yc}) and mass fraction (f_{yc}) of the second burst, which provides the young component ('yc') of the stellar population in the galaxy. For each galaxy, parameters are estimated by comparing each observed galaxy to every model in the synthetic library, with the likelihood of each model ($\exp -\chi^2/2$) calculated using the value of χ^2 computed in the standard way. From the joint probability distribution, we marginalise over the dust and metallicity to extract the t_{yc} vs. f_{yc} probability space (see next section) for each galaxy. This space shows, for every galaxy, the probability that the recent star formation is described by a particular value of t_{yc} and f_{yc}. This allows us to explore the characteristics of the recent star formation in the individual BCGs and correlate them to the presence (or absence) of a blue core in the optical image. The error in the χ^2 is calculated by adding, in quadrature, the observational uncertainties and typical errors in the stellar models, which we assume to be 0.05 mag in each optical filter and 0.1 mag for the GALEX UV filter (Yi 2003). Note that the method is similar in design to past techniques designed to detect small 'frostings' of young stars over a underlying old stellar population, either using rest-frame UV data (e.g. Ferreras and Silk 2000) or spectroscopic line indices (e.g. Trager et al. 2000).

The sensitivity of the UV to young stars is demonstrated in Figure 2. We assume two instantaneous bursts of star formation, where the first burst is fixed at $z = 3$ and the second burst is allowed to vary in age and mass fraction. The near-UV colour of the composite stellar population is plotted as a function of the age (symbol type) and mass fraction (x-axis) of the second burst. It is apparent that even a very small mass fraction (∼1%) of young stars (∼ 0.1 Gyrs old) causes a dramatic change in the $NUV - r$ colour compared to what might be expected from a purely old stellar population ($NUV - r \sim 6.8$) or from the analysis of any optical colour-magnitude relation. Given that typical observational uncertainties in the $NUV - r$ colours from modern instrumentation are ∼ 0.2 mag, the usefulness of the UV in detecting residual amounts of recent star formation becomes quite apparent. Note that the NUV filter is taken from the GALEX filter set.

4 RESULTS AND DISCUSSION

In Figure 3, we present the UV-optical colours of the 7 BCGs in our final sample. In Figures 4 and 5, we present the quantitative SFH parameter estimation in terms of t_{yc} and f_{yc} for the red-core and blue-core BCGs respectively.[3]

Since the BCGs span a large range in redshift we do not simply show their ($NUV - r$) colours because their 'red sequence' positions (i.e. the position of a old, passively evolving population) are very different. Instead, we show, in Fig. 3, the *difference* between the ($NUV - r$) colour of each galaxy and the 'red sequence' position at its given redshift, calculated using a dustless, solar-metallicity simple stellar population (SSP) forming at $z = 3$. The local early-type population (Kaviraj et al. 2007a) is shown over-plotted using the small black dots. The value of $M_{\rm r}$ for the BCGs presented here is calculated by converting from the magnitudes in the CFHT Mould and Megaprime r-band filters (from Bildfell et al.) using a solar-metallicity SSP that forms at $z = 3$. Note that this local population is drawn mainly from the field and its local density distribution varies strongly from that of the BCG population (see Figure 5 in Schawinski et al. 2007).

Two results are immediately apparent on inspection of Figs. 3–5. First, the BCGs that do not exhibit blue cores

[3] We caution the reader that the estimates of t_{yc} and f_{yc} for the BCG in MS1512 are not particularly well constrained because of the large error in NUV flux due to extremely short exposure — see Table 1.

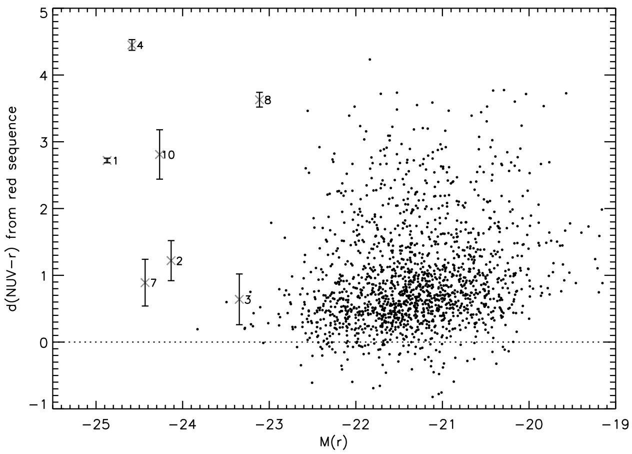

Figure 3. The difference between the red sequence position of each BCG at its given redshift, calculated using a solar metallicity simple stellar population (SSP) which forms at $z = 3$, and the $(NUV - r)$ colour. The local early-type population is shown over-plotted using the small lack dots. The numbers identify the galaxies according to the order in Table 1.

(i.e. nos. 2, 3, 7) are much closer to the NUV color of their respective red sequence positions: $d(NUV - r) < 1.5$. In other words, the red optical color corresponds to red NUV color. This is not necessarily surprising but it does provide us with a baseline. What is interesting, however, is that all of these UV-red BCGs are somewhat displaced by from their respective red sequence positions, suggesting that the star formation history of even these UV-red BCGs is inconsistent with their stellar content having formed entirely at high redshift ($z \sim 3$) and that they likely experienced low-level star formation events within the past ~ 2 Gyrs. This is the 'time window' during which the UV signal remains detectable (see top panel of Fig. 7 in Kaviraj et al. 2007a). This conjecture is borne out by the fact that the (t_{yc}, f_{yc}) map for the red-core BCGs (Figure 4) is not concentrated exclusively at very old ages. In the case of A2111 BCG, for example, the recent star formation is consistent with intermediate age populations (since t_{yc} is around 1 Gyr and f_{yc} is around a few percent).

Given our small sample, we cannot reject the possibility that the $d(NUV - r)$ for our red core BCGs is likely biased high due to the requirement that they must be detected in the UV before entering the sample. Based on this, we would expect that any missing red core systems would likely lie even closer to the red sequence than the ones shown here, further emphasizing the gap in UV color between the optically blue core BCGs and their red core counterparts. On the other hand, the offsets exhibited by our red-core BCGs appears to be comparable to those of the local early-type population as a whole and suggest that low-level star formation events are not uncommon or restricted to BCGs only. A careful analysis of the UV light in a large sample of elliptical galaxies indicates that luminous elliptical galaxies form up to 10-15 % of their stellar mass after $z \sim 1$, although for the bulk of the population, the typical young stellar mass fraction is much smaller, around a few percent (Kaviraj et

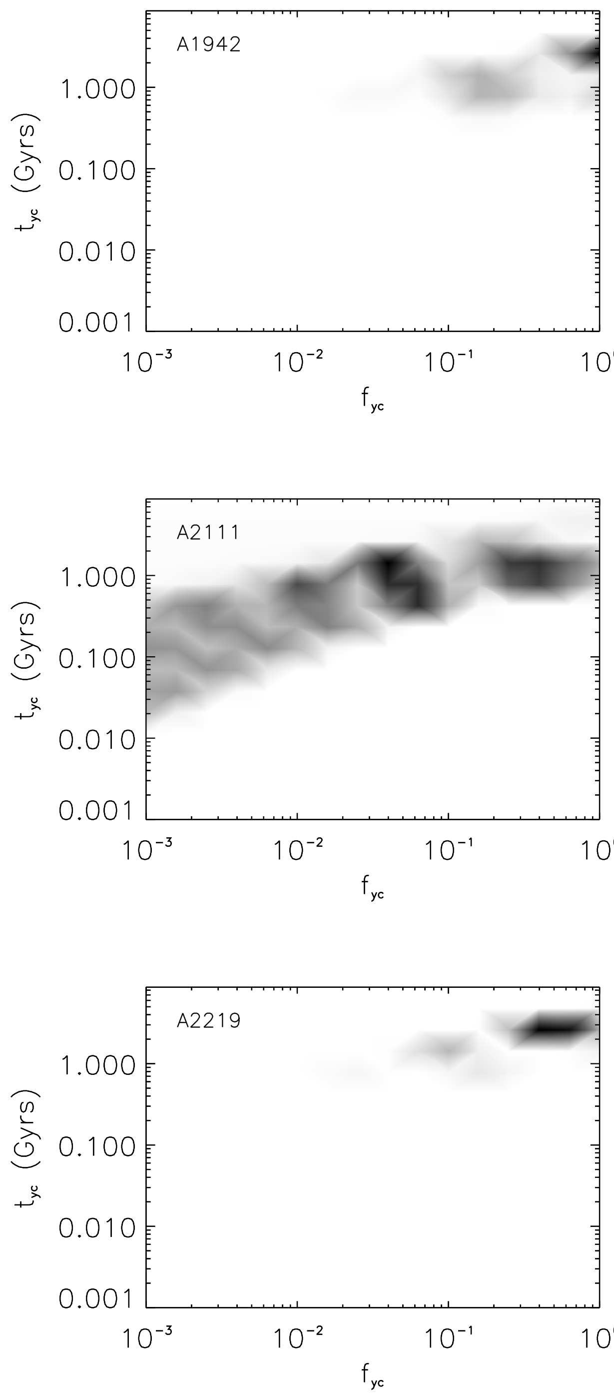

Figure 4. Probability maps for t_{yc} and f_{yc} for the UV-red BCGs. Recall that t_{yc} and f_{yc} represent the age and mass fraction of the recent star formation in the galaxy. From top to bottom the BCGs shown are: A1942, A2111 and A2219. We find that the 'young component' ('yc') in each of these galaxies is composed of intermediate age populations with ages greater than 1 Gyr. Note that none of the galaxies are consistent with purely old (> 3 Gyr old) populations. This is consistent with the fact that all the UV-red BCGs lie at least 1 mag away from the red sequence positions at their given redshifts.

al. 2007a; 2008; see also Kaviraj 2008 for a review of these recent results).

Second and perhaps most interestingly, Figs. 3–5 reveal an unambiguous *one-to-one correspondence between UV 'blueness' and a blue core in the optical image* in our BCG sample. Every BCG that is far from the red sequence position (i.e. has $d(NUV - r) > 2.5$), which is rarely seen in the regular ellipticals, is also a blue core system, and vice versa. Given that we associate the excess UV flux with star formation, this one-to-one correspondence, combined with the fact that UV-red BCGs do not show anomalous colour profiles, bolsters our earlier assertions (as well as those of Bildfell et al. 2008) that the blue-core BCGs show the features that they do because they host active star formation in their central regions. This association is further strengthened by independent confirmation of ongoing star formation based on optical and infra-red spectroscopic work in three of our four blue-core systems. These three galaxies and the measured rate at which they are forming stars in their central regions are as follows: A2390 is estimated to be forming stars at $\sim 5\ M_\odot\ \mathrm{yr}^{-1}$, CL0910 at $\sim 40\ M_\odot\ \mathrm{yr}^{-1}$ and A1835 at $\sim 120\ M_\odot\ \mathrm{yr}^{-1}$ (see Table 3 in Bildfell et al. and references therein).

Setting aside the results for MS1512 for reasons noted at the beginning of this Section, Figure 5 indicates that the recent star formation in the blue-core BCGs typically has an age less than 200 Myrs and contributes mass fractions of less than a percent. Using the values of the most likely t_{yc} and f_{yc} inferred for the young stellar component in our blue-core BCGs, we can estimate an upper limit for the SFR in the last ~ 0.2 Gyr for the UV-blue ellipticals by assuming that a mass of stars $f_{yc} \times M_{*,BCG}$ is assembled over a time t_{yc}. The rates span the range $\sim 20 - 100 M_\odot/yr$. These rates are broadly consistent with the published star formation rates determined by other means though we note that the agreement is much better for systems with high star formation rates and that our derived rates tend to be higher than the rates derived from spectroscopy for systems with low star formation rates. That our results tend to be slightly higher is perhaps not a surprise especially when one allows for the fact that we have assumed that all of the observed UV flux from the blue-core BCGs comes from the stellar component whereas this flux may include some (small) contribution from the AGN. One could also argue that even in the absence of any AGN contamination, our estimated star formation rates are upper limits because of the way we have chosen to model this process as an instantaneous burst, as opposed to a prolonged event that extends towards the present. While true in general, we do not expect this to be an issue here because the age of the young stellar population in our blue-core galaxies is comparable to the typical lifetimes of O and B stars. In such cases, the extended and instantaneous models should both give similar results.

4.1 Plausible mechanisms for fueling the recent star formation in UV-blue BCGs

Several of our blue-core BCGs, including A1835 and A2390, show evidence for significant accumulation of dust and molecular gas in their central regions (Edge et al. 2002, Egami et al. 2006). This reservoir is believed to provide the fuel for the ongoing star formation but where did this gas come from? Three obvious sources are: (1) gaseous flows associated with the cooling of the intracluster medium, (2) gas deposition during mergers, and (3) gas ejected from the stars that comprise the BCG (Menanteau et al. 2001a; 2001b).

Of these, Bildfell et al (2008) strongly favor the first on the strength of the correlations between the presence (or absence) of star formation in the BCGs and the global X-ray properties for the host clusters. Bildfell et al. (2008) showed that the blue-core BCGs are exclusively located in clusters that define the high-luminosity edge of the scatter in the L_x-T_x plane. In other words, at a fixed temperature, only clusters with the highest L_x display observable signatures of active star formation.

This region of the L_x-T_x diagram is known to be populated predominantly by cool-core clusters. In the absence of a heating mechanism that can fully compensate for the efficient loss of thermal energy through radiative losses, the cooling gas would be expected to flow inward towards the center of the potential, giving rise to cooling flows. Cooling flows provide a natural way to account for the reservoir of molecular gas in detected in some of the BCGs. More recently, the link between the central cooling timescale of the intracluster medium and star formation was further strengthened by the results of Cavagnolo et al (2008) and Rafferty et al. (2008), who used Chandra observations to determine the central gas densities and temperatures for a large number of clusters and found that star formation typically only occurs in those clusters with central cooling times $t_c < 1$ Gyr. Interestingly, a detailed analysis of the individual BCG-cluster systems in their CCCP sample led Bildfell to discover that while being embedded in a cool core cluster is a necessary condition for recent star formation in a BCG, it is not a sufficient condition. The BCG must also lie at the centre of the cluster potential. It is the combination of these two trends that led Bildfell et al. (2008) to support the cooling flow hypothesis.

The fact that all of our blue-core systems show evidence of a young stellar population (< 200 Myr) suggests that either we have caught these systems within 200 Myrs of their most recent bout of star formation, or that these systems have been forming stars for most of their lifetime. We find the latter to be much more plausible especially since *all* the BCGs in the CCCP sample that are hosted by clusters with high central X-ray surface brightness and are situated within $\sim 10\mathrm{h}^{-1}$ kpc of the center of the host cluster potential (identified as the peak of the X-ray surface brightness distribution) are blue-core and hence, actively star forming systems.[4]

If the star formation in the centrally located BCGs in cool core clusters is indeed fueled by cooling flows, then the above-mentioned results also provide insights into the nature of cooling flows. In the absence of ongoing heating, the short central cooling times of observed cool core clusters imply that radiative cooling would rapidly establish extreme centrally-peaked gas density profiles and sharply declining central temperature profiles, with gas temperatures tending towards zero at the cluster center. However, Chandra and XMM-Newton X-ray observations have convincingly demonstrated that present-day cool core clusters are not in the

[4] These systems comprise $\sim 20\%$ of the full CCCP systems.

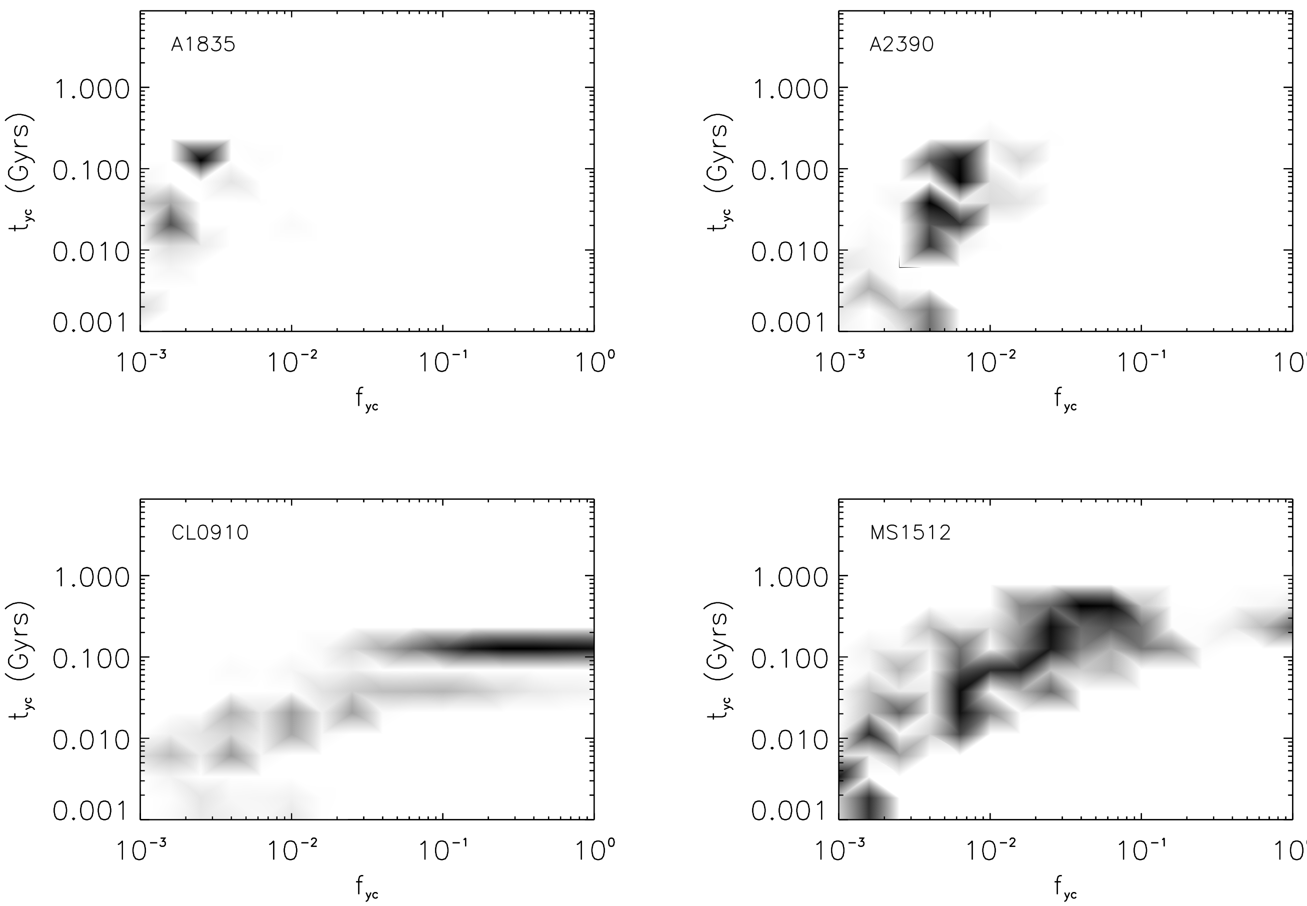

Figure 5. Probability maps for t_{yc} and f_{yc} for the UV-blue BCGs. Recall that t_{yc} and f_{yc} represent the age and mass fraction of the recent star formation in the galaxy. The recent star formation in the blue BCGs typically has an age less than 0.2 Gyrs and contributes mass fractions of less than a percent.

state just described — their central cores are warmer than expected (e.g., Peterson et al. 2003). This has led to claims in the literature that the AGNs in the centrally located BCGs are injecting sufficient energy into the intracluster medium to offset radiative losses and prevent the formation of cooling flows.

We do not dispute that the intracluster gas is being heated; rather, based on our results, we assert that once the cooling flow is established, it is essentially "on" for most of the time and that heating only acts to temper the cooling flow, not prevent them. This is contrary to strong feedback models of De Lucia et al. (2006). We cannot preclude the possibility of temporary disruption by mergers or AGN activity, only that if disrupted, they reform quickly. That is, in models where AGN feedback actually manages to heat the cluster gas sufficiently so as to halt the flow of cold gas towards the cluster center, such a phase must have a relatively short lifetime ($<$ 200 Myrs), after which the flow and the associated star formation resumes. Otherwise, we would expect to see a fraction of the centrally located BCGs in cool core systems showing "E+A"-like characteristics (i.e. the latest generation of stars with $t_{yc} \sim 1$ Gyr). Admittedly, our sample is small and we are mindful of that; however, the results for our blue-core systems stand in stark contrast to those of the BGCs in non-cool core clusters, in which the youngest stellar populations have ages >1 Gyr.

Regarding the other two potential explanations for the cold gas and star formation, (Kaviraj et al. 2007a) find the recycling of the internal reservoir of gas built up from mass loss from the extent stellar population (Menanteau et al. 2001a; 2001b) is not efficient enough to render the ellipticals UV-blue. Moreover, if this was the explanation, one would also expect the BCGs in non-cool core clusters to show evidence of current star formation, at variance with the findings of Bildfell et al. (2008) and Rafferty et al. (2008). Additionally, one would expect that central star formation fueled by recycled gas would tend to preserve and possibly even reinforce the radial metallicity gradients that is typically found in BCGs[5] (see Pipino et al. 2006, Pipino et al. 2008). Cardiel et al. (1998), however, found that in BCGs featuring emission-lines (due to recent star formation), the

[5] A decrease of the metal content in the stars of -0.3 dex per decade in radius is typically observed with mild (if any) correlation with galactic mass in ellipticals (e.g. Carollo et al. 1993) and BCGs (e.g. Fisher et al. 1995, Brough et al. 2007).

gradients in the spectral indices are flat or even positive inside the emission-line regions. Outside the emission-line regions, and in cooling flow galaxies without emission lines, gradients are negative and consistent with those measured in giant elliptical galaxies (Fisher et al., 1995). At the same time, a residual star formation can lower the central [α/Fe] abundance ratio (e.g. Pipino & Matteucci, 2006) and make blue BCGs differ from massive ellipticals. Larger samples, as the one by Loubser et al. (2008) will shed more light on the details of the chemical evolution in BCGs compared to normal ellipticals, providing additional clues into the source of the gas that is fueling the observed star formation and to the integral star formation histories.

The accretion of gas-rich galaxies by the central BCG is another mechanism by which the latter can acquire its reservoir of gas. In fact, this mechanism may seem to be plausible for BCGs because they are likely to have more companions than the average elliptical galaxy in the field and because dynamical friction within the cluster halo is likely to facilitate the orbital decay of these galaxies. Kaviraj et al. (2007c) find that galaxy mergers of mass ratios less than 1:4 and where the cold gas amounts to 20% of the merging satellite mass, produce good agreement with the observed UV colors of regular ellipticals. There are, however, several problems with this particular explanation, of which the two most important are: (a) The galaxies orbiting in or falling through the inner cluster environments are typically gas poor; it is believed that they have either lost their gas to the intracluster medium via ram pressure stripping, or it was consumed by star formation and not replenished because of the nature of the local environment. (b) This mechanism for delivery of cold gas should, to first order, be equally applicable to centrally located BCGs in both cool core and non-cool core clusters. Consequently, we would expect to see blue-core galaxies in both types of clusters. We don't. Additionally, there does not appear to be any outright correlation between presence or absence of a blue-core and the local density of galaxies in the neighborhood of the BCG. For instance, MS1455[6] has very few satellites but exhibits a blue core while Abell 2537[6] has a red core but many satellites.

Of the three mechanisms discussed above, the *cooling flow* explanation seems to be the most promising primary mechanism for fueling the observed star formation.

Finally, the confirmation of recent star formation in early-type galaxies calls for a dedicated survey to detect Type II supernovae (SNII) in these systems. From a theoretical point of view, in fact, the current observational upper limit in the central parts of galaxy clusters (0.027 SNuM[7], Mannucci et al. 2008) poses a strong constraint on the recent star formation even if this value is slightly higher than for the ellipticals as a whole. In principle, we should be able to observe SNII events in blue core BCGs. However, the typical brightness of SNII, combined with the fact that the recent star formation takes place in the bright centres of the galaxies, implies that the probability of finding SNII in such galaxies using the current generation of surveys is probably low. In fact, according to Mannucci et al. (2007), 5-10% of the local SNII remain out of reach of current supernova surveys. The fraction of missing events rises sharply towards $z = 1$, when about 30% of the SNII might be undetected. Nevertheless, some good candidates do exist, such as the BCG in A1835, which have very high star formation rates across an extended star forming region, enhancing our chances of finding SNII. Furthermore, the SNIa rate seems to be slightly higher in radio-loud galaxies, indicating that recent star formation may have boosted the *prompt* channel of SNIa progenitors (for details see Della Valle et al. 2005, Mannucci et al. 2006).

5 CONCLUSIONS

In a recent study, Bildfell et al. (2008) showed that the majority of Brightest Cluster Galaxies (BCGs) in the Canadian Cluster Comparison Project (CCCP) have shallow optical colour profiles that become bluer with increasing radius. However, a substantial minority of the BCGs in the sample (25%) deviates from this simple behaviour, exhibiting blue optical cores instead. In this study, we have presented a joint analysis of the near ultra-violet (NUV) data from the GALEX mission and optical colour profiles for a sample of 7 BCGs from the Bildfell et al. sample.

We find that every BCG that has a blue NUV colour also shows a blue-core in its optical colour profile. Conversely, BCGs that lack blue cores and show monotonic colour gradient are red in the UV. Although the sample studied here is small, we demonstrate, *for the first time*, that a one-to-one correspondence between blue cores and UV-enhancement is a clear indicator of recent star formation. The UV-enhancement is not due to old evolved stellar populations such as horizontal branch stars. While we cannot outrightly rule out a contribution to the observed UV-flux from an obscured central AGN in the BCG, a number of factors including the physical size of the blue cores and the fact that obscured AGNs are expected to contribute to the optical signal at a few percent level lead us to assert that AGNs are not the principal agents of the optical and NUV observations. Our assertions are in agreement with other independent indicators of star formation in BCGs based on optical and infra-red observations (e.g. Cardiel et al. 1998, Crawford et al. 1999, Edge 2001, Goto 2005, McNamara et al. 2006, Wilman et al. 2006, Bildfell et al. 2008, Cavagnolo et al. 2008, O'Dea et al. 2008, Rafferty et al. 2008).

The young stellar component in all of our blue core BCGs typically has an age less than 200 Myrs. The presence of ongoing star formation strongly implies that these systems have been forming stars for most of their life time, albeit at a low rate. Given that *all* the BCGs in the CCCP sample that are hosted by clusters with high central X-ray surface brightness and situated within $\sim 10h^{-1}$ kpc of the center of the host cluster potential are blue-core, we must accept that all such systems must be steadily forming stars over a cosmological time.

We discuss several possible sources of gas for feeding the recent star formation in the blue core BCGs: (a) cooling flows (Bildfell et al. 2007); (b) recycling of stellar ejecta (Menanteau et al. 2001); (c) mergers with gas-rich galaxies (Kaviraj et al. 2007c). However, an analysis of each of these possibilities combined with unambiguous linkages between

[6] Not analysed here, but present in the Bildfell et al sample
[7] SNuM = SN explosion per century per $10^{10} M_{\odot}$

the color of the BCG core, the location of the BCG within the host cluster, as well as the excess X-ray luminosity (Bildfell et al. 2008) of the cluster and the short central cooling time of the intracluster gas (Rafferty et al. 2008) leads us to conclude that the cooling flow is the primary mechanism for fueling the recent star formation BCGs. In this regard, BCGs seem to behave differently from the rest of elliptical galaxies. This also means that heating from the AGN largely moderates the cooling flow, as opposed to preventing its formation altogether like in the strong feedback model of De Lucia et al. (2006).

Finally, we note that while we have demonstrated a direct correspondence between the presence of a blue optical core and a blue UV colour in a small sample of BCGs, the result needs to be confirmed through an analysis of a much large sample of elliptical galaxies, drawn from a wide range in luminosity and environments. Among the interesting issues to consider is whether BCGs in group environments because similarly to our cluster BCGs. Future work will focus on repeating the analysis presented here on GALEX-detected early-type galaxies that have SDSS images (from which colour profiles can be extracted) to test the robustness of the preliminary results presented in this study.

ACKNOWLEDGMENTS

The authors thank the referee for his careful reading and his insightful comments. Enlightening discussions with F.Mannucci, R.Maiolino, I. McCarthy and B. McNamara are acknowledged. AP acknowledges partial support from NSF grant AST-0649899. SK acknowledges research support through a Leverhulme Early-Career Fellowship, a BIPAC Fellowship and a Research Fellowship from Worcester College, Oxford. AB and HH acknowledge support from NSERC through the Discovery Grant program.

GALEX (Galaxy Evolution Explorer) is a NASA Small Explorer, launched in April 2003, developed in cooperation with the Centre National d'Etudes Spatiales of France and the Korean Ministry of Science and Technology.

Funding for the SDSS and SDSS-II has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Science Foundation, the U.S. Department of Energy, the National Aeronautics and Space Administration, the Japanese Monbukagakusho, the Max Planck Society, and the Higher Education Funding Council for England. The SDSS Web Site is http://www.sdss.org/.

The SDSS is managed by the Astrophysical Research Consortium for the Participating Institutions. The Participating Institutions are the American Museum of Natural History, Astrophysical Institute Potsdam, University of Basel, University of Cambridge, Case Western Reserve University, University of Chicago, Drexel University, Fermilab, the Institute for Advanced Study, the Japan Participation Group, Johns Hopkins University, the Joint Institute for Nuclear Astrophysics, the Kavli Institute for Particle Astrophysics and Cosmology, the Korean Scientist Group, the Chinese Academy of Sciences (LAMOST), Los Alamos National Laboratory, the Max-Planck-Institute for Astronomy (MPIA), the Max-Planck-Institute for Astrophysics (MPA), New Mexico State University, Ohio State University, University of Pittsburgh, University of Portsmouth, Princeton University, the United States Naval Observatory, and the University of Washington.

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