THE SPATIAL DISTRIBUTION OF GALAXIES OF DIFFERENT SPECTRAL TYPES IN THE MASSIVE INTERMEDIATE-REDSHIFT CLUSTER MACS J0717.5+3745

Cheng-Jiun Ma, Harald Ebeling, David Donovan, and Elizabeth Barrett
Institute for Astronomy, University of Hawaii, 2680 Woodlawn Drive, Honolulu, HI 96822
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ABSTRACT

We present the results of a wide-field spectroscopic analysis of the galaxy population of the massive cluster MACS J0717.5+3745 and the surrounding filamentary structure (z = 0.55), as part of our systematic study of the 12 most distant clusters in the MACS sample. Of 1368 galaxies spectroscopically observed in this field, 563 are identified as cluster members; of those, 203 are classified as emission-line galaxies, 260 as absorption-line galaxies, and 17 as E+A galaxies (defined by (Hα + Hγ)/2 > 6 Å and no detection of [O II] and Hβ in emission). The variation of the fraction of emission- and absorption-line galaxies as a function of local projected galaxy density confirms the well-known morphology-density relation, and becomes flat at projected galaxy densities less than ~20 Mpc⁻². Interestingly, 16 out of 17 E+A galaxies lie (in projection) within the ram-pressure stripping radius around the cluster core, which we take to be direct evidence that ram-pressure stripping is the primary mechanism that terminates star formation in the E+A population of galaxy clusters. This conclusion is supported by the rarity of E+A galaxies in the filament, which rules out galaxy mergers as the dominant driver of evolution for E+A galaxies in clusters. In addition, we find that the 42 e(a) and 27 e(b) member galaxies, i.e., the dusty-starburst and starburst galaxies respectively, are spread out across almost the entire study area. Their spatial distribution, which shows a strong preference for the filament region, suggests that starbursts are triggered in relatively low-density environments as galaxies are accreted from the field population.

Subject headings: galaxies: clusters: individual (MACS J0717.5+3745) — galaxies: elliptical and lenticular, cD — galaxies: evolution — galaxies: starburst — large-scale structure of universe — techniques: spectroscopic

Online material: color figures

1. INTRODUCTION

It is widely accepted that the effect of environment is one of the most important factors for galaxy evolution. Unlike field galaxies, for which the dominant physical mechanism driving evolution is galaxy-galaxy mergers, as has been revealed in many large-scale surveys (Gomez et al. 2003; Lewis et al. 2002; Cooper et al. 2008), cluster galaxies evolve in a more complex fashion (see, e.g., the review by Bower & Balogh 2004). As a result, cluster galaxies behave differently from field galaxies at the same epoch. One of the best-studied examples of this difference between the properties of galaxies in clusters and in the field is the morphology-density relation (Oemler 1974; Dressler 1980), i.e., the fact that the fraction of late-type galaxies drops precipitously toward the center of a cluster, whereas the fraction of early-type galaxies increases dramatically. In addition, the Butcher-Oemler effect (Butcher & Oemler 1978), which states that galaxies in rich clusters tend to be bluer and more active (i.e., feature emission lines) with increasing cluster redshift out to at least z ~ 0.8, implies that the build-up of the morphology-density relation is still ongoing at redshifts less than 1. Therefore, much effort (Couch & Sharples 1987; Dressler et al. 1997; Poggianti et al. 1999; Smith et al. 2005; Postman et al. 2005; Moran et al. 2006; Tran et al. 2007) has gone into establishing whether, and if so how, blue late-type galaxies are transformed into early-type galaxies, specifically S0 galaxies.

Clusters at intermediate redshift (z ~ 0.5) provide us with a unique opportunity to examine this hypothesized transformation, as well as the dominant physical mechanisms driving it. Recent work in this field includes a study of the morphological distribution of galaxies in the cluster Cl 0024+16 at z = 0.39 (Tran et al. 2003), and a comparison of the spatial distribution and spectroscopic properties of spiral galaxies with quenched star formation (passive spirals) and newly formed S0 galaxies in, again Cl 0024+16, as well as in the more massive system MS 0451.6−0305 at z = 0.55 (Moran et al. 2007). The authors of these studies suggest that ram-pressure stripping (Gunn & Gott 1972) is not the only mechanism involved in building up the population of S0 galaxies from late-type galaxies, although it does accelerate the process. The transformation is actually initiated much farther away from the cluster center, and at a slower pace, by the processes of strangulation (Larson et al. 1980) or galaxy-galaxy harassment (Moore et al. 1996). Additional evidence of this evolution from blue late-type galaxies to S0 galaxies is presented by Tran et al. (2007), who, using the spectroscopic diagnostics Hα and D₂⁰⁰⁰⁰ (Kauffmann et al. 2003) in their study of the cluster MS 1054.4−0321 (z = 0.823), confirm that S0 galaxies in the cluster are in general younger than the elliptical galaxies. Tran et al. (2007) suggest that these S0 galaxies have recently been converted from late-type galaxies falling in from the field (see also Tran et al. 2005).

To improve our understanding of the different physical effects governing galaxy evolution from the cluster outskirts to the cluster.
core, we have embarked on an extensive magnitude-limited wide-field spectroscopic survey of the galaxy population of 12 clusters with redshifts above 0.5, selected from the MASSive Cluster Survey (MACS; Ebeling et al. 2001, 2004, 2007). In this paper we present results from our pilot study of MACS J0717.5+3745 \((z = 0.545)\). MACS J0717.5+3745, which has the most extensive spectroscopic data set of these 12 at present, features a complex X-ray morphology in the cluster core, as well as a giant filament described by Ebeling et al. (2004). We here focus on the spectroscopic analysis and classification of galaxies in MACS J0717.5+3745, with special emphasis on E+A galaxies, a galaxy type that, as explained in the following section, holds great promise as a diagnostic for cluster-related mechanisms of galaxy evolution.

This paper is organized as follows. In § 2, we review the properties of E+A galaxies. In § 3, we describe the data used for this study and give an overview of the data-reduction procedure. In § 4 we discuss the selection of the cluster members used in our analysis, and describe the equivalent-width measurement and spectral classification. In § 5, we present results based on the spatial distribution of each spectral type. In § 6 we interpret our findings; a conclusion is given in § 7. Throughout this paper, we adopt the concordance ΛCDM cosmology with \(h_0 = 0.7, \Omega_m = 0.3\). Magnitudes are quoted in the AB system. Color versions of the figures are available in the online edition.

2. E+A GALAXIES

One of the most promising approaches to understanding how blue and active late-type galaxies are transformed into red and passive early-type systems (Bower & Balogh 2004) is through studies of galaxies caught in transition between the two types, for example E+A galaxies (Dressler & Gunn 1983), also called k+a, a+k, or post-starburst galaxies. Although there is no unique definition of this transition type, its representatives are characterized by the presence of strong Balmer absorption lines in their spectra, indicating a large fraction of A-type stars, and weak or no ongoing star formation, often quantified by the strength of the [O ii] emission line. Since the duration of the E+A phase is relatively short (less than 1 Gyr), E+A galaxies should be good tracers of the environment that is host to a critical part of the evolution of galaxies in clusters.

Although E+A galaxies were first found in clusters at intermediate redshift (e.g., Dressler & Gunn 1983; Couch & Sharples 1987), their origin and habitat was soon proven to be more varied by the discovery that the majority of E+A galaxies in the local universe are in fact located in dense environments (Zabludoff et al. 1996; Goto et al. 2003; Goto 2007; Hogg et al. 2006; Quintero et al. 2004). As for the possible physical origin of this type of galaxy, Zabludoff et al. (1996) and Yang et al. (2004) report that many of the E+A galaxies in the field show evidence of galaxy mergers. At higher redshift, however, E+A galaxies are predominantly found in the much denser environment of clusters (Tran et al. 2003, 2004), which have thus been suspected of being instrumental in the termination of star formation activity in these systems. In addition, Poggianti et al. (2004) show that, at \(M_r > -18.5\), the post-starburst galaxies in Coma are fainter than the typical E+A galaxies found in clusters at higher redshift, which suggests that the evolution of post-starburst galaxies follows the “downsizing” trend proposed by Cowie et al. (1996). Any discrepancies between the properties of E+A galaxies in the local field and in intermediate-redshift clusters may thus be explained by a combination of evolution and selection biases, in the sense that the local surveys sample predominantly luminous galaxies and hence do not probe the population of fainter E+A galaxies in clusters (the faintest E+A galaxy in Zabludoff et al. [1996] features \(M_r \sim -18.5\), whereas the magnitude limit in Goto et al. [2003] is \(M_r < -21.84\)).

Unlike previous studies (Tran et al. 2003, 2004; Goto et al. 2003), the goal of this work is not to investigate whether E+A galaxies are more likely to be found in clusters or in the field; rather, we focus on the spatial distribution of E+A galaxies around the massive cluster MACS J0717.5+3745 in order to isolate the most probable physical mechanism responsible for their creation in a cluster environment. In this context, we also attempt to address the question of the origin of the E+A population by investigating the spatial distribution of possible starburst galaxies, the so-called e(a) and e(b) galaxies (Dressler et al. 1999; Poggianti & Wu 2000).

3. DATA AND ANALYSIS

Using optical images obtained with the Suprime-Cam wide-field camera on the Subaru 8 m telescope on Mauna Kea (Miyazaki et al. 2002), we identify galaxies within the \(34 \times 27\) arcmin\(^2\) Suprime-Cam field of view. We then employ color selection to obtain spectra of a subset of presumed cluster members, primarily using the DEep Imaging Multi-Object Spectrograph (DEIMOS) on the Keck-II 10 m telescope. In order to study the spectroscopic properties of galaxies in different environments, the DEIMOS masks are designed to cover the entire cluster, including the filament and a satellite cluster. We use the spectroscopic data to determine the redshifts of galaxies, as well as their spectral types. We follow the spectral classification scheme of Tran et al. (2003), with some modifications, to categorize the cluster galaxies into emission-line, absorption-line, and E+A galaxies. The emission-line galaxies can be further subdivided into e(a), e(b), and e(c) galaxies according to the equivalent width of the H\(\alpha\) absorption and [O ii] emission lines (Dressler et al. 1999). Complementing our optical analysis of the galaxy population of this system, X-ray data obtained with the imaging array of the Chandra Advanced CCD Imaging Spectrometer (ACIS-I) are analyzed to provide a basic model of the gaseous intracluster medium.

3.1. Optical Photometry

We use images in the B, V, R\(_C\), I\(_C\), and z' bands obtained with Suprime-Cam, supplemented by images in the u' band obtained with the MegaPrime camera on the CFHT 3.6 m telescope. The observations were performed from 2000 December to 2004 February. All data are reduced employing standard techniques, which have, however, been adapted to deal with the special characteristics of the Suprime-Cam and MegaPrime data; details are given by Donovan (2007).

In order to allow a robust estimate of the spectral energy distribution (SED) to be obtained for all objects within the field of view, the imaging data from the various passbands are seen-matched using the technique described in Kartaltepe et al. (2008); this ensures that the images for all bands have the same effective spatial resolution of 1".

Object catalogs are then created with SExtractor version 2.4.3 (Bertin & Arnouts 1996) in “dual image” mode, with the R-band image as the reference detection image. We separate stars from galaxies by fitting the stellar sequence in the distributions of magnitude vs. peak surface brightness, and magnitude vs. half-light radius. Isophotal galaxy magnitudes calculated for elliptical apertures are returned by SExtractor in the m\(_{\text{AB}}\) and AUTO parameter. The photometric calibration of the Suprime-Cam imaging data is performed by means of a snapshot observation of a nearby SDSS
field\textsuperscript{2} and uses hundreds of stars with magnitudes ranging from 16 to 18 mag. The calibration of our MegaCam data is supplied with Chandra’s ACIS-I detector in the 0.5–7 keV band. The image shown has been adaptively smoothed using the \texttt{asmooth} algorithm (Ebeling et al. 2006), requiring a minimal significance with respect to the local background of 99\%. The shaded cross marks the regions falling onto the chip gaps of the ACIS-I detector. A close-up view of the cluster core based on the same X-ray data has been previously published by Ebeling et al. (2007). [See the electronic edition of the Journal for a color version of this figure.]

### 3.2. X-Ray Data

The X-ray data are used to derive global cluster properties, most importantly the virial radius and the ram-pressure stripping radius. To this end, we analyze the data taken with the Chandra ACIS-I instrument in 2003 January, with a total exposure time of 60 ks (ObsID 4200). The data reduction is performed following the procedure described by Ruderman & Ebeling (2005). Figure 1 shows the adaptively smoothed X-ray emission in the 0.5–7 keV band as observed by ACIS-I. The X-ray luminosity and temperature are listed in Table 5; a dynamical analysis based on the X-ray properties and the velocity dispersion will be presented in § 5.3.

### 3.3. Optical Spectroscopy

MACS J0717.5+3745 has the most extensive spectroscopic data in our ongoing follow-up study of the dynamical structure and galaxy properties in 12 clusters with $z > 0.5$ in the MACS sample (Ebeling et al. 2007; Kartaltepe et al. 2008). The spectroscopic data set used here is compiled primarily from the observation of 18 masks with the DEIMOS spectrograph on the Keck-II telescope. In addition, some spectra obtained using the Low Resolution Image Spectrometer (LRIS) on the Keck-I telescope, and the Gemini Multi-Object Spectrographs (GMOS) on the Gemini telescope, are included. The instrumental configuration of these observations is summarized by Barrett (2005), from which we have extracted the essential information listed in Table 1. The chosen setup is a compromise between the requirements of wavelength coverage from the [O ii] $\lambda \lambda 3727$ line to the H$\beta$ line at a redshift of about 0.5, and moderately high spectral resolution. After reducing the spectra using the standard DEIMOS pipeline developed by the DEEP2 team, the redshifts are determined and verified manually using at least two prominent spectral features, such as (in absorption) Ca H and K, H$\beta$, or the G band, and (in emission) [O ii] $\lambda \lambda 3727$, H$\beta$, and [O iii] $\lambda \lambda 4959, 5007$. Based on repeated observations of individual objects, we estimate the error in the resulting redshifts to be about 70 km s$^{-1}$, which is consistent with the spectral resolution of the observations.

The final spectroscopic catalog comprises 1103 galaxies, of which 563 are cluster members (Table 3). Figure 2 shows the location of the spectroscopically observed objects within our study region, which is highlighted by the outline of the DEIMOS masks. The full redshift distribution is shown in Figure 3. Cluster membership is assigned to all galaxies with $0.522 < z < 0.566$, the redshift range given by $z = z_{cl} \pm 2.5 \sigma$, where the cluster redshift $z_{cl} = 0.5458$ and velocity dispersion $\sigma = 1660$ km s$^{-1}$ (Table 5) are determined from the redshift distribution of galaxies in the central 1 Mpc region of the cluster (Ebeling et al. 2007). The final catalog, including redshifts and equivalent widths of the spectral features ([O ii], H$\alpha$, H$\gamma$, D$_{4000}$, H$\beta$, and [O iii]), will be published in a separate data paper.

### 4. SPECTROSCOPIC ANALYSIS

#### 4.1. Object Selection and Completeness

Since it is impractical to cover the entire sample of galaxies spectroscopically from the cluster core to the outskirts, we had to select targets in a way that increases the efficiency of cluster member detections while minimizing any potential bias. Since at the time this project started we did not have imaging data in a

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\textsuperscript{2} The SDSS photometry is transformed into the Johnson-Cousin system using the equation of R. Lupton (2005), available at http://www.sdss.org/dr5/algorithms/sdssLBVRITransform.html.

\textsuperscript{3} See http://www.cfht.hawaii.edu/Instruments/Elixir/.
sufficient number of bandpasses to determine credible photometric redshifts, the target list for our spectroscopic observations is selected using the color-magnitude diagram for the $V$ and $R_C$ filters (Fig. 4), making use of the cluster red sequence. To maximize completeness, we limit our survey to relatively bright objects ($m_{R_C} < 22.25$, which is, equivalently, $M_{R_C} < M^* + 2$ at $z = 0.55$), while adopting a generous color cut toward the blue end of the distribution. The latter was adjusted in the course of the survey such that its locus coincides with the $V - R_C$ color (relative to the red sequence) at which the fraction of galaxies found to be cluster members falls below 20% (Fig. 5). However, there will unavoidably be a few extremely blue galaxies that are in fact cluster members but do not satisfy our selection criteria. We estimate the resulting incompleteness by fitting a heuristic Gaussian model to the data shown in Figure 5. If we assume that the probability derived from the observed sample is representative, and...
that the Gaussian fit can be extrapolated to yet bluer colors, we would expect our survey to be incomplete at the $\sim 2\%$ level. We note, however, that this incompleteness is severely color-dependent which, as we will show in § 5.2, could potentially cause the fraction of emission-line galaxies, but not the fraction of E+A galaxies, to be significantly underestimated.

We define the completeness of our spectroscopic survey as the ratio of the number of sources observed to the number of sources in the photometric catalog (within the color band marked in Fig. 4), including spectra from which we failed to measure a redshift.\footnote{We include in this statistic a small number of stars which failed to be eliminated by the star-galaxy separation discussed in § 3.1.} In addition, we define the efficiency of our survey as the ratio of the number of high-quality spectra, from which both the redshift and the equivalent width of spectral features can be measured accurately (again within the color limits marked in Fig. 4). The completeness and efficiency as a function of galaxy magnitude are shown in the top panel of Figure 6. Inside the entire study region, the completeness is roughly constant at about 70\% at $R_C < 21.75$, with the curve only dropping within the very last bin before the magnitude limit at $R_C = 22.25$. Also shown in the top panel of Figure 6 is the completeness within a radius of 2 Mpc from the center of the cluster; again, the completeness is roughly independent of magnitude (except for the final bin before our global magnitude limit), but now at a much higher level, near unity. Although the difference between these two curves shows that the completeness of our survey is not spatially uniform, the relative spatial distribution of galaxies of different types should be unaffected.

The bottom panel in Figure 6 shows the efficiency in determining the galaxy redshift and the efficiency for spectroscopic classification. The former is almost perfect over the full magnitude range. The criteria used to classify galaxies according to spectral type (defined in the following two sections) are much stricter; still, the efficiency for spectroscopic classification remains better than 0.8 at all magnitudes, reflecting the good signal-to-noise ratio of most of our spectra. Only a handful of spectra feature very low signal-to-noise ratios, which are caused either by poor slit positioning or by erroneously high magnitudes reported by SExtractor. If the redshift can be measured but no spectral type can be determined, it is usually because the key spectral features fall onto the chip gap or coincide with telluric lines.

4.2. Equivalent Width Measurement

In order to allow a comparison of our results with those from previous spectroscopic studies of cluster galaxies, we follow the approach of Tran et al. (2003) for measuring equivalent widths (EW), i.e., the inverse-variance weighted integration of the flux.

Fig. 6.—Completeness (top) and efficiency (bottom) of our spectroscopic survey as a function of galaxy magnitude. The color criterion of Fig. 4 has been applied. Top: Survey completeness for the entire study region (filled symbols) and for region A (open symbols). Bottom: Survey efficiency, i.e., success rate for redshift determination (open symbols) and spectral classification (filled symbols). In both panels, the dashed line indicates the magnitude limit of the spectroscopic sample.
over a spectral line, using integration windows as defined in Fisher et al. (1998). The EW of the spectral features [O ii] 2372, Hδ, and Hγ are measured this way. For those galaxies with strong emission features but weak or nondetectable continuum, a lower limit to the EW is calculated based on the variance of the spectrum near the spectral feature in question. An exception is the case of the Hβ emission line, for which the EW could be underestimated if absorption is also present. We account for this potential bias by subtracting the EW of the Hβ absorption as provided by stellar population models (Bruzual & Charlot 2003) fitted to the data from 4060 to 5360 Å (rest frame) using the template-fitting code PPHF (Cappellari & Emsellem 2004). We adopt the convention that negative (positive) EW values indicate emission (absorption). Hereafter, we use the convention that [O ii] refers to the EW of [O ii] in emission, whereas Hδ and Hγ refer to the EW of the respective lines in absorption. Since we have fitted the emission and absorption components of Hβ separately, the EW of Hβ in absorption and emission will be specified as Hβ_ab and Hβ_em.

4.3. Spectral Type Classification

We classify cluster galaxies as emission-line galaxies, absorption-line galaxies, and E+A galaxies, following the spirit of the classification used by Tran et al. (2003), with a few modifications. The classification scheme of Tran et al. (2003) only requires the relatively blue features [O ii], Hδ, and Hγ, which is convenient for spectroscopic surveys of clusters out to redshift z ≈ 1, for which redder spectral lines are observationally inaccessible in the optical passband. [O ii] emission is an indicator of current activity (be it star formation or the presence of an active nucleus), whereas the two Balmer line features are indicators of star formation within the last few hundred million years. The Balmer emission lines, however, are more robust diagnostics of star formation activity (e.g., Moustakas et al. 2006) than [O ii]. Since the latter is easily underestimated because of extinction, the absence of [O ii] emission does not necessarily preclude the presence of star formation or other galaxy activity. Although Hα is not accessible to optical surveys for galaxies at z > 0.5, the Hβ line is available in the observable spectral range (although it comes dangerously close to the broad atmospheric H₂O absorption band at 7600 Å). We therefore use both [O ii] and Hβ_em to define emission-line galaxies, the specific criteria being [O ii] < −5 Å (the same cutoff as Tran et al. 2003), or Hβ_em < −5 Å. Galaxies with [O ii] > −5 Å and Hβ_em > −5 Å will be classified as absorption-line galaxies if (Hδ + Hγ)/2 < 4 Å (the latter criterion being identical to the one used by Tran et al. 2003).

For E+A galaxies, we deviate yet further from Tran et al. (2003), who simply define E+A galaxies to be all galaxies that are neither emission- or absorption-line galaxies. The definition adopted for this work is more conservative, in that we require an E+A galaxy to have no detectable [O ii] or Hβ_em, and (Hδ + Hγ)/2 > 6 Å (as compared to the cutoff value of 4 Å of Tran et al. 2003). This definition leaves a small fraction of our galaxy sample unclassified, in recognition of the aforementioned gray areas between E+A galaxies and both emission- and absorption-line galaxies.

The motivation for our choice of more stringent criteria is twofold. As shown by Goto et al. (2003) and Goto (2007), local samples of E+A galaxies compiled without information about Hα may suffer from as much as 52% contamination by Hα emission-line galaxies. Blake et al. (2004) however, found that a linear combination of the strengths of three Balmer absorption lines (Hβ, Hδ, and Hγ) can be efficiently used to identify this contaminating population. Following Zabludoff et al. (1996), we thus calculate the average of Hδ, Hγ, and Hβ_em for all galaxies in our sample that meet the more generous definition of E+A galaxies of Tran et al. (2003) and for which the Hβ line is observable. We find that only 45% of them meet the criterion that (Hβ_em + Hγ + Hδ)/3 > 5.5 Å (Blake et al. 2004), implying that more than half of the population thus selected may in fact feature Hα in emission. If, however, we raise the threshold value for (Hγ + Hδ)/2 from 4 to 6 Å, then 100% of the galaxies thus selected, and for which the Hβ line is available, fulfill the criteria of Blake et al. (2004). The second motivation for our more stringent definition of E+A galaxies is that the detection of [O ii] in a galaxy is not an unambiguous sign of star formation, but could also be indicative of nonstellar radiation. Indeed, Yan et al. (2006) find that a large fraction of post-starburst galaxies may be misidentified as undergoing current star formation, although the [O ii] emission actually originates from an active galactic nucleus (AGN).

Since our project has currently no means of efficiently distinguishing between starbursting galaxies and post-starburst galaxies containing AGNs, and since the compilation of a statistically complete sample of post-starburst galaxies is not the main goal of this work, we exclude from our E+A sample all galaxies featuring any [O ii] emission, in order to keep the resulting sample as clean as possible and avoid complications caused by the presence of AGNs for the interpretation of the mechanisms responsible for the termination of star formation activity. Although the sample of E+A galaxies selected by our more conservative criteria thus misses a possibly sizeable and interesting fraction of the entire post-starburst population, as suggested in Yan et al. (2006), it is better suited to study the interactions between galaxies and the intracluster medium, and it is also less contaminated by weakly star-forming galaxies.

Following Dressler et al. (1999), we can classify the emission-line galaxies further into e(a), e(b), and e(c) subtypes based on the strength of the Hδ absorption and [O ii] emission lines. Both of these features are indicative of starbursts within a few million to one billion years before the time of observation. Specifically, e(a) galaxies are defined as systems with Hδ > 4 Å and −40 Å < [O ii] < −5 Å, whereas e(b) galaxies feature [O ii] < −40 Å, regardless of Hδ; the spectral evidence of young and massive stars in either of these subtypes suggests recent starbursts. All other emission-line galaxies, i.e., systems lacking signs of explosive star formation in the recent past, are classified as e(c). The difference between e(b), e(a), and E+A galaxies is thus the decreasing strength of the [O ii] emission line. The absence of [O ii] in E+A galaxies suggests that the star formation activity has halted, whereas, at the opposite extreme, strong [O ii] emission makes the e(b) subtype promising candidates for starburst galaxies. The intermediate (in terms of [O ii] strength) e(a) galaxies, on the other hand, are not easily placed in this sequence, since, as mentioned before, the strength of [O ii] emission is highly sensitive to dust extinction. Poggianti & Wu (2000), for instance, find about half of a sample of very luminous infrared galaxies [log (LIR/L⊙) > 11.5] to exhibit e(a) spectra. The distinction between these three populations is thus ambiguous; some of the
E+A galaxies may actually be e(a) galaxies whose [O ii] emission is completely extinguished by dust. Conversely, some of the e(a) galaxies could in fact be post-starburst galaxies with some residual star formation. In spite of these ambiguities, we emphasize that e(a) and E+A galaxies are in general distinct populations, which is (as we shall demonstrate) reflected in their different distribution within the cluster environment. The relevance of e(a) and e(b) galaxies in the context of this study is the potential for both galaxy types to trace the E+A progenitor population.

The definition of the spectral types is summarized in Table 2, and the number of galaxies of each type is given in Table 3. Note that, because of our conservative definition of E+A galaxies, about 8% of all cluster members with spectroscopic information are missing in Table 3, as well as in the analysis that follows. These are the population with weak [O ii], weak Hβ, and Balmer absorption lines whose strength falls between the absorption-line and E+A criteria [4 A < (Hβ + Hγ)/2 < 6 A]. They are probably a mixture of dusty star-forming galaxies and post-star-forming galaxies. In Tran et al. (2003, 2004), galaxies of this type are also classified as E+A galaxies.

5. RESULTS

5.1. Photometric Redshift

From our photometry in the u*, B, V, RC, IC, and z' bands, photometric redshifts are derived for galaxies with RC < 24.0 (~M* + 4 at z = 0.55) using the adaptive SED-fitting code LePhare (Arnouts et al. 1999; Ilbert et al. 2006). LePhare employs χ² optimization, comparing the observed magnitudes with those predicted from an SED library. An adaptive method is applied to adjust the photometric zero points for all passbands by using the sample of spectroscopic redshifts as a training set.⁷ No Bayesian prior for the galaxy redshift distribution is assumed. We use the library of empirical templates of Ilbert et al. (2006) and the Calzetti extinction law (Calzetti 2001) for reddening corrections applied to templates later than Sbc. The training set is obtained from the spectroscopic redshift database by selecting all galaxies with an RC band magnitude brighter than 21.5 and a minimal separation from the closest SExtractor-detected neighbor of 3.5'' to avoid photometric errors from close pairs or blended sources. The resulting training set comprises 273 galaxies at redshifts ranging from 0.15 to 0.9. The comparison of spectroscopic and photometric redshifts is shown in Figure 7. The statistical error of the photometric redshifts, as derived from the Gaussian

### TABLE 2
DEFINITION OF SPECTRAL TYPES

| Type               | Criteria                                                                 |
|--------------------|--------------------------------------------------------------------------|
| Emission-line      | [O ii] < −5 Å or Hβ<sub>em</sub> < −5 Å                                 |
| Absorption-line    | [O ii] > −5 Å Hβ<sub>em</sub> > −5 Å and (Hβ + Hγ)/2 < 4 Å              |
| E+A                | No detection of [O ii] and Hβ<sub>em</sub> and (Hβ + Hγ)/2 > 6 Å        |
| e(a)               | Emission-line galaxies with Hβ > 4 Å and −40 Å < [O ii] < −5 Å          |
| e(b)               | Emission-line galaxies with [O ii] < −40 Å                              |
| e(c)               | Emission-line galaxies with Hβ < 4 Å and −40 Å < [O ii] < −5 Å          |

### TABLE 3
SPECTRAL TYPE SUMMARY

| Type                        | All | Cluster Members |
|-----------------------------|-----|-----------------|
| All spectra                 | 1368|                 |
| Sample spectra              | 1147|                 |
| Redshift measurements       | 1103| 563             |
| Spectra with spectral diagnostics | 1023| 530             |
| Emission-line galaxies      | 507 | 203             |
| Absorption-line galaxies    | 426 | 260             |
| E+A galaxies                | 21  | 17              |
| Unclassified                | 69  | 50              |
| e(a)                        | 76  | 42              |
| e(b)                        | 66  | 27              |
| e(c)                        | 365 | 134             |

* No magnitude or color cuts are applied. Spectra obtained serendipitously are included.

³ The resulting correction of typically 0.05 mag is consistent with the statistical and systematic uncertainty of our photometric calibration.

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![Fig. 7.—Photometric vs. spectroscopic redshifts for galaxies in the field of MACS J0717.5+3745; we only show galaxies from our LePhare training set (see text for details). The lower panel shows the residuals dz as a function of the spectroscopic redshift, while the insert in the top left corner shows the histogram of the residuals, as well as a Gaussian model used to estimate their standard deviation Δz. [See the electronic edition of the Journal for a color version of this figure.]](image-url)
distribution of the residuals shown in the insert of Figure 7, is found to be $\Delta z = 0.024$.

The main purpose of the photometric redshift catalog is to allow us to estimate the local projected galaxy density with better statistics than would be feasible from the spectroscopic data set alone. On the basis of photometric redshifts, we define cluster members to be the galaxies with $|z_{\text{ph}} - z_{\text{cl}}| < \sigma_{\text{ph-z}}$, where $\sigma_{\text{ph-z}} = (1 + z_{\text{cl}})\Delta z$. Note that this redshift cut ($\pm \sigma_{\text{ph-z}} = \pm 0.036$) is much more generous than that used before for the spectroscopic redshifts ($\pm 3\sigma = \pm 0.022$); the chosen cutoff value represents a good compromise between completeness and contamination. The resulting catalog of “photometric” cluster members includes 2218 galaxies, and allows us to estimate the local galaxy density in the entire Suprime-Cam field of view. The much higher accuracy of our spectroscopic redshifts, on the other hand, provides us with an opportunity to study the dynamical structure of the cluster-filament system in detail.

Using the photometrically selected set of cluster members, we map the surface density of cluster galaxies. A smoothed version of this distribution (shown in Fig. 2) is obtained with the adaptive-smoothing algorithm asmooth (Ebeling et al. 2006), which preserves the signal-to-noise ratio of all significant features on all scales. The comparison of the result with the maps derived by Ebeling et al. (2004) and Kartaltepe et al. (2008) using only galaxies on the cluster red sequence proves instructive, in as much as it highlights the dominance of blue galaxies in low-density, filamentary environments. We show in Figure 8, side by side, the galaxy surface density maps obtained by us using photometric redshifts as described above, and the equivalent map from Kartaltepe et al. (2008), which is based entirely on galaxies with $V-R_C$ colors consistent with the cluster red sequence. Note the dramatic difference in the relative prominence of the main cluster and the filament.

In order to allow a direct comparison with the results from earlier work on the impact of cluster environment on galaxy activity (Kodama et al. 2001; Balogh et al. 2004; Sato & Martin 2006), we also calculate for all “photometric” cluster members the projected local density $\Sigma_{10}$, defined as the galaxy number density within a circle whose radius is given by the separation to the 10th closest neighbor. The resulting values of $\Sigma_{10}$ are consistent with the surface density distribution shown in the top panel of Figure 8.

### 5.2. Broadband Colors of Cluster Members of Different Spectral Types

The comparison of Figure 4 with the color-magnitude diagram for different spectral types of galaxies (left panel of Fig. 9) illustrates the potential bias caused by the blue color cut discussed in § 4.1. Not surprisingly, all of the bluest cluster members found in our study are emission-line galaxies, the fraction of which is thus likely to be underestimated. This is particularly true for the e(b) subtype, which we find to be heavily concentrated at the blue, faint end of our selection in color-magnitude space. If all cluster members bluer than our color cut are in fact e(b) galaxies (clearly the worst-case scenario), the number of e(b) galaxies in MACS J0717.5+3745 could be underestimated by as much as $\sim 30\%$. We shall keep this in mind below when discussing the fraction of e(b), e(a), and emission-line galaxies in general. Note, however, that the E+A and absorption-line galaxies lie well away from the color cut, so that their numbers can be expected to be unaffected by color-dependent incompleteness.

Figure 9 compares the magnitude and color distributions of cluster members of different spectral type. As has been noted before by other authors, for example Dressler & Gunn (1983) and Tran et al. (2003, 2007), E+A galaxies are found to exhibit broadband colors that are intermediate between those of absorption- and emission-line galaxies, as is to be expected from their spectral definition as a composite of old and new stellar populations. Differences between the various spectroscopic types can be characterized by measuring the mean and scatter of the relative $V-R_C$ color of a given galaxy class with respect to the red sequence (Table 4). The mean relative color of zero found for absorption-line galaxies confirms our linear fit to the cluster red sequence calculated without selection of any specific spectroscopic types.
The small scatter in the relative $V/C0_R$ color of absorption-line galaxies is consistent with the result of, e.g., Blakeslee et al. (2006) and Tran et al. (2007) that early-type cluster members are formed at $z < 2$. The mean relative colors of the other spectroscopically defined galaxy types discussed in this study are, in order of increasing blueward distance from the red sequence, E+A galaxies, and emission-line galaxies, a ranking consistent with the hypothesis that E+A galaxies represent an intermediate stage in the evolutionary sequence from active emission-line galaxies to passively evolving early-type galaxies. Interestingly, this scenario is also supported by the different scatter around the mean relative color for the different populations: the color scatter of the E+A galaxies is significantly smaller than that of e(a) and e(b) galaxies, their potential precursors (Poggianti et al. 1999), but still larger than that of the evolved population of absorption-line galaxies forming the cluster red sequence. Although their spectral properties imply that E+A galaxies evolved from the e(a) and/or e(b) population less than 1 billion years ago, their color characteristics

![Fig. 9](image-url)

**TABLE 4**

| Type                  | Mean  $^a$ | Scale $^a$ |
|-----------------------|-----------|------------|
| Absorption-line galaxies | 0.006 ± 0.005 | 0.0068 ± 0.0004 |
| E+A galaxies          | 0.03 ± 0.03 | 0.08 ± 0.01 |
| Emission-line galaxies $^b$ | 0.26 ± 0.01 | 0.176 ± 0.006 |
| e(a) galaxies $^b$    | 0.30 ± 0.02 | 0.12 ± 0.03 |
| e(b) galaxies $^b$    | 0.42 ± 0.04 | 0.18 ± 0.06 |
| e(c) galaxies $^b$    | 0.23 ± 0.02 | 0.17 ± 0.09 |

$^a$ Mean and scale are calculated using the biweight estimator in Beers et al. (1990).

$^b$ Because of the blue color cut mentioned in § 4.1, the mean and scattering of the emission-line galaxies and the subtypes, in particular the e(b) galaxies, may be biased.
have thus already become remarkably similar to those of absorption-line galaxies.

Another interesting fact that emerges from Figure 9 relates to the mean color of e(b) galaxies. Their locus at the extreme blue end of the distribution shown in the left bottom panel of Figure 9 is not solely the result of the strong [O ii] emission to which they owe their definition. Since [O ii] falls into the $V$ band at $z = 0.55$, the fact that the majority of the e(b) galaxies found in our study also exhibit very blue $U-V$ colors (right bottom panel of Fig. 9) indicates significant continuum emission in the UV rest frame. Follow-up observations are needed of the few e(b) galaxies that are found to be unusually red to establish whether nuclear activity is responsible for the strong [O ii] emission observed.

5.3. Dynamical Scales

A fundamental problem of many forms of dynamical analysis is the inherent assumption of virial equilibrium. Models appropriate for the description of clusters in the process of active assembly, such as MACS J0717.5+3745 or (albeit to a lesser degree) MS 0451.6−0305 (Moran et al. 2007), would have to take into account the effects of mergers and complex substructure on a wide range of scales. With the exception of the simplest cases, this is infeasible, in part owing to our insufficient knowledge of the true three-dimensional geometry of the system. With this caveat in mind, we note that the simplistic dynamical scales derived in this section should only be considered crude estimates.

The most relevant dynamical scales for this work are the virial radius $R_{\text{vir}}$ and the ram-pressure stripping radius $R_{\text{str}}$. To obtain estimates of these quantities, we need a description of the cluster’s gas density profile and a global X-ray temperature. The former is obtained by fitting a $\beta$-model (Cavaliere & Fusco-Femiano 1976),

$$\rho_{\text{gas}} = \rho_0 \left[ 1 + \left( \frac{r}{r_c} \right)^2 \right]^{-\frac{3}{2}} \beta,$$

(1)

to the observed X-ray surface brightness. Specifically, the center of the X-ray emission is determined by fitting a two-dimensional elliptical $\beta$-model to the exposure-weighted image after point sources have been removed. The radial profile is then extracted using this center position. The subsequent fit of a one-dimensional $\beta$-model is limited to radii larger than $11\ arcmin$ (70 kpc) to minimize the impact of the complex merging features in the heavily disturbed cluster core. A global X-ray temperature is measured by extracting the X-ray spectrum from $r = 70$ kpc to $r = 0.94$ Mpc ($r_{1000}$) and using Sherpa to fit a MEKAL plasma model (Mewe et al. 1985), with the absorption term frozen at the Galactic value. From the X-ray temperature and the $\beta$-model profile, we estimate the virial radius $R_{\text{vir}}$ using the formula of Arnaud et al. (2002),

$$R_{\text{vir}} = 3.80 \beta_T^{1/2} \Delta_c^{-1/2} (1 + z)^{-3/2} \times (kT/10 \text{ keV})^{1/2} \frac{1}{h_{50}} \text{ Mpc},$$

with

$$\Delta_c = \left( \frac{200 \Omega_0}{18 \pi^2 \Omega_c} \right).$$

Here $\beta_T$ is the normalization of the virial relation, i.e., $GM_*/(2R_{\text{vir}}) = \beta_T kT$. The virial radius thus derived is about 2.9 Mpc, which is consistent with the virial radius (3 Mpc) estimated from the velocity dispersion using the relation (Gunn & Gott 1972)

$$R_{\text{vir}} = 1.7 h^{-1} \text{ Mpc} \frac{\sigma}{1000 \text{ km s}^{-1}} \left( \frac{\Omega_0 (1 + z)^3 + \Omega_{\Lambda}}{\Omega_0} \right)^{-0.5}.$$

The ram-pressure stripping radius is estimated by equating the gas pressure required to strip a Milky-Way-like galaxy from all its gas to the gas density obtained previously in our X-ray analysis (eq. [1]). The former can be obtained from the stripping requirement (Gunn & Gott 1972; Treu et al. 2003)

$$\rho_{\text{gas}} v_{\text{f}}^2 > 2.1 \times 10^{-12} \text{ N m}^{-2} \left( \frac{r_{\text{rot}}}{220 \text{ km s}^{-1}} \right)^2 \left( \frac{r_{\text{b}}}{10 \text{ kpc}} \right)^{-1} \times \left( \frac{\Sigma_{\text{HI}}}{8 \times 10^{20} \text{ cm}^{-2}} \right).$$

Here $v_{\text{f}}$ is the velocity of the infalling galaxy which, in all other respects (rotation velocity $v_{\text{rot}}$, scale length $r_{\text{b}}$, and $\text{H I}$ surface density $\Sigma_{\text{HI}}$), is assumed to be similar to the Milky Way, as indicated by the units used above. The infall velocity $v_{\text{f}}$ is estimated as

$$v_{\text{f}}(r) = \sqrt{\frac{2GM_X}{r} - \frac{2GM_X}{R_{\text{vir}}}},$$

where $M_X$ is the total mass within $R_{\text{vir}}$ derived from the X-ray properties of the cluster (see, e.g., Maughan et al. 2003). A summary of the results, as well as related X-ray cluster properties, is given in Table 5.

| Parameter | Value |
|-----------|-------|
| $f_X$ | $2.74 \pm 0.03 \times 10^{-12} \text{ ergs s}^{-1} \text{ cm}^{-2}$ |
| $L_X$ | $24.6 \pm 0.3 \times 10^{44} \text{ erg s}^{-1}$ |
| $kT$ | $11.6 \pm 0.5 \text{ keV}$ |
| $\beta$ | $1.1 \pm 0.1$ |
| $\rho_0$ | $1.71 \pm 0.05 \times 10^{14} \text{ M}_\odot \text{ Mpc}^{-3}$ |
| $r_c$ | $92^\circ \pm 6^\circ$ |
| $z_b$ | $0.5446 \pm 0.0005$ |
| $\sigma$ | $1612 \pm 70 \text{ km s}^{-1}$ |
| $R_{\text{vir}}$ | $3.0 \pm 0.2 \text{ Mpc}$ |
| $R_{\text{str}}$ | $2.9 \pm 0.1 \text{ Mpc}$ |
| $M_X$ | $28 \pm 5 \times 10^{14} \text{ M}_\odot$ |
| $R_a$ | $1.9 \text{ Mpc}$ |

$^a$ Ebeling et al. (2007).
$^b$ The values for the mean redshift $z_{\text{d}}$ and velocity dispersion $\sigma$ are calculated iteratively using the redshifts of cluster members within the virial radius (3 Mpc) and thus differ slightly from the values published by Ebeling et al. (2007), where a radius of 1 Mpc was used.
$^c$ The uncertainty is estimated by error propagation.
are efficient at larger radii, with the starvation radius being equivalent to the virial radius (Balogh et al. 2000), and harassment being almost independent of cluster-centric distance (Moore et al. 1996, 1998). Since probably all cluster galaxies under study here are thus subject to harassment, it would not be easy to isolate the impact of this particular effect. The last mechanism, galaxy merging, is largely irrelevant in the densest parts of the cluster environment, owing to the large velocity dispersion, but peaks near the virial radius (see, e.g., Ghigna et al. 1998).

5.4. Redshift Distribution of Cluster Members

The dynamical scales derived in the previous section refer to the primary cluster, but exclude the filament. As a first look into the properties of the large-scale structure observed, all the way from the cluster core to the extended peak in the galaxy density in region B, we show in Figure 10 the distribution of galaxy redshifts projected onto a line starting northwest of the cluster center and ending southeast of the filament, as indicated in Figure 2. We find the average redshift of the galaxies in region B, \(\bar{z}_B = 0.5468 \pm 0.0004\), to be significantly higher than that of the galaxies around the main cluster, \(\bar{z}_A = 0.544 \pm 0.0006\). The velocity difference between these two regions is thus 630 km s\(^{-1}\).

In addition, the velocity dispersion of the galaxies in region B is \(\sigma_B = (1050 \pm 65)\) km s\(^{-1}\), significantly less than the value of \(\sigma_A = (1630^{+75}_{-93})\) km s\(^{-1}\) found in region A. Although the Chandra ACIS-I image of MACS J0717.5+3745 covers a fair fraction of region B, it just misses the galaxy density peak at its center. Since, in addition, the exposure of this observation is only 60 ks, we are currently unable to obtain an estimate of the gas temperature and mass in region B. Deriving a mass estimate from \(\sigma_B\) is not meaningful, because of the clearly unvirialized nature of this structure.

5.5. Spatial Distribution of Cluster Members

We show in Figure 11 the distribution of different galaxy types as a function of (radial) distance to the cluster center. The fraction of absorption-line galaxies drops from \(\sim 80\%\) in the cluster core to \(\sim 30\%\) at the virial radius, while the fraction of emission-line galaxies shows the opposite behavior, increasing from about \(5\%\) at the cluster center to almost \(70\%\) at the virial radius. Beyond 3.5 Mpc, however, both trends are reversed as we approach the galaxy density peak of region B at 4.5 Mpc. At the largest radii probed by our study, the ratio of the number of absorption- and emission-line galaxies begins to approach the field value.

An interpretation of our data in the context of the well known morphology-density relation (Dressler 1980) will be given in the next section.

Interestingly, the distribution of E+A galaxies follows neither of the above trends. Rather, almost all E+A galaxies (16 out of 17) are found to reside in region A. No E+A galaxy is detected at cluster-centric distances exceeding 2 Mpc, with the sole exception of a single specimen near the southern edge of region B. Remarkably, the radial locus of the abrupt decline in the number of E+A galaxies thus coincides almost perfectly with the ram-pressure stripping radius, \(R_{\text{ps}} = 1.9\) Mpc.

The spatial distribution of starburst galaxies is very different again: the distribution of both e(a) and e(b) galaxies follows, qualitatively, the distribution of their parent type, emission-line galaxies in general. Comparing the e(a) and e(b) distributions, the fraction of e(b) galaxies appears to show a more gradual and monotonic rise with cluster-centric distance than that of e(a) galaxies. The difference between the e(a) and e(b) distributions is, however, not significant: a Kolmogorov-Smirnov test finds the
probability of them being drawn from the same parent distribution to be 0.69. We note, however, that the aforementioned incompleteness of up to 30% in our e(b) sample would likely increase the fraction of e(b) galaxies at all cluster-centric radii.

Although more difficult to interpret quantitatively, the two-dimensional spatial distribution of galaxies of different spectral types provides additional insight. To facilitate a visual analysis, in Figure 12 we show the respective distributions separately for emission-line galaxies, absorption-line galaxies, and, in a third panel, E+A, e(a), and e(b) galaxies. The contours of the projected galaxy density of Figure 8 (top panel) are overlaid. We compare the distributions shown in these three panels in the following.

The absorption-line galaxies are strongly concentrated in the double core of MACS J0717.5+3745 proper, a region that is almost entirely devoid of emission-line galaxies. High concentrations of absorption-line galaxies are also found at the locations of two galaxy groups embedded in the filament, both of which are also detected in X-rays (Fig. 1). The string of three high-density regions near the nominal cluster center thus causes an excess of absorption-line galaxies in region A, which extends linearly over almost 3 Mpc northwest to southeast of the cluster core. By contrast, the observed overdensity of cluster members in region B has a much less pronounced effect on the distribution of absorption- and emission-line galaxies; overall, both galaxy types exhibit similar concentrations. Interestingly, absorption-line galaxies in this region are found preferentially south of the center of region B, whereas emission-line galaxies dominate the northern part of this area, roughly 0.5 Mpc away in projection. It is this large-scale segregation between absorption- and emission-line galaxies that is responsible for the shift of the overall distribution of cluster members in region B shown in the top and center panels of Figure 8; the apparent, not well-defined center of this region is inhabited by a concentration of e(a) and e(b)

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Fig. 12.—Projected spatial distribution of different galaxy types in the MACS J0717.5+3745 system. Symbols are as in Fig. 9, with the addition of small black dots, which mark the locations of all galaxies within our study region that have been observed spectroscopically. Also shown are the galaxy-density contours from Fig. 2. The circles have radii of $R_{200}$ (dashed) and $R_{ps}$ (solid), respectively, as estimated in § 3.3. [See the electronic edition of the Journal for a color version of this figure.]
galaxies (bottom panel of Fig. 8). Relating these observations to the true three-dimensional distribution of galaxy types in region B is, however, greatly complicated by both projection effects and the likely presence of significant peculiar velocities (Barrett 2005). Looking at yet larger scales, it is clear from Figure 12 that the distribution of emission-line galaxies is vastly more extended over our study region than is the distribution of absorption-line galaxies. The lack of pronounced overdensities in the distribution of emission-line galaxies suggests strongly that a significant fraction of emission-line galaxies observed apparently near high-density regions of the MACS J0717.5+3745 is the result of projection effects. Since the small number of E+A galaxies in our sample does not allow us to derive a deprojected radial density profile, at present we cannot distinguish between a spatial model in which E+A galaxies inhabit a shell around the cluster core and one in which their distribution increases toward the cluster core, as is expected for the absorption-line galaxies. Although a comparison of the respective projected radial distributions of E+A and absorption-line galaxies suggests the former, a Kolmogorov-Smirnov test finds them to be consistent with each other at the 1 σ confidence level. From our study of this cluster alone, we are thus unable to address the issue of whether E+A galaxies avoid the very cores of galaxy clusters, as has been suggested by other authors (Tran et al. 2003; Dressler et al. 1999).

5.6. Projected Density Distribution of Cluster Galaxies

One of the most important parameters for studies of galaxy evolution is the density of the local environment. In Figure 13 we plot the fraction of galaxies of different types as a function of projected local density. Symbols are as in Fig. 12. Error bars assume Poisson statistics. The symbols for E+A galaxies and absorption-line galaxies are slightly shifted horizontally for clarity. [See the electronic edition of the Journal for a color version of this figure.]

The histogram of the Σ10 values observed in regions A and B shown in Figure 14 illustrates that the range of projected local galaxy densities in region B overlaps significantly with the one encountered in the primary cluster region. Indeed, both emission- and absorption-line galaxies show the same trends in either region (Figs. 11, 13); their fractions are mainly a function of Σ10. This is not true for E+A galaxies; although the majority of E+A galaxies found in MACS J0717.5+3745 are associated with Σ10 values that are most commonly encountered in region B, only one out of our 17 E+A galaxies is in fact detected there. If density were the determining factor in the creation of E+A galaxies, their distribution with Σ10 in region A would lead to a prediction of 9 E+A galaxies in region B, a number that is inconsistent with the observed count of one at the 3 σ significance level. We conclude that, at least for the system under investigation here, a different physical mechanism must be responsible for the termination of star formation in this galaxy type.
6. DISCUSSION

Arguably the most interesting result of our spectral analysis of the galaxy population of the cluster/filament system MACS J0717.5+3745 is the spatial distribution of E+A galaxies, which may provide important clues to the physical mechanism triggering the E+A transition phase between actively star forming and passively evolving galaxies. Three aspects need to be considered in this context: the origin of the galaxies that evolve into E+A galaxies, the mechanisms that trigger the starburst, and the mechanism(s) responsible for terminating it.

6.1. E+A Progenitors

A first clue to the origin of the E+A galaxies in MACS J0717.5+3745 can be obtained from their spatial distribution. If the galaxies that develop the E+A spectral characteristics originated from the large-scale filament or the galaxy groups embedded therein, one would expect E+A galaxies to be found preferentially near the filament-cluster interface. According to Figure 12, this is not the case. Although the spatial distribution of E+A galaxies exhibits a slight elongation in the direction of the (projected) direction of infall along the filament, their location with respect to the cluster core is consistent with a roughly spherical distribution, which in turn suggests an isotropic distribution of the progenitor population.

A different approach would be to attempt to directly identify the most likely progenitors. The strong H$\alpha$ absorption in the spectra of E+A galaxies indicates not only that the starburst stopped both abruptly and recently (within a few hundred million years), but also that a very significant population of young stars was thus generated (e.g., Barger et al. 1996, and the review in Poggianti et al. 2004). This is particularly true for this study, since we have intentionally selected the E+A galaxies with extreme Balmer absorption features. Galaxies currently undergoing strong star formation, i.e., the (a) and (b) subtypes of emission-line galaxies, are thus natural candidates for the role of progenitors of E+A galaxies, and should, to some extent, trace the spatial distribution of the progenitor population. Examining Figure 12 again, we see that both (a) and (b) galaxies show a rather flat distribution, which, however, prefers the general direction of the filament, and is globally distinctly unisotropic with respect to the cluster core. Although the distribution of (a) and (b) galaxies thus does not rule out the hypothesis that the filament represents an important reservoir from which E+A galaxies originate, the combined evidence appears to favor a picture in which E+A galaxies evolve from a population of galaxies residing predominantly in a halo surrounding the entire cluster+filament complex. The characteristic density of this typical (a)(b) environment is higher than that of the infall region, but lower than the one found in galaxy groups; as a result, these potential E+A progenitors are missing from the denser regions of our study area as well as from the field.

Results from our complete survey of the galaxy population of the most distant MACS clusters should allow us to address these issues with a much larger degree of certainty.

6.2. Source of Starburst Galaxies

The next question is how the starbursts are triggered in cluster galaxies. The spatially fairly even distribution of (a) and (b) galaxies Figure 12, which nonetheless shows a preference for the general area of the filament, is evidence that starbursts are triggered in regions well outside the cluster, and in fact well outside the central regions of the filament as well. The densities typical of the environment in which (a) and (b) galaxies predominantly reside can be estimated from both the spatial distribution in the filament region (Fig. 12) and our direct measure of the projected galaxy density (Fig. 13). Taking into account the certainty of projection effects, we arrive at § 5.5. This result that star formation is triggered at radii approaching the virial radius and environmental densities well below that of galaxy groups is qualitatively consistent with the findings of Kodama et al. (2001) and Marcillac et al. (2007).

6.3. Star Formation Termination

Although it is generally accepted that environmental effects other than galaxy mergers are important to quench star formation in E+A galaxies in clusters (Tran et al., 2003, and references therein), there has so far been little direct observational evidence that would favor any particular physical mechanism. From our wide-field study of the spatial distribution of E+A and other types of spectrally classified galaxies in MACS J0717.5+3745, we believe to have found the strongest evidence to date that ram-pressure stripping is the most effective, and in fact possibly only, mechanism driving the rapid evolution of E+A galaxies in clusters. This is because almost all of the E+A galaxies in the MACS J0717.5+3745 system are found to lie, in projection, near the cluster core$^9$ and within the ram-pressure stripping radius $R_T$. Simulations (e.g., Tonnesen et al. 2007) show that ram-pressure stripping is the most efficient mechanism for removing the gas in the galaxies, and therefore terminate star formation. Furthermore, the complex substructure in both X-ray emission (Fig. 1) and galaxy density (Fig. 8) makes MACS J0717.5+3745 a perfect representative of the kind of cluster merger explored in the numerical simulation of Fujita et al. (1999). The latter authors find that the ram pressure on galaxies near the cluster core increases dramatically as clusters collide, and that cluster mergers also bring many blue galaxies near the cluster center; the combination of these two effects leads to an increase in the fraction of post-starburst galaxies in the cluster core. The results of our study firmly rule out galaxy mergers as the primary driver for the creation or evolution of E+A galaxies. If galaxy mergers were responsible for the termination of star formation in E+A galaxies, we would expect to see their distribution peak in regions where the galaxy densities and relative velocities are most conducive to mergers, i.e., in group-like environments and the cluster infall region itself. This is clearly inconsistent with the results presented in § 5.6 (Figs. 12 and 14). The less violent galaxy-galaxy interaction mechanisms of harassment and starvation are ruled out as well, not only because they cannot explain the observed concentration of E+A galaxies near the regions of steeply increasing intra-cluster gas density, but also because they act over effective timescales (Treu et al. 2003) of several billion years, and are thus too slow to sharply terminate the star formation in E+A galaxies. By contrast, the time (Treu et al. 2003) needed for a galaxy to fall from the virial radius, where star formation would be triggered, to the ram-pressure stripping radius, where the star formation would be terminated again essentially instantaneously, and then on to the cluster core (∼1 Gyr), is well matched to the lifetime of the E+A phase (∼1 Gyr). We note, however, that

$^9$ Note that we refer here to the extreme E+A galaxies as defined by our strict criteria of Balmer line absorption. We do not rule out the possibility that other physical mechanisms play a significant role in the evolution of post-starburst galaxies with weaker Balmer absorption lines.

$^9$ Although spurious trends could conceivably be introduced into the observed spatial distribution if all or most of our E+A galaxies were in fact dust-enshrouded emission-line galaxies (Smail et al. 1999; Sato & Martin 2006), it is difficult to imagine reasons why any dust-extinction patterns should correlate this closely with cluster radius.
galaxy mergers are not ruled out in terms of effective timescale (a few hundreds million years) as a mechanism for the creation of E+A galaxies in general. In the field, mergers indeed appear to be the dominant mechanism (Zabludoff et al. 1996; Yang et al. 2004; Goto et al. 2003; Tran et al. 2004). This dichotomy between the origin of E+A galaxies in low- and high-density environments has previously been suggested by Tran et al. (2003, 2004).

6.4. Comparison to Other Clusters

To test whether our conclusions extend beyond MACS J0717.5+3745, we investigate the distribution of E+A galaxies in the only two other clusters at intermediate redshift for which spectroscopic data of comparable quality are available over a similarly large field of view, namely MS 0451.6−0305 and Cl 0024+1610 (Treu et al. 2003; Moran et al. 2007). Although details of the survey in Moran et al. (2007), such as the selection criteria, magnitude limit, instrumental setup, and technical details of the EW measurements,12 are different from those of our work, a qualitative comparison should still be possible. In addition, we attempt a comparison between MACS J0717.5+3745 and a similarly massive cluster in the local universe, to test whether the spatial distribution of E+A galaxies is consistent. This would imply that, regardless of any redshift evolution in the relative prevalence of galaxies of a given spectroscopic type, ram-pressure stripping is the sole physical mechanism driving the evolution of E+A galaxies in clusters at all epochs. Since E+A galaxies are rare in local clusters, we are left with a single system featuring enough E+A galaxies for a statistically meaningful comparison, the Coma Cluster (Poggianti et al. 2004).

MS 0451.6−0305 (ρ = 0.54, $L_X = 17 \times 10^{44}$ erg s$^{-1}$, $T_X = 7$ keV; Gioia & Luppino 1994; Ebeling et al. 2007) is comparable to MACS J0717.5+3745 in that it is one of the most X-ray luminous and best-studied clusters at $z \sim 0.5$. Unlike MS 0451.6−0305 and MACS J0717.5+3745, Cl 0024+16 ($z = 0.39$) is an optically selected cluster and much less X-ray luminous ($L_X = 2.9 \times 10^{44}$ ergs s$^{-1}$, $T_X = 3.5$ keV; Zhang et al. 2005). We nonetheless include here for comparison purposes to investigate the relevance of cluster properties such as total mass, dynamical state, and core density. The Coma Cluster, our local reference, is the most massive cluster at $z < 0.05$ ($T_X = 9.0$ keV; Donnelly et al. 1999).

As shown in Figure 15, E+A galaxies are rare in both MS 0451.6−0305 (1 $\pm$ 0.1%) and Cl 0024+16 (0 $\pm$ 0.7%) compared to MACS J0717.5+3745 (3.2 $\pm$ 1.8%), although the uncertainties are large. However, their spatial distribution (all within $R_{500}$) is consistent with what we observe in MACS J0717.5+3742. In addition, the fact that the E+A galaxies in MS 0451.6−0305 avoid the dense cluster core lends support to the hypothesis (see §5.5) that the true three-dimensional spatial distribution of this type of galaxies resembles a shell inside the ram-pressure stripping radius. No E+A galaxy at all is found in Cl 0024+16. However, as reflected in its much smaller ram-pressure stripping radius, this cluster is much less massive than either MS 0451.6−0305 or MACS J0717.5+3745. In fact, the density of this cluster’s core region is still likely to be overestimated, because of the unusual geometric and dynamical properties of Cl 0024+16, which is known to be a high-velocity merger along our line of sight (Czoske et al. 2002). Our results for MACS J0717.5+3742 are consistent with the distribution of e(a)/e(b) galaxies in MS 0451.6−0305 and Cl 0024+16, too. In either cluster, these starburst candidates are distributed much more widely than the E+A or absorption-line population.

The spatial distribution of E+A galaxies in Coma (Poggianti et al. 2004) is also consistent with our result.12 Poggianti et al. (2004) separate E+A galaxies into two categories according to

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10 EW measurements for these systems were obtained from http://www.astro.caltech.edu/~smm/clusters/.  
11 Moran et al. (2007) adopt the Lick system (Worthey et al. 1994) for their EW measurements; we perform our spectral classification using their H${\alpha}$ and H${\beta}$ values. Although use of the Lick system results will affect our classification to some extent, we expect the differences to be insignificant compared to other systematic uncertainties.

12 The study of Poggianti et al. (2004) addresses properties of k+a galaxies selected based on H${\beta}$ and [O ii], although this definition is different from ours, the selected galaxy type is similar to our E+A galaxies.
their color. Based on the relative position of the red sequence and the E+A galaxies in Figure 9, the E+A galaxies in MACS J0717.5+3745 mostly belong to the class of "blue E+A" galaxies, which Poggianti et al. (2004) find to be concentrated near the core of Coma. A similar subpopulation is selected by focusing on the "extreme" E+A galaxies with Hδ > 6 Å (see also § 4.3). Applying this criterion to the k+a sample of Poggianti et al. (2004), we again find most of them (7 out of 9) to be located near the cluster center but avoiding the very core. Finally, Poggianti et al. (2004) speculate that the distribution of these youngest E+A galaxies in Coma traces the X-ray substructure, suggesting that the origin of these extreme E+A galaxies may be related to merger-induced shocks in the cluster gas. While qualitatively this picture is not in conflict with our findings for MACS J0717.7+3745, a known major merger (Fig. 1 shows the complex X-ray morphology of the cluster core), this hypothesis would make the absence of E+A galaxies in Cl 0024+16 even harder to explain.

7. CONCLUSION

MACS J0717.5+3745 is a very X-ray luminous cluster at z = 0.55 which shows complex subcluster and filamentary structure in both X-ray surface brightness and galaxy density. Along the filament, we detect a significant offset in the average redshift of galaxies, corresponding to ~630 km s^{-1} in velocity, as well as a decrease in velocity dispersion from the core of the primary cluster to the end of filament. These variations are likely a combination of spatial (Hubble flow) and kinematic effects (peculiar velocities) in this highly disturbed, merging system; a detailed analysis and discussion of the three-dimensional geometry and dynamics of MACS J0717.5+3745 will be presented in a forthcoming paper.

Using the spectroscopic data obtained by us, primarily with the DEIMOS spectograph on the KECK-II telescope, we perform an extensive analysis of the spatial distribution of galaxies of different spectroscopic types, from the cluster core to the cluster outskirts and the connected linear filament. The spectroscopic sample is selected using blue and red color cuts defined relative to the empirical cluster red sequence in the $V$ and $R_C$ bands. The final spectroscopic catalog is more than 70% complete at $R_C < 21.75$. The applied blue color cut causes the number of emission-line galaxies in this structure, in particular the starburst galaxies, to be underestimated; our analysis of the spatial distribution of the cluster members of various spectroscopic types should, however, not be affected.

We classify cluster members into emission-line, absorption-line, and E+A galaxies using the strength of the [O ii] and Hβ emission lines, as well as the absorption features Hδ and Hγ. The emission-line galaxies are further categorized into the subtypes e(a), e(b), and e(c), depending on the strengths of the [O ii] emission- and Hδ absorption-line features. We emphasize that in order to eliminate contamination from absorption- or emission-line galaxies, we adopt a very strict criterion for our definition of E+A galaxies, namely (Hδ + Hγ)/2 > 6 Å, and also require the absence of [O ii] and Hβ emission. The location of these E+A galaxies in color-magnitude and color-color diagrams confirms that they represent the transition phase between emission-line galaxies, in particular the e(a) and e(b) subtypes, and absorption-line galaxies.

The main result of this study is that E+A galaxies are found to reside almost exclusively within the ram-pressure radius of the cluster. Since E+A galaxies are not observed in significant numbers in other regions of this system where the local galaxy density is similarly high, and since the relatively high galaxy velocities near the ram-pressure radius are unfavorable for galaxy mergers, we conclude that galaxy-gas interactions, rather than galaxy mergers, are likely the dominant mechanism for the evolution of the E+A galaxies, at least in clusters at intermediate redshift. Our interpretation that the star formation in these galaxies is terminated because the gas reservoir is being stripped away by the intracluster medium as galaxies fall into the cluster core is consistent with the results obtained for two other clusters, MS 0451.6−0305 and Cl 0024+16. E+A galaxies are only found within the ram-pressure radius of MS 0451.6−0305, and no E+A galaxies at all are found in Cl 0024+16, a low-mass system featuring a very small ram-pressure stripping radius. The large number of E+A galaxies around the core of MACS J0717.7+3745, compared to the similarly X-ray luminous cluster MS 0451.6−0305, can be naturally explained by the significant merger activity in the latter system, an effect that is consistent with the results of numerical simulations.

Although the spatial distribution of E+A galaxies in MACS J0717.7+3745 shows clear evidence of environmental effects on galaxy evolution in clusters, many issues still need further investigation. Specifically, we need to better understand the role of cluster mergers, and what exactly triggers starbursts as galaxies are falling into the cluster. Both of these questions can be addressed by extending this work to the full sample of the 12 most distant MACS clusters, thereby covering systems of very different dynamical states and a wide range of large-scale environments. For MACS J0717.7+3745, accurate star formation rates measured from infrared data obtained with Spitzer will help greatly in this regard. In addition, we aim to use galaxy morphologies and deep X-ray observations to study in detail the gas-galaxy interactions which we suspect to be responsible for the termination of star formation activity and thus the creation of E+A galaxies in clusters.

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