THE STAR-FORMING DWARF GALAXY POPULATIONS OF TWO z ~ 0.4 CLUSTERS: MS 1512.4+3647 AND A851

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ABSTRACT

We present the results of a deep narrowband [O II] λ3727 emission line search for faint (g < 27), star-forming galaxies in the field of the z = 0.37 MS 1512.4+3647 cluster. We find no evidence for an overdensity of emission-line sources relative to the field at z ~ 0.4 and therefore conclude that the MS 1512.4+3647 sample is dominated by field [O II] emission line galaxies that lie along the ~180 Mpc line of sight immediately in front of and behind the cluster. This is surprising, given that the previously surveyed z = 0.41 cluster A851 has 3–4 times the field emission-line galaxy density. We find that the MS 1512.4+3647 sample is deficient in galaxies with intermediate colors (1.0 < g−i < 2.0) and implied star formation exponential decay timescales τ ~ 100 Myr–1 Gyr that dominate the A851 emission-line galaxy population. Instead, the majority of [O II] emission line galaxies surrounding the MS 1512.4+3647 cluster are blue (g−i ≤ 1.0) and forming stars in bursts with τ < 100 Myr. In both samples, galaxies with the shortest star formation timescales are preferentially among the faintest star-forming objects. Their luminosities are consistent with young stellar populations ~108–109 $M_{\odot}$, although an additional factor of 10 in stellar mass could be hiding in underlying old stellar populations. We discuss the implications for the star formation histories of dwarf galaxies in the field and rich clusters.

Subject headings: galaxies: clusters: individual (A851, MS 1512.4+3647) — galaxies: high-redshift

1. INTRODUCTION

The formation of stars in the smallest galaxies provides a strong test for current theories for structure formation. Hierarchical models require the production of many small halos to act as the building blocks for larger halos. However, star formation within small dark matter halos must be suppressed to a large degree to prevent the universe from “overcooling” and the overproduction of Local Group dwarf galaxies (Klypin et al. 1999; Moore et al. 1999). This may be achieved by invoking strong stellar feedback within dwarfs (e.g., Dekel & Silk 1986) or by heating and photoionizing the gas in dwarf halos during the epoch of reionization (Bullock, Kravtsov, & Weinberg 2000). However, neither simple wind models nor reionization alone are able to reproduce the dependence of dwarf galaxy morphology and star formation history on its local environment.

Environment is perhaps the most important regulator of dwarf galaxy star formation. Gas-poor dwarf galaxies are the most strongly clustered galaxies in the local universe, found only as the satellites of larger galaxies or in clusters of galaxies (Binggeli, Tarenghi, & Sandage 1990; Hogg et al. 2003), and are dominated by old and intermediate-age stellar populations (see reviews by Ferguson & Binggeli 1994; Grebel 1997). Like late-type spirals and star-forming dwarf galaxies (dIs), dwarf ellipticals (dEs) and dwarf spheroidals (dSphs) possess exponential surface brightness profiles. The existence of an intermediate class of dwarfs with low gas fractions, low star formation rates (SFRs), significant rotation (Simien & Prugniel 2002), and in several cases residual spiral arm structure (Jerjen, Kelln, & Binggeli 2000) implies an evolutionary transition between late-type gas-rich dwarfs and dEs (Lin & Faber 1983; Moore, Lake, & Katz 1998). However, many dEs do not rotate (Geha, Guhathakurta, & van der Marel 2002) and have higher surface brightnesses (Bothun et al. 1986) and higher chemical abundances (Grebel, Gallagher, & Harbeck 2003) than expected for dIs which have simply lost their gas and stopped forming stars.

The origin of these dEs remains unknown. Several different possibilities imply distinct star formation and accretion histories for the cluster dE populations. If dwarf formation is strongly suppressed after reionization, dwarfs in high-density regions may be more able to survive because they are more likely to collapse and form stars before the epoch of reionization (Tully et al. 2002). The pressure of the intracluster gaseous medium can prevent strong winds from blowing out much of the dwarfs’ gas and allow them to quickly form multiple generations of stars (Babul & Rees 1992). In this scenario, the dE cluster populations are among the oldest cluster members. On the other hand, dynamical studies of the dwarf galaxy populations in the nearby Virgo and Fornax Clusters suggest that the dE populations are not as relaxed as the giant elliptical populations and may have been recently accreted by the cluster potentials (Drinkwater, Gregg, & Colless 2001; Conselice, Gallagher, & Wyse 2001). Over time, processes such as ram-pressure stripping, strong tidal interactions, and “galaxy harassment” may remove the gas and halt star formation in galaxies in cluster environments as they are accreted from the field (e.g., Moore et al. 1998). Compared to the field populations at similar epochs, bright cluster galaxies have suppressed SFRs and lower fractions of star-forming and blue galaxies (Balogh et al. 1997; Ellingson et al. 2001). Gas removal by the cluster environment may be even more
efficient for low-mass galaxies and could transform star-forming dwarfs into dEs and dSphs. Therefore, many dEs may be recent cluster acquisitions with relatively young stellar populations.

At $z \geq 0.4$, where H$\alpha$ is shifted out of the optical wavelength region, the [O II] $\lambda3727$ emission doublet is one of the strongest optical tracers of the low-density, photoionized nebulae associated with star-forming regions. Early high-resolution spectroscopy by Koo et al. (1997) identified several strong [O II] $\lambda3727$ emission line dwarf galaxies in the $z \sim 0.4$ cluster Cl 0024+1624. In Martin, Lotz, & Ferguson (2000, hereafter Paper I), we conducted a deep narrowband [O II] $\lambda3727$ emission line search for the faint star-forming galaxies in the extremely massive and morphologically irregular cluster A851 at $z = 0.41$. We detected several hundred [O II] emission line galaxy candidates with a number density 3–4 times that observed for field [O II] galaxies at similar redshifts. However, we found a deficit of extremely high [O II] equivalent width objects relative to the field and concluded that A851’s environment is suppressing strong star formation. Therefore, many of A851’s faint star-forming galaxies could fade into the dE cluster population observed today.

In this paper we present a similar [O II] $\lambda3727$ emission line search in the less massive but more relaxed $z = 0.37$ cluster MS 1512.4+3647 and compare the properties of its star-forming dwarf population to that of A851. In § 2 we present the narrowband [O II] $\lambda3727$ observations of MS 1512.4+3647 and identify interlopers by their broadband colors. In § 3 we compare the luminosity function and clustering properties of MS 1512.4+3647 [O II] emission line candidates to the A851 and field [O II] emission line populations. We find that, unlike A851, the MS 1512.4+3647 [O II] luminosity function shows no excess above the field and is likely dominated by field [O II] emitters that surround the cluster. In § 4 we constrain star formation histories and timescales of the field-dominated MS 1512.4+3647 star-forming galaxy sample and compare the derived star formation histories to those found for A851. We discuss the impact of the two cluster environments on the star-forming galaxy population at $z \sim 0.4$ and the implications for the formation of dEs. We assume $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.3$, and $\Omega_\Lambda = 0.7$ throughout this paper.

### 2. EXPERIMENTAL DESIGN

#### 2.1. MS 1512.4+3647 Observations

MS 1512.4+3647 is a rich cluster at $z = 0.372$, first identified by the *Einstein Medium-Sensitivity Survey* (Gioia et al. 1990; Stocke et al. 1991) with $L_X (2-10$ keV) $\sim 5.6 \times 10^{43}$ ergs s$^{-1}$. This cluster has been the subject of much study because of the detection of the lensed protogalaxy candidate eBS8 at $z = 2.7$ close to the central cluster galaxy (Yee et al. 1996) and is part of the CNOC1 cluster sample (Canadian Network for Observational Cosmology Cluster Redshift Survey; Abraham et al. 1998). The cluster appears to be elongated along the line of sight with a complex velocity structure and velocity dispersion $\sigma = 575$ km s$^{-1}$ (Borgani et al. 1999). High-resolution ROSAT X-ray maps of MS 1512.4+3647 are relatively smooth and elliptical, and the X-ray emission is centered on the central cluster galaxy (Lewis et al. 1999). MS 1512.4+3647’s virial mass and radius are approximately $8 \times 10^{14}$ $M_\odot$ and 2 Mpc, respectively (Molikawa et al. 1999).

MS 1512.4+3647 was observed on 1998 June 20–23 at the Kitt Peak National Observatory 4 m telescope at prime focus using the T2KB CCD. The on-band filter W021 ($\lambda_c = 5135$ Å, $\delta \lambda = 100.5$ Å) was chosen to match the redshifted [O II] $\lambda3727$ emission doublet of the cluster galaxies. The off-band filter W022 ($\lambda_c = 5261$ Å, $\delta \lambda = 44.24$ Å) samples the continuum 126 Å redward of the on-band. Emission-line galaxies with velocities within $+10$ and $-5$ $\sigma$ of the mean cluster velocity are detectable with this filter setup. The width of the on-band filter allows us to observe [O II] $\lambda3727$ emission line objects along a line of sight much deeper ($\sim 180$ Mpc) than the angular width of our field of view ($\sim 4 \times 4$ Mpc at $z = 0.37$). Deep broadband images in the SDSS $ugri$ ($\lambda_c = 3513$ Å), $g$ ($\lambda_c = 4759$ Å), and $i$ ($\lambda_c = 7734$ Å) bandpasses were taken as well during the third night.

The images were processed using the IRAF CCD reduction package CCDPROC. Each image was overscan subtracted and bias subtracted. The images were then corrected for variation in pixel sensitivity using dome flats for each filter. Twilight sky images were used to correct for any residual large-scale illumination patterns. The cluster images were aligned to within 0.1 pixels, combined and cosmic-ray corrected with the iterative IRAF cosmic-ray rejection algorithm CRREJ. Although observing conditions were photometric throughout the run, the W021 and W022 images taken during the fourth night had lowered sensitivity because the CCD had a slightly higher temperature that night. These images were scaled to match the flux level of previous nights’ images before they were combined. The final images subtend $\sim 12.5 \times 12.7$ with typical seeing $\sim 1.4$ in W021, W022, $g$, and $i$ and $\sim 2.2$ in $u$. The astrometric solution was calculated with the IRAF task IMCOORDS. CCMAP using the positions of $\sim 50$ stars from the Guide Star Catalog II. The resulting solution is accurate to $\pm 0.4$ in right ascension and $\pm 0.78$ in declination.

A number of photometric and spectrophotometric standard stars (Landolt 1992; Massey et al. 1988) were observed throughout the run and used to calibrate the flux of the broadband and narrowband cluster images. The UBVRJ photometry of the Landolt (1992) standards was converted to SDSS $ugri$ magnitudes using the Fukugita et al. (1996) transformations. Archived *Hubble Space Telescope (HST)* WFPC2 F814W images of the central region of MS 1512.4+3647 were also used to calibrate the $i$-band image. The uncertainty in the broadband calibration is 0.15 mag in $i$, 0.09 mag in $g$, and 0.12 mag in $u$. The uncertainty in the narrowband calibration is 7% in both bands. The final cluster images have 4 $\sigma$ limiting magnitudes $\sim 25.5$ in $u$, 27.3 in $g$, and 25.8 in $i$. The limiting on- and off-band flux densities are $1.1 \times 10^{-19}$ and $1.3 \times 10^{-19}$ ergs s$^{-1}$ cm$^{-2}$ Å$^{-1}$. The [O II] $\lambda3727$ line flux (excess on-band flux) is $\sim 2.5 \times 10^{-17}$ ergs

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The Guide Star Catalog II is a joint project of the Space Telescope Science Institute and the Osservatorio Astronomico di Torino. The Space Telescope Science Institute is operated by the Association of Universities for Research in Astronomy, for the National Aeronautics and Space Administration under contract NAS 5-26555. The participation of the Osservatorio Astronomico di Torino is supported by the Italian Council for Research in Astronomy. Additional support is provided by European Southern Observatory, Space Telescope European Coordinating Facility, the International GEMINI project, and the European Space Agency Astrophysics Division.
\[ s^{-1} \text{ cm}^{-2} \text{ at the 30\% completeness level, which equals a SFR of } 0.13 \, M_{\odot} \, \text{yr}^{-1} \text{ at the distance of the cluster (see § 4.1 for [O II]-to-SFR conversion assumptions).} \]

2.2. Detection of the Faintest Emission-Line Objects

The sum of the final on- and off-band images was used as the detection image for the galaxy photometry software package SExtractor version 1.2 (Bertin & Arnouts 1996). This summed image was convolved with a 4 pixel FWHM Gaussian and searched for objects with 3 or more joined pixels with a flux level \( \geq 1.5 \sigma \) above the sky noise. A total of 2883 objects were detected in the convolved summed image. The isophotal apertures determined from the summed image were used to measure the object fluxes in the W021, W022, and broadband images. Using a model of the image’s point-spread function, SExtractor attempts to distinguish stars from galaxies by their isophotal area and flux and assigns each object a probability that it is a star. Objects with SExtractor “stellarity index” CLASS_STAR greater than 90\% were considered stars and removed from the catalog (Fig. 1). This left 2633 remaining “galaxies.” Confusion between stars and galaxies is inevitable at fluxes less than \( 5 \times 10^{-18} \, \text{ergs s}^{-1} \text{ cm}^{-2} \text{ A}^{-1} \), but galaxies should greatly outnumber stars at those flux levels. We expect to observe \( \sim 200 \) stars fainter than \( 5 \times 10^{-18} \, \text{ergs s}^{-1} \text{ cm}^{-2} \text{ A}^{-1} \), assuming the Galaxy model B in Reid et al. (1998). We found 12 objects classified as stars by SExtractor with on-band excess emission greater than 4 \( \sigma \). However, all of these objects have continuum fluxes brighter than \( 2 \times 10^{-17} \, \text{ergs s}^{-1} \text{ cm}^{-2} \text{ A}^{-1} \) and are too bright to be misclassified emission-line galaxies.

The [O II] \( \lambda 3727 \) line flux was calculated assuming

\[
T_{\text{ON}} F_{\text{[O II]}} = F_{\text{ON}} - F_{\text{OFF}} \frac{\int_{\text{ON}} T(\lambda) d\lambda}{\int_{\text{OFF}} T(\lambda) d\lambda},
\]

where \( F_{\text{ON}} \) and \( F_{\text{OFF}} \) are the observed on- and off-band fluxes and \( T_{\text{ON}} \) is the average transmission of the on-band filter. The error in the line flux depends on the error in both the on- and off-band fluxes but is dominated by the error in the continuum level determination because the off-band filter W022 is less than half as wide as the on-band filter W021. While a large number of excess on-band objects were detected, only 95 objects have line fluxes greater than 4 \( \sigma \) (Fig. 2). A number of excess off-band objects were detected as well; we believe that many of these may be galaxies with [O II] emission or a strong 4000 A break associated with a known subclump behind the cluster at \( z = 0.41 \) (Abraham et al. 1998).

The detection of emission-line sources and the measurement of their excess on-band flux become increasingly difficult as the sources decrease in surface brightness and line flux. Galaxies that are intrinsically very faint in continuum but have strong [O II] emission may be detected only in our on-band image. In this case, the uncertainty in the continuum flux will dominate the error in the line flux determination and only objects with high equivalent widths will have significantly detected on-band excesses. On the other hand, the weakest emission-line galaxies may have bright continua and be well detected in both the on- and off-band images, but the emission-line flux may be on the level of a few times the uncertainty in the on-band flux. Thus, our emission-line search will be incomplete for both intrinsically faint objects with low continuum fluxes and objects with higher continuum fluxes but faint [O II] emission. Because the sum of the on- and off-band images was used to detect the objects, our ability to detect an object is primarily a function of its summed on- and off-band flux and will decrease as the object’s total summed flux approaches the detection limit.

**Fig. 1.**—log isophotal area (pixels) vs. log continuum flux \( F_{\lambda} \) for all detected objects. The filled circles have been classified as stars by their flux concentration.

**Fig. 2.**—Signal-to-noise ratio (S/N) for \( F_{\text{[O II]}} \) line flux vs. the continuum flux \( F_{\lambda} \). The 3 and 4 \( \sigma \) cutoffs are marked as dashed lines. The dependence of the survey’s sensitivity on the [O II] EW and surface brightness is shown for three models: [O II] EW of 100 A and isophotal area of 10 pixels, [O II] EW of 50 A and isophotal area of 100 pixels, and [O II] EW of 10 A and isophotal area of 300 pixels.
However, the detection of a galaxy depends on not only its total flux but also its surface brightness. Galaxies with normally observable total fluxes but large scale lengths and low surface brightnesses may not be detected because the flux per pixel is comparable to the sky noise. We do not find objects in the summed image above the 1.5 $\sigma$ SExtractor detection level with central surface brightness $\mu_0$ fainter than $1.0 \times 10^{-17}$ ergs $s^{-1}$ cm$^{-2}$ arcsec$^{-2}$ (=26.9 AB mag arcsec$^{-2}$). Simulations of artificial galaxies with fixed total flux and varying surface brightness were added to the original image to determine the effect of surface brightness on the incompleteness at a given total flux. We find that the detection efficiency drops rapidly at $\mu_0 > 26.5$ mag arcsec$^{-2}$ for total fluxes fainter than $\sim 10^{-16}$ ergs $s^{-1}$ cm$^{-2}$.

To compute an effective incompleteness correction that accounts for the scatter in $\mu_0$ at each total flux level, we simulated galaxies with the same distribution of observed surface brightnesses as the original image. We chose real galaxies within a given flux range at random from the SExtractor output catalog. The total flux, semimajor axis length, and ellipticity of each chosen galaxy were used to model that galaxy using the IRAF ARTDATA.MKOBJECTS task. The simulated galaxy was added at random positions to the original image 100 times. SExtractor was run again on the modified image to determine the detection efficiency for that galaxy. This process was repeated for 10 randomly selected galaxies within each 0.1 dex flux bin, and the resulting detection efficiencies were averaged to compute the effective completeness for that flux bin. We find that the effective completeness for galaxies with $\mu_0 < 26.9$ mag arcsec$^{-2}$ is 85% for galaxies with total summed fluxes brighter than $8 \times 10^{-17}$ ergs $s^{-1}$ cm$^{-2}$ and 30% for galaxies fainter than $3 \times 10^{-17}$ ergs $s^{-1}$ cm$^{-2}$.

2.3. Interlopers/False Detections

We find 95 objects with excess on-band flux greater than 4 $\sigma$ in the $\sim 160$ arcmin$^2$ cluster field. A fraction of these detections will not be [O ii] $\lambda$3727 emission line galaxies associated with the cluster, but rather foreground or background galaxies with spectral features that create excess on-band emission. Here we determine how many such false [O ii] detections have contaminated our sample and identify the probable interlopers.

2.3.1. Broadband Color Selection

To determine which galaxies may produce false [O ii] $\lambda$3727 detections, we have calculated the excess on-band EW expected as a function of redshift for irregular, spiral, and elliptical galaxy spectral templates (Fig. 3; Coleman, Wu, & Weedman 1980). The [O ii] $\lambda$5007 and H$\beta$ emission of foreground irregular galaxies at $z \leq 0.03$ and 0.06 will show up as excess on-band objects. However, the volume sampled for [O ii] and H$\beta$ by our on-band is only 14 and 67 Mpc$^3$, respectively. We expect to detect approximately three foreground emission-line galaxies given the local density of emission galaxies (Salzer 1989).

Elliptical galaxies in the cluster may also produce excess on-band flux. This is because the CN $\lambda$3883 absorption band found in elliptical galaxy spectra (Davidge & Clark 1994) falls into our off-band at $z \sim 0.37$. The CN absorption band lowers our estimation of the continuum and results in false on-band excesses with typical rest-frame equivalent widths $\leq 20$ A. For this paper, we will assume that galaxies with red colors and on-band excess flux are not true [O ii] emitters. It is possible that a fraction of these objects are forming stars, but follow-up spectroscopy is needed to confirm the presence of [O ii] emission.

The on-band will also probe a large volume at high redshifts. Background starbursting galaxies may have strong Ly$\alpha$ emission that will fall into our on-band filter at redshifts 3.18–3.26. Deep Ly$\alpha$ surveys at $z = 4.5$ (Rhoads et al. 2000; Hu, Cowie, & McMahon 1998) find $\sim$4000 objects per square degree per unit redshift with EW$\alpha > 80$ A and line plus continuum fluxes greater than $2.6 \times 10^{-17}$ ergs cm$^{-2}$ s$^{-1}$. Therefore, we expect $\sim$13 Ly$\alpha$ emitters in our field of view sampled by our on-band. However, the surface densities of Ly$\alpha$ emitters can vary by a factor of 1.5 from field to field (Rhoads et al. 2000) and are highly clustered (Steidel et al. 1999). Given the intrinsic field-to-field variations and that our survey is slightly less sensitive than the Rhoads et al. (2000) survey, we may detect few background Ly$\alpha$ galaxies.

We use the broadband colors in order to distinguish between star-forming cluster galaxies and the elliptical and high-redshift interlopers. Figure 4 shows the broadband color evolution of each spectral type with redshift. Ly$\alpha$ emitters will drop out of the u image and be easily distinguished from cluster members by their very red $u-i$ and $u-g$ colors. Elliptical galaxies in the cluster will also have red colors ($u-i \geq 3.0$, $g-i \geq 2.0$, $u-g \geq 1.5$). Irregular star-forming galaxies will have very blue colors ($u-i \leq 1.5$, $g-i \leq 1.0$, $u-g \leq 0.5$), and spiral galaxies will have intermediate colors. We expect the majority of our true [O ii] $\lambda$3727 emitters to have rest-frame colors similar to irregular and spiral galaxies. On-band excess objects with $g-i > 2.0$ and $u-i > 3.0$ are probably interlopers and are removed from our sample.
2.3.2. Spectroscopic Surveys of MS 1512.4+3647

We have cross-checked our on-band excess detections with the results of the CNOC1 spectroscopic survey of MS 1512.4+3647 (Abraham et al. 1998) to test the reliability of our emission-line detection and broadband color classification. Abraham et al. (1998) obtained spectroscopy for greater than 50% of galaxies brighter than \( r' = 21 \) in \( \sim 220 \) arcmin\(^2\) surrounding MS 1512.4+3647. They determined each observed galaxy’s redshift and spectral type by cross-correlating its spectrum with template SEDs. Our observations include 36 cluster member galaxies and 63 field galaxies targeted by the Abraham et al. (1998) spectroscopic survey. We compare these galaxies’ CNOC spectral classification (E/S0, spiral, or emission line/Im) to our broadband colors and on-band fluxes (Fig. 5; Table 1). We find that our broadband colors reliably predict the spectral type of the galaxy and allow us to eliminate elliptical galaxies from our emission-line sample. Once these objects are removed from our sample, our false detection rate is less than 4%. We observe \([\text{O} \, \text{II}]\) emission above the 4 \(\sigma\) level in half of the spectroscopically classified late-type spirals and irregular galaxies.

We have assumed that most on-band excess galaxies redder than \( g-i = 2.0 \) are not \([\text{O} \, \text{II}]\) emitters, but elliptical galaxies with strong absorption at CN \( \lambda 3883 \). Six of these red on-band excess galaxies have been observed spectroscopically by Ziegler & Bender (1997, hereafter ZB97; Table 2). The \([\text{O} \, \text{II}]\) \( \lambda 3727 \) line did not fall into the ZB97 observed spectral range (6500–7500 Å), and therefore we cannot directly determine if these objects are truly \([\text{O} \, \text{II}]\) emitters; however, the \( \text{H} \beta \) line, another good star formation indicator, was measured by ZB97. The central cluster galaxy (2435, M09) has \( \text{H} \beta \) emission and is probably a true \([\text{O} \, \text{II}]\) emission line galaxy. The other five galaxies do not have either strong \( \text{H} \beta \) emission or absorption indicative of recent star formation and are most likely false \([\text{O} \, \text{II}]\) detections. By removing the red excess on-band objects with \( g-i > 2.0 \) from our sample, we may miss few true emission galaxies, but we will eliminate the largest source of contamination from the \([\text{O} \, \text{II}]\) emission line galaxy sample.

2.3.3. \( \text{Ly} \alpha \) Candidates

We expect that background \( \text{Ly} \alpha \) candidates will possess high EWs and be undetected in \( u \). We find three on-band excess objects with \( \text{EW}_{\text{Ly} \alpha} > 80 \) Å that drop out of our \( u \)-band image. Object 1696 has \( \text{EW}_{\text{Ly} \alpha} \sim 91 \) Å, \( i = 24.78 \pm 0.13 \), and \( g-i = 0.50 \pm 0.16 \), consistent with a faint star-forming dwarf galaxy at \( z = 0.37 \). However, the other two high-EW \( u \)-band dropouts have \( \text{EW}_{\text{Ly} \alpha} \sim 100 \) Å (Table 3). The rest-frame \([\text{O} \, \text{II}]\) EWs of local star-forming galaxies rarely exceed 100 Å, whereas \( \text{Ly} \alpha \) emitters could have rest-frame EW as high as 200 Å (Charlot & Fall 1993) and therefore \( \text{EW}_{\text{Ly} \alpha} \sim 800 \) Å. Object 2218 has \( \text{EW}_{\text{Ly} \alpha} \sim 340 \) Å, \( g-i = 4.21 \pm 0.21 \), is undetected in \( u \), and is therefore a good \( \text{Ly} \alpha \) candidate. We also find one extremely high \( \text{EW}_{\text{Ly} \alpha} \sim 1100 \) Å faint object (413) that is not detected in \( u \) and may be a high-redshift \( \text{Ly} \alpha \) emitter as well. This object is detected in the on-band and \( g \) (=27.25±0.36), but not in \( i \). Assuming \( g-i \sim 1.5 \) for \( \text{Ly} \alpha \) galaxies at \( z = 3.2 \), the expected \( i \) magnitude would be 25.8, just at our 4 \(\sigma\) detection limit. We cannot rule out the possibility that object 413 is a dwarf undergoing massive starburst with a rest-frame \([\text{O} \, \text{II}]\) EW of \( \sim 800 \) Å, but it is more likely that it is a background \( \text{Ly} \alpha \) emitter, and we exclude it from our \([\text{O} \, \text{II}]\) emission line candidates. We do not find any other \( \text{Ly} \alpha \) candidates above the 4 \(\sigma\) cutoff. Gravitational lensing by the cluster potential is expected to increase, not decrease, the number of detected \( \text{Ly} \alpha \) galaxies as the effect of the luminosity amplification factor should dominate over angular scattering by the lens.
on the observed high-redshift background galaxy number counts (Broadhurst, Taylor, & Peacock 1995). A lensing model would be needed to determine the significance of the low number of Ly\(\alpha\) candidates toward the cluster core. However, the low number we find is not obviously in conflict with the populations described by Rhoads et al. (2000) and Hu et al. (1998).

### 2.4. MS 1512.4+3647 [O \(\text{ii}\)] Emission Line Candidates

We have detected 66 [O \(\text{ii}\)] emission line candidates in the MS 1512.4+3647 field with excess on-band fluxes greater than 4 \(\sigma\) and \(g-i < 2.0\). In Table 4 we give the positions, colors, and fluxes of the emission-line candidates. In Figure 6 we plot the observed [O \(\text{ii}\)] integrated line flux against the...
continuum flux for all detections above the 3 σ level. The red interlopers are plotted as triangles, and the galaxies with spiral and irregular colors are plotted as circles and stars, respectively. Objects with $g - i$ photometric errors greater than 0.5 are plotted as open squares. The vertical solid lines are lines of constant equivalent width. Contours of constant summed flux show where the data are 85% and 30% complete. The upper dashed line is the 4 σ cutoff, below which...
objects are excluded from our sample (see Fig. 2), and the lower dashed line is the 3σ cutoff. All of the 4σ [O ii] EW > 100 Å emission-line candidates were visually inspected and found to be spatially extended and significantly detected in at least one broadband image; therefore, they are unlikely to be spurious noise detections. We do not detect dwarfs above the 4σ cutoff with SFRs below 0.13 M⊙ yr⁻¹ (T_{ON}F[O ii] < 2.5 × 10⁻¹⁷ ergs s⁻¹ cm⁻²).

3. CLUSTER MEMBERS OR FIELD GALAXIES?

The question of cluster membership for the MS 1512.4+3647 emission-line objects is a key issue that must be addressed. We expect very few foreground [O ii] λ5007 emitters, and, with our color selection, we are confident that the majority of our detections are [O ii] λ3727 emitters at z ~ 0.37 and not background Lyα galaxies. However, in addition to star-forming galaxies bound to the cluster, our on-band filter samples field [O ii] λ3727 emission line galaxies that lie along the ~180 Mpc line of sight immediately in front of and behind the MS 1512.4+3647 cluster. In order to determine the field contamination of our MS 1512.4+3647 [O ii] candidates, we compare their density and clustering properties to the field [O ii] galaxies at z ~ 0.4, as well as the z = 0.41 cluster A851.

3.1. [O ii] λ3727 Luminosity Function

We find that the MS 1512.4+3647 [O ii] λ3727 luminosity function shows little evidence for an excess star-forming galaxy population associated with the cluster. We have calculated the [O ii] luminosities of the MS 1512.4+3647 emission-line candidates from their integrated line fluxes assuming a spherical symmetry and correcting the observed line flux for the average transmission of our on-band, T_{ON} = 72%. At L[O ii] = 2.4 × 10⁸ ergs s⁻¹ (T_{ON}F[O ii] = 5.0 × 10⁻¹⁷ ergs s⁻¹ cm⁻²), the MS 1512.4+3647 luminosity function is ~85% complete down to EW ~ 10 Å (Fig. 6).

We used the simulations described in § 2.2 to determine the probability p_{ij} of detecting a galaxy with continuum flux I and line flux f. The number of [O ii] emission line candidates is multiplied by the number of missing galaxies per detected galaxy, 1/N \sum_{i<j} 1/p_{ij}. The incompleteness-corrected number counts were divided by the comoving volume sampled by the on-band filter in our 12.5 × 12.7 field of view (2802 Mpc³). The resulting luminosity function is given in Table 5.

In Figure 7 we compare the MS 1512.4+3647 [O ii] λ3727 luminosity function to the z ~ 0.4 field [O ii] luminosity function from the spectroscopic survey of Hogg et al. (1998), the z = 0.41 A851 cluster luminosity function, and

\[ g_{\text{obs}} < 2.0, \quad g_{\text{em}} = g_{\text{obs}} - 0.43. \]

We have found a +0.43 mag error in the A851 g photometry given in Paper I, as a result of an error in the previously published A851 g photometry (Dressler & Gunn 1992) used for our original calibration. In this paper we have recalibrated our A851 g photometry with new high-quality BVRI photometry (I. Small 2002, private communication) and the SDSS-Johnson photometry conversions computed by Fukugita et al. (1996). We have reselected the A851 [O ii] emission line candidates based on the revised g-i colors (g-i < 2.0, g-i_{em} = g-i_{obs} - 0.43). This has increased the A851 [O ii] emission line candidates by 42 objects.
the $z = 0.37$ foreground field of A851 from Paper I. The Hogg et al. (1998) spectroscopic survey is 90% complete to 23 $R$ magnitude at [O II] $EW \sim 10$ Å, ∼1 mag deeper than our survey limit at $EW = 10$ Å. The A851 survey was also a narrowband imaging survey using a slightly different filter setup and is complete down to $EW \sim 10$ Å at $L[O II] = 10^{40}$ ergs s$^{-1}$ (see Fig. 5 in Paper I). The foreground field of A851 was observed with the same filter setup and similar exposure times as MS 1512.4+3647, and its selection effects are similar to those for our MS 1512.4+3647 sample.

The [O II] luminosity function of MS 1512.4+3647 shows little excess relative to the field at $z \sim 0.4$, even at bright [O II] luminosities where our survey is complete. This suggests that the majority of our detections are simply field galaxies immediately in front of and behind the cluster for which [O II] $\lambda 3727$ falls into our on-band and the density of star-forming galaxies bound to MS 1512+3647 is indistinguishable from the field. On the other hand, the A851 luminosity function shows an excess of [O II] emission line galaxies 3–4 times the density of the field [O II] galaxies at $z = 0.4$ (Paper I) and the MS 1512.4+3647 sample.

### 3.2. Clustering Properties of [O II] Emission Line Candidates

We find that the MS 1512.4+3647 emission-line objects are not strongly clustered toward the central cluster galaxy (filled square; top of Fig. 8). This is in contrast to the galaxies with elliptical-like colors ($g-i > 2.0$; open squares),

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**Table 5**

[O II] Luminosity Function of MS 1512.4+3647 Cluster Field

| $T_{ON}$ $F[O II]$ (ergs s$^{-1}$ cm$^{-2}$) | $L[O II]$ (ergs s$^{-1}$) | $N$ | $H^a$ | $N_c$ | $\Phi$ (Mpc$^{-3}$) |
|-------------------------------------------|-------------------------|-----|-------|-------|-------------------|
| $-15.0$ ................................... | 41.68                   | 1   | 1.00  | 1.00  | 0.00036 ± 0.00036 |
| $-15.5$ ................................... | 41.14                   | 18  | 1.06  | 19.08 | 0.0068 ± 0.0016   |
| $-16.0$ ................................... | 40.68                   | 42  | 1.17  | 47.04 | 0.0168 ± 0.0026   |

* Incompleteness correction factor.
which are more likely to be found around the central cluster galaxy at projected radii less than $R_{200}$. ($R_{200}$ is the radius at which the mean inner density of the cluster is 200 times the critical density of the universe, $\sim 1.2$ Mpc for MS 1512.4+3647 assuming cluster velocity dispersion $\sigma = 575$ km s$^{-1}$.) At $z = 0.37$, our field of view is $\sim 4$ Mpc $\times 4$ Mpc and will include most of the cluster. The surface density of [O II] emitters is consistent with the field [O II] emission line population (Hogg et al. 1998). Except for the inner 100" ($\sim 770$ kpc), A851 star-forming galaxies are also weakly clustered relative to the red galaxies (bottom of Fig. 8) out to 1.5$R_{200}$, even though the surface density of star-forming galaxies observed in the A851 field is well above that expected for field [O II] emitters.

Given that the MS 1512.4+3647 luminosity function shows no overdensity of [O II] emitters and the surface density of star-forming galaxies is likely to be dominated by field galaxies at all cluster radii, it seems likely that most of our MS 1512.4+3647 sample are field galaxies surrounding MS 1512.4+3647 that are not bound to the cluster potential. MS 1512.4+3647 does possess some galaxies that have had recent star formation: the CNOC1 survey found that $\sim 20\%$ of spectroscopically confirmed cluster members brighter than $M_r = -19.0$ in the core of MS 1512.4+3647 are bluer than $g-r = 0.25$, like other clusters observed by CNOC1 at similar redshifts (Ellingson et al. 2001). If MS 1512.4+3647 is a typical $z = 0.4$ cluster, then most clusters at $z \sim 0.4$ do not have high densities of star-forming galaxies but are instead slowly swallowing up the field galaxy population. Assuming that accreted galaxies eventually cease star production and have detectable [O II] emission for $\sim 1$ Gyr (Balogh, Navarro, & Morris 2000), an average $z = 0.4$ cluster has assembled most of its mass at redshifts $> 0.5$.

A851, on the other hand, is clearly an unusual cluster in terms of its mass, X-ray luminosity, and density of star-forming galaxies. Its virial mass is approximately 10 times that of MS 1512.4+3647, and its bolometric X-ray luminosity is over twice that of MS 1512.4+3647 (16.08 $\times 10^{44}$ ergs s$^{-1}$ vs. 7.62 $\times 10^{44}$ ergs s$^{-1}$; Wu et al. 1999). This cluster has significant substructure in its X-ray emission (Schindler & Wambsganss 1996) and galaxy distribution (Kodama et al. 2001). It appears to be a cluster in formation and has most likely acquired its large number of star-forming galaxies from a collapsing system of groups and filaments as opposed to gradual accretion of the surrounding field population.

The vast difference between the MS 1512.4+3647 and A851 [O II] emission line galaxy densities implies that the density of star-forming galaxies in a cluster relative to the field may be a strong tracer of the recent assembly history of the cluster. Balogh et al. (2002) reached a similar conclusion when they found a significantly higher density of H$\alpha$-emitting galaxies in the $z = 0.18$ cluster A1689 than in the more relaxed but more distant cluster AC 114 at $z = 0.31$. Normalizing each of our cluster’s densities of [O II] emitters by their bolometric X-ray luminosities and correcting for selection effects, we find that the normalized density of star-forming galaxies above the MS 1512.4+3647 detection limits is 0.0058 $\pm 0.0005$ Mpc$^{-3}$ $L_{X}(10^{44}$ ergs s$^{-1}$)$^{-1}$ for A851 and 0.0031 $\pm 0.0004$ Mpc$^{-3}$ $L_{X}(10^{44}$ ergs s$^{-1}$)$^{-1}$. These values are a lower limit for A851 as our field of view encompassed only the inner half of the cluster (Paper I) and an upper limit for MS 1512.4+3647 due to the significant field contamination. Therefore, A851 has at least twice (and possibly 10 times) as many star-forming galaxies per unit volume and X-ray luminosity than the more typical cluster MS 1512.4+3647.

**Fig. 7.** [O II] $\lambda 3727$ luminosity functions of the MS 1512.4+3647 cluster, A851 cluster and foreground fields (Martin et al. 2000), and the field at $z = 0.4$ (Hogg et al. 1998). The open symbols give the luminosity function prior to the incompleteness correction.

**Fig. 8.** Surface density of [O II] emission line candidates (filled squares) and red galaxies with $g-i > 2.0$ (open squares) in the fields of the MS 1512.4+3647 and A851 clusters. The dotted line gives the expected surface density of field [O II] emitters within our on-band (Hogg et al. 1998). $R_{200}$ is shown for each cluster.
4. STAR FORMATION PROPERTIES AND HISTORIES OF EMISSION-LINE GALAXIES

In this section we use the [O ii] emission line equivalent widths and broadband colors of the MS 1512.4+3647 [O ii] candidates to constrain their recent star formation. We then compare the derived star formation histories of the MS 1512.4+3647 field-dominated and the A851 cluster-dominated [O ii] emission line galaxy samples for clues to the origin of the disparity in the density of star-forming galaxies between the two clusters. Finally, we discuss the implications for dwarf galaxy evolution in the field and clusters.

4.1. [O ii] λ3727 Emission as a Tracer of Star Formation

The dependence of [O ii] luminosity on the SFR has been empirically calibrated using both Hα and Hβ emission (Kennicutt 1992; Gallagher, Bushouse, & Hunter 1989). We adopt the observed [O ii] λ3727–Hβ relation \( F_{\text{[O ii]}} = 3.2 F_{\text{Hβ}} \) derived for local star-forming galaxies (Gallagher et al. 1989). To convert the observed (and dust-extincted) [O ii] flux to an SFR, we assume a dust correction for the observed Hβ flux, derive the intrinsic ratio of Hβ to Hα flux, and assume an intrinsic Hα-to-SFR relation. We adopt \( A_\beta = 1.0 \) extinction correction, typical of nearby star-forming dwarfs and irregular galaxies (Hunter & Hoffman 1999).

Assuming nebular temperature equal to 10,000 K, case B recombination, and \( A_{\text{Hα}} = 0.59 \) for \( A_\beta = 1.0 \), we derive extinction-corrected Hα fluxes 2.0 times larger than the measured, uncorrected [O ii] fluxes. Finally, we adopt the Kennicutt, Tamblyn, & Congdon (1994) intrinsic Hα-SFR calibration, assuming the Kennicutt (1983) initial mass function from 0.1 to 100 \( M_\odot \):

\[
\text{SFR} (M_\odot \text{ yr}^{-1}) = \frac{L_{\text{Hα}}}{1.36 \times 10^{41} \text{ ergs s}^{-1}} \tag{2}
\]

By choosing an extinction correction appropriate for low-mass galaxies, we will systematically underestimate the extinction and (SFR) in luminous galaxies by a factor of 2–3 (Kennicutt 1992) or more. The observed [O ii]/Hα ratio depends strongly on reddening and metallicity and can vary by an order of magnitude for galaxies with \( -14 > M_B > -22 \) (Jansen, Franx, & Fabricant 2001).

Comparison of SFRs derived from [O ii] λ3727 emission and near-infrared, far-infrared, and radio data of “post-starburst” cluster galaxies at \( z \sim 0.4 \) and local dusty starburst galaxies suggests that optical extinction could be as high as \( A_\beta = 2–3 \) mag (Poggianti & Wu 2000; Smail et al. 1999). However, these extreme extinction levels are found primarily in the most massive “E+A” galaxies and dusty starbursts. Dwarf galaxies have low metallicities and thus are likely to have much less dust than these massive galaxies. Thus, while we may underestimate the extinction and intrinsic SFRs in massive, dusty, and metal-rich galaxies in our sample, our assumption of modest extinction and a relatively low [O ii]/Hα ratio should be appropriate for the majority of our detections.

4.2. MS 1512.4+3647 [O ii] Emission Line Galaxy Star Formation Histories

The [O ii] emission line population detected in the field immediately surrounding MS 1512.4+3647 is dominated by blue \((g-i < 1.0)\), faint \((i > 21)\) galaxies. At \( z \sim 0.4 \), the \( u-i \) and \( g-i \) colors span the redshifted 4000 Å break and are therefore sensitive to the luminosity-weighted age of the observed stellar population. In Figures 9 and 10 we compare the broadband luminosities and colors of the MS 1512.43647 [O ii] on-band excess detections to population synthesis model tracks for an instantaneous burst and constant star formation with constant stellar mass and varying age (Bruzual & Charlot 2003). The broadband colors of the MS 1512.4+3647 [O ii] emission line candidates imply a young (<100 Myr) fading burst or a somewhat older (>500 Myr) continuous star formation history. The models assume a metallicity ~1/3 Z⊙ and Calzetti (1997) dust extinction with \( A_B = 1.0 \); adopting a higher metallicity or extinction would give younger ages. The red CN λ3883 absorption line interlopers clearly separate from the bluer [O ii] emission line candidates in the color-color diagrams. These bright red low-EW interlopers have colors and luminosities consistent with an unreddened 1–5 Gyr, 1010–1011 \( M_\odot \) burst.

The majority of MS 1512.4+3647 [O ii] emission line candidates are dwarf galaxies. Comparison of the galaxies’ colors and \( i \) magnitudes to the population synthesis models allows us to place a lower limit on their stellar masses (Fig. 10). Many of the emission-line candidates have implied stellar masses \( \sim 10^8–10^9 M_\odot \). However, any underlying population of old stars will be virtually undetectable, and up to 90% of a galaxy’s stellar mass could be hidden in a \( \sim 10 \) Gyr population by a 40 Myr burst without significantly reddening its \( g-i \) and \( u-i \) colors. Nevertheless, even with an additional factor of 10 in stellar mass, many of the faint star-forming galaxies would still have sub-L* stellar masses \(<10^{10} M_\odot \). The faint [O ii] emission line galaxies tend to be compact in our images with projected radii less than a few kiloparsecs, giving further evidence that these galaxies are intrinsically small. Archived high-resolution HST WFC2 F814W images of MS 1512.4+3647 contain only three [O ii] emission line candidates from our sample. One is the central galaxy (2435), which has an elliptical halo but bright irregular nucleus and several close companions; the other two objects appear to be distorted spirals (2565 and 2437).

The MS 1512.4+3647 objects with the highest EWs are also the faintest and bluest galaxies (Figs. 10 and 11). Locally, galaxies with rest-frame [O ii] EWs of greater than 40 Å tend to be very late type low-mass Sdm/Im galaxies (Kennicutt 1992), and many of the blue dwarfs observed by Gallagher et al. (1989) have [O ii] EWs of \( \sim 50 \) Å or greater. Therefore, many of these faint, high-EW objects are probably late-type, low-mass galaxies undergoing rapid star formation. In Figure 11 we compare the colors and observed [O ii] EWs to the \( A_\beta = 1.0 \) reddened and redshifted population synthesis model tracks for three different exponentially decaying star formation timescales [SFR \( \propto \exp(-t/\tau) \), \( \tau = 10 \) Myr, 100 Myr, and 1 Gyr] and a constant star formation model (\( \tau = \infty \)). The model [O ii] EWs were calculated from their instantaneous SFRs using the empirical conversion described in § 4.1. Older, continuously star-forming galaxies have relatively high EWs as a result of the constant production of new stars but redder continua due to the older stellar population. Young fading bursts have rapidly decreasing EWs as the massive stars die off but remain relatively blue as long as [O ii] emission is detectable. We find that the majority of the MS 1512.4+3647 [O ii] candidates’ colors and [O ii] EWs are best described by an exponentially decaying model with \( \tau \leq 100 \) Myr and ages 20–300 Myr.
Fig. 9.—Plot of $g-i$ vs. $u-g$ (left) and $u-i$ (right) colors for the MS 1512.4+3647 on-band excess objects (filled squares). The sizes of the points are proportional to log([O ii] EW). The error bars show the typical photometric errors of the galaxies at $i = 23$. The model tracks are the predicted colors for a burst star formation history (dotted line) and a constant star formation history (dashed line) observed at redshift $z = 0.37$ (Bruzual & Charlot 2003). The tick marks on the model tracks are at 10 Myr, 50 Myr, 100 Myr, 500 Myr, 1 Gyr, 5 Gyr, 10 Gyr, and 13 Gyr. The models assume an internal extinction of $A_B = 1.0$, $Z = 1/3 Z_\odot$, and a Salpeter initial mass function.

Fig. 10.—Plot of $i$ vs. $g-i$ (left) and $u-i$ (right) colors for the MS 1512.4+3647 on-band excess objects (filled squares). The size of the points is proportional to log([O ii] EW). The error bars show the typical photometric errors of the galaxies at $i = 23$. The models tracks are for constant mass ($10^{10}$, $10^9$, and $10^8 M_\odot$) and increasing age for a burst star formation history (dotted line) and a constant star formation history (dashed line; same as Fig. 9).
4.3. MS 1512.4+3647 versus A851

The distribution of colors and [O II] EWs for the MS 1512.4+3647 [O II] emission line galaxy candidates appears more like that of the faint field population at \( z = 0.4 \) than the rich cluster A851. A851 possesses a large number of [O II] emission line candidates with intermediate \( g-i \) colors and [O II] EWs consistent with star formation decay timescales \( \tau \sim 100 \) Myr–1 Gyr (Fig. 12; see also Paper I). Such galaxies are rare in the foreground A851 field (Fig. 12) and the MS 1512.4+3647 cluster field. We also find fewer high [O II] EW objects in the A851 cluster sample than in the MS 1512.4+3647 sample or the foreground A851 field. In A851, we found only seven objects with EW > 100 \( \AA \) compared to 39 high-EW off-band “field” sources. Direct comparison to our MS 1512.4+3647 sample is difficult, as many of the detected A851 on- and off-band high-EW objects have line fluxes well below the MS 1512.4+3647 limiting line flux. Nevertheless, we do find over twice as many faint EW > 100 objects with \( F[\text{O II}] > 10^{-17} \text{ergs s}^{-1} \text{cm}^{-2} \) in our MS 1512.4+3647 3 \( \sigma \) detections as we do for the A851 cluster, and it is probable that more high-EW objects lie below the MS 1512.4+3647 3 \( \sigma \) detection limit (Fig. 6).

In Paper I we concluded that the lack of high [O II] EW A851 cluster galaxies was evidence for the suppression of starbursts in A851 relative to the field galaxy population. Infalling galaxies are predicted to have their gaseous reservoirs removed by the cluster environment on timescales of 1–3 Gyr (Balogh et al. 2000). If star formation in field galaxies is gradually suppressed as they enter the cluster environment, one may expect to find a population of cluster galaxies with slowly fading star formation. The deficit of intermediate-color, \( \tau > 100 \) Myr objects in MS 1512.4+3647 and the foreground field of A851 implies that relatively few emission-line galaxies have been accreted and “strangled” by the MS 1512.4+3647 cluster within the previous few Gyr.

The suppression of star formation within the cluster core should be evident as a dependence of SFR (and [O II] emission) on cluster-centric radius. In Figure 13 we plot the average SFR and \( L[\text{O II}] \) of the MS 1512.4+3647 and A851 [O II] emission line candidates with projected radius. The average SFR of the central regions (\( r < 100'' \)) of both clusters is dominated by the central cluster galaxies, which appear to be undergoing minor mergers. Otherwise, the mean SFR is approximately constant with projected radius out to \( \sim 3R_{200} \) in MS 1512.4+3647 and \( \sim 1R_{200} \) in A851. If the MS 1512.4+3647 sample is dominated by field galaxies, we would not expect to see any radial trend. Furthermore, the effect of the cluster environment on infalling galaxies is believed to be strongest outside of the virial radius (Ellingson et al. 2001; Diaferio et al. 2001) and therefore outside of our field of view for A851. Therefore, it is difficult to rule out galaxy “strangulation” in these two clusters, despite the lack of radial dependence on the observed average SFR.

4.4. Implications for Dwarf Galaxy Evolution

Most of the faint star-forming galaxies in the field surrounding MS 1512.4+3647 are best described by low-mass starbursts with \( \tau < 100 \) Myr, as are the off-band excess objects in the field in front of A851 (Figs. 11 and 12).

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8 The recalibration of our A851 \( g \) photometry has strengthened this conclusion, as the revised colors have been shifted blueward and allow more intermediate-color galaxies to meet our [O II] emission line candidate criteria.
Galaxies with longer star formation timescales above our detection limit of 0.13 $M_\odot$ yr$^{-1}$ are absent from our “field” galaxy samples, implying that short bursts dominate the star formation in many field galaxies. Both the derived star formation histories of local irregular galaxies (Grebel 1997) and the lack of red, faded, low-mass field galaxies in the Hubble Deep Field at $z < 0.5$ suggest that field dwarf galaxies (Lotz 2003; Ferguson & Babul 1998) undergo multiple bursts throughout their evolution.

However, further star formation may be suppressed if the galaxy falls into a rich cluster environment. Local clusters are filled with thousands of dwarf galaxies that are gas-poor and no longer forming stars. If the observed [O II] emission line galaxies fade quickly and do not undergo another episode of star formation, many could become as faint as present-day dEs. A galaxy with a $\tau = 10$ Myr exponentially decaying burst, an age of 40 Myr, and an observed $i$ magnitude of $\sim 22$ at $z = 0.37$ would fade to an $M_R \sim -16$ by $z = 0$. A galaxy with $\tau = 100$ Myr, an age of 300 Myr, and an observed $i$ magnitude of $\sim 22$ at $z = 0.37$ would fade to $M_R \sim -18$ by $z = 0$.

At $z \sim 0.4$, we are only able to observe the progenitors of cluster dEs brighter than $M_R = -15.0$, which number $\sim 300$ in Virgo. To produce this number of faded emission-line galaxies in MS 1512.4+3647, over 4 times the number of [O II] candidates observed in the MS 1512.4+3647 field must accrete onto the cluster by the present day. Correcting the observed density of field emission-line galaxies for the duty cycle, this requires a field volume infall rate greater than 50 Mpc$^3$ Gyr$^{-1}$ in order to accrete similar numbers of bright dEs in the 4–5 Gyr since $z = 0.4$. Our observations of MS 1512.4+3647 suggest a maximum infall rate for emission-line galaxies of a few Mpc$^3$ Gyr$^{-1}$, if recently accreted galaxies are able to form stars and have [O II] emission visible for $\sim 1$ Gyr. Therefore, it is unlikely that most bright dEs in typical clusters were acquired by the gradual infall of star-forming field galaxies since $z \sim 0.4$. But if most dE progenitors are accreted in clumps as groups merge intermittently with the cluster, as is the case for A851, then one or two such major mergers could account for the majority of the dE population observed in local clusters. In this case, clusters

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**Fig. 12.**—log([O II] EW) vs. $g-i$ for A851 on-band excess cluster objects (left) and off-band excess foreground objects (right). The model tracks are the same as in Fig. 11.

**Fig. 13.**—Average SFR and [O II] luminosity of the MS 1512.4+3647 and A851 emission-line candidates as a function of cluster radius. The open symbol (top) is the average SFR in the inner 275 kpc excluding MS 1512.4+3647’s central cluster galaxy. (Note that the A851 sample has a lower limiting [O II] flux than the MS 1512.4+3647 sample and therefore the average SFR rate for the detected A851 sample is lower.)
that have assembled more recently would have significantly younger dE populations. In the Virgo Cluster, bright nucleated dEs (dE,N) and faint dSph/dEs are as spatially clustered as the giant ellipticals (Ferguson & Sandage 1989). Could a \( z \leq 0.4 \) infalling galaxy population become as clustered by \( z = 0 \) as local dE populations? Dynamical friction timescales grow longer with smaller satellite mass and \(<10^9 \, M_\odot\) galaxies would sink quite slowly in the cluster potential: dwarf galaxies accreted 4–5 Gyr ago do not have enough time to become as spatially clustered as the local dE cluster population. However, the Fornax and Virgo dwarf galaxy populations (which are dominated by dE,N) have higher velocity dispersions than the giant elliptical galaxy populations (Drinkwater, Gregg, & Colless 2001; Conselice et al. 2001), which is consistent with recent infall. One way to reconcile the spatial distribution of dE,N with their high cluster velocities is to form the nuclei as the dwarfs pass through the cluster center on timescales less than a few Gyr. Gas-rich dwarfs may form centralized stellar excesses via galaxy harassment in a few Gyr, and galaxies that form nuclei are more likely to survive within the central regions of clusters than those that do not (Moore et al. 1998). Most dE nuclei are compact, globular cluster–like objects and could also be formed by the decay of massive globular clusters into the center via dynamical friction (Lotz et al. 2001). The timescale for this process may be shorter for dwarfs within the central regions of clusters than those on the outskirts (Oh & Lin 2000).

5. SUMMARY

We have presented the results of a deep narrowband [O \( \text{ii} \)] \( \lambda 3727 \) emission line survey for faint star-forming galaxies in the \( z = 0.37 \) MS 1512.4+3647 cluster. Using broadband \( u-i \) and \( g-i \) colors, we are able to distinguish \( z \sim 0.37 \) [O \( \text{ii} \)] emission line candidates from \( z \sim 0.37 \) elliptical galaxies that may produce false on-band excesses and background \( z \sim 3.2 \) Ly\( \alpha \) emitters. We find two Ly\( \alpha \) candidates with \( EW > 300 \) A and undetected \( u \) fluxes. We identify 66 [O \( \text{ii} \)] emission line candidates in the MS 1512.4+3647 field.

The observed density of [O \( \text{ii} \)] emission line galaxies surrounding MS 1512.4+3647 is identical to the field population at \( z \sim 0.4 \) and is most likely dominated by [O \( \text{ii} \)]-emitting field galaxies within \( \sim 180 \) Mpc of the cluster along the line of sight. This is in strong contrast to the previously studied \( z = 0.41 \) cluster A851, which has an [O \( \text{ii} \)] emission line galaxy density at least 3–4 times that of the field. We find that A851 has 2–10 times as many star-forming galaxies per unit volume and X-ray luminosity as MS 1512.4+3647. A851 is a cluster in formation, with many merging subclumps and filaments, unlike the more typical, relaxed MS 1512.4+3647 cluster. Thus, the density of star-forming galaxies in a cluster relative to the field appears to be a strong tracer of its recent assembly history.

The field-dominated MS 1512.4+3647 and foreground A851 field samples lack the galaxies with star formation decay timescales \( \tau \sim 100 \) Myr–1 Gyr that dominate the A851 cluster emission-line galaxy population. Such star formation timescales are expected if star formation is gradually suppressed as field galaxies are accreted by the cluster (Balogh et al. 2000). Therefore, the low density of [O \( \text{ii} \)] emission line galaxies and the absence of intermediate-color emission-line galaxies in MS 1512.4+3647 suggests that relatively few star-forming galaxies have been accreted by the MS 1512.4+3647 cluster in the previous Gyr. On the other hand, the abundance of intermediate-color emission-line galaxies and the absence of high [O \( \text{ii} \)] EW galaxies in A851 are consistent with the recent accretion of many of A851′s star-forming galaxies.

The field emission-line galaxy population surrounding MS 1512.4+3647 is forming stars in bursts with \( \tau \sim 10–100 \) Myr. Galaxies with the highest [O \( \text{ii} \)] EWs and bluest colors in both samples are typically among the lowest luminosity systems. These faint starbursts have young stellar populations with masses \( \geq 10^8–10^9 \, M_\odot \) but could hide up to an additional factor of 10 in stellar mass in an old faded stellar population. If the observed star-forming galaxies around MS 1512.4+3647 and A851 fall into the clusters’ potential wells and rapidly cease star production, they could fade to be as faint as dE in local clusters. However, the large numbers of present-day cluster dEs require typical infall rates much greater than those implied by our observations of MS 1512.4+3647. The large dE cluster populations can be acquired only if most have been accreted before \( z \sim 0.4 \) or in several major merger events (as in A851).

We would like to thank Ian Smail for access to his photometry of A851. J. M. L. thanks Joel Primack, Piero Madau, and the Santa Cruz Institute for Particle Physics at UCSC for support during the final stages of this paper. C. L. M. gratefully acknowledges financial support from the Sherman Fairchild Foundation through Caltech and from NASA through the Hubble Fellowship Program.
