STAR FORMATION IN CLUSTER GALAXIES AT 0.2 < z < 0.55

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Received 1997 May 27; accepted 1997 August 12; published 1997 September 18

ABSTRACT

The rest-frame equivalent width of the [O II] λ3727 emission line, W₁(O II), has been measured for cluster and field galaxies in the Canadian Network for Observational Cosmology redshift survey of rich clusters at 0.2 < z < 0.55. Emission lines of any strength in cluster galaxies at all distances from the cluster center, out to 2R₂₀₀, are less common than in field galaxies. The mean W₁(O II) in cluster galaxies more luminous than M₁ < −18.5 + 5 log h (q₀ = 0.1) is 3.8 ± 0.3 Å (where the uncertainty is the 1 σ error in the mean), which is significantly less than the field galaxy mean of 11.2 ± 0.3 Å. For the innermost cluster members (R < 0.3R₂₀₀), the mean W₁(O II) is only 0.3 ± 0.4 Å. Thus, it appears that neither the infall process nor internal tides in the cluster induce detectable excess star formation in cluster galaxies relative to the field. The color-radius relation of the sample is unable to fully account for the lack of cluster galaxies with W₁(O II) > 10 Å, as expected in a model of cluster formation in which star formation is truncated on infall. Evidence of suppressed star formation relative to the field is present in the whole cluster sample, out to 2R₂₀₀, so the mechanism responsible for the differential evolution must be acting at a large distance from the cluster center and not just in the core. The mean star formation rate in the cluster galaxies with the strongest emission corresponds to an increase in the total stellar mass of less than about 4% if the star formation is due to a secondary burst lasting 0.1 Gyr.

Subject headings: galaxies: clusters: general — stars: formation

1. INTRODUCTION

It is well established that galaxy populations vary with the density of neighboring galaxies (see, e.g., Dressler 1980; Whitmore, Gilmore, & Jones 1993); however, the physical mechanisms responsible for the variation are not known. It has also been observed that cluster galaxies have, on average, older stellar populations than field galaxies (e.g., Bower et al. 1990; Rose et al. 1994). Thus, if clusters evolve by accreting field galaxies, star formation in the infalling galaxies must be truncated prematurely, relative to isolated field galaxies. If clusters are to be used to determine the mass density of the universe (see, e.g., Carlberg et al. 1996), the effect of this differential evolution between cluster and field galaxies on the average galaxy stellar mass must be understood.

Star formation may be truncated following an increase in star-forming activity that rapidly consumes and/or expels the available gas in a galaxy. Several physical processes have been proposed that may have such an effect, including shocks induced by ram pressure from the intracluster medium (ICM; Bothun & Dressler 1986; Guavazzi & Jaffe 1987), effects of the cluster tidal field (Byrd & Valtonen 1990), and galaxy-galaxy interactions (Barnes & Hernquist 1991; Moore et al. 1996). The increase in the fraction of blue, star-forming cluster galaxies with redshift (BO effect; Butler & Oemler 1984) has been well established, and several authors (e.g., Couch & Sharples 1987; Moss & Whittle 1993; Caldwell et al. 1996; Barger et al. 1996) have shown that there are cluster galaxies, even at low redshift, in which significant star formation has occurred in the past 2 Gyr. It is not yet clear, however, whether this activity is in excess relative to that in the field.

Alternatively, star formation may be halted in infalling galaxies without an initial increase, as suggested by the results of the analysis of colors, spectral features, and morphologies of galaxies in the Abell 2390 cluster (Abraham et al. 1996). This may be achieved by interaction with the hot ICM by ram pressure stripping (Gunn & Gott 1972) or transport processes such as viscous stripping and thermal evaporation (Nulsen 1982). In this case, cluster galaxies can be treated as representative of the field at the epoch of infall, and the BO effect is interpreted as an increase in the infall rate of field galaxies, which themselves show evidence of more star-forming activity at higher redshift.

The luminosities of Balmer emission lines in galaxy spectra are directly related to the ionizing fluxes of hot stars embedded in H II regions and thus can be used to determine the star formation rate (SFR) in the observed region of the galaxy (Kennicutt 1992). Although Hα is the best observable indicator of SFR, it is redshifted out of convenient observing bands at even moderate redshifts. The [O II] λ3727 emission line is then the feature of choice, as its strength is found to be correlated with Hα in local samples (Kennicutt 1992; Guzman et al. 1997; but see Hammer et al. 1997). It has been clearly shown (e.g., Dressler, Thompson, & Shectman 1985; Hill & Oegerle 1993; Abraham et al. 1996; Biviano et al. 1997) that the fraction of galaxies with strong emission lines is much smaller in clusters than in the field. Since emission lines are much more commonly found in late spirals than in early-type galaxies (see, e.g., Kennicutt 1992; Biviano et al. 1997), this effect may be consistent with the morphology-radius relation, if the fraction of spiral galaxies is lower in clusters by the amount necessary to account for the decrease in observed emission. However, if star formation is truncated in field galaxies falling into the cluster, the number of galaxies with [O II] line emission will be lower than expected from the morphological composition at a given clustercentric radius, as the [O II] feature disappears shortly after
star formation ceases, whereas morphological change due to disk fading occurs on timescales of about 1 Gyr (Abraham et al. 1996).

In this Letter, the dependence of [O ii] line strength on distance from the cluster center is presented and compared with that of the field sample. In § 2 the data sample is described, selection effects are considered, and cluster membership and cluster-centric radius are defined. In § 3 the emission-line properties of cluster galaxies are compared with those of the field sample. The results are interpreted in § 4 by computing star formation rates and comparing the fraction of emission-line properties of cluster galaxies to those of the field.

Throughout this Letter, a cosmology of formation rates and comparing the fraction of emission-line properties of cluster galaxies are compared with those of the field. The solid line displays the $M_r = -18.5 + 5 \log h$ with at least an 80% success rate. A magnitude weight $W_r$, which is the ratio of the total number of galaxies to the number of galaxies with redshifts in a magnitude bin centered around the galaxy, is calculated for each galaxy in the sample to correct for incompleteness. To ensure that the sample is not biased toward emission-line objects, galaxies with $W_r > 5$ are excluded. The remaining, magnitude-weighted sample is complete to about $M_r = -18.5 + 5 \log h$; galaxies less luminous than this limit are excluded from the sample.

Cluster velocity dispersion profiles of the form $\sigma^2(r) = B(r + b)$, where $r$ is the projected radius from the cluster center, are calculated by Carlberg, Yee, & Ellingson (1997) on the basis of a volume density function of the form $\nu(r) = A/r^{-1}(r + a)^{-3}$ and an anisotropy parameter, $\beta = 0.5$. Galaxies with a velocity difference relative to the cluster mean of less than $3\sigma(r)$ are considered to be cluster members. The field sample is selected from galaxies with a velocity difference greater than $3\sigma(r)$ that lie within a filter-dependent redshift range that minimizes selection effects (YEC). The population with intermediate velocities is classified as "near field" and may contain infalling field galaxies. These galaxies are not included in the present analysis to ensure as clear a differentiation between field and cluster galaxies as possible. The $W_r(O\ ii)$ properties of this population are not, however, statistically different from those of the field.

The clustercentric distance $R$ for cluster members is defined as the projected distance from the brightest cluster galaxy (BCG). For field galaxies, $R$ is the Hubble flow distance determined from the redshift difference between the galaxy and the cluster mean. Since the sample consists of clusters of dif-

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2. SAMPLE SELECTION AND MEASUREMENTS

The galaxy sample was selected from the Canadian Network for Observational Cosmology (CNOC; Yee, Ellingson, & Carlberg 1996, hereafter YEC) spectroscopic sample of 15 X-ray–luminous clusters at moderate redshift ($0.2 < z < 0.55$). This sample consists of about 2500 cluster and field galaxies with determined redshifts, for which selection effects are well understood (YEC).

For each spectrum, the rest-frame $[O \, ii] \lambda 3727$ equivalent width, $W_3(O\ ii)$, was automatically computed by summing the flux above the continuum in pixels between 3713 $< \lambda < 3741$ Å. The continuum level was estimated by fitting a straight line to the flux between 3653 $< \lambda < 3713$ Å and 3741 $< \lambda < 3801$ Å by means of weighted linear regression, with weights from the Poisson noise vector generated by optimally extracting the spectra with IRAF. The error in $W_3(O\ ii)$ is computed from equation (A8) in Bohlin et al. (1983). An average $W_3(O\ ii)$, weighted by this error, is adopted for multiply observed galaxies in the sample. The mean and median errors in $W_3(O\ ii)$ are 5 and 3 Å, respectively, for the full sample. The accuracy of the measurements and errors was verified by comparing measurements made on artificial spectra that consist of a power-law continuum component ($f_\nu \propto \nu^{\alpha}$) added to the spectrum of M31 (making the bulge spectrum mimic a late-type spiral in the continuum) and a Gaussian emission line at $\lambda = 3727$ Å with a velocity width of 5 Å (400 km s$^{-1}$) FWHM. The standard deviation of $W_3(O\ ii)$ measurements for each set of 250–1000 spectra at the same signal-to-noise ratio (SNR) and $W_3(O\ ii)$ was found to compare well with the average error estimate. In addition, the difference between two independent measurements of the same (real) galaxy, when available, was compared with $\sigma$, the quadrature sum of the two error estimates. This analysis indicates that the $W_3(O\ ii)$ errors do not represent a normal distribution, as only about 50% of the differences between two measurements are less than $1 \sigma$ and only 92% are less than $3 \sigma$. The quoted error estimates are still meaningful, however, so long as they are interpreted in this sense. A copy of the FORTRAN code used to measure $W_3(O\ ii)$ and its error (as well as several other indices) can be obtained from the first author.

The CNOC selection procedure is described in YEC and is designed to sample the cluster galaxies to $M_r \leq -18.5 + 5 \log h$ with at least an 80% success rate. A magnitude weight $W_r$, which is the ratio of the total number of galaxies to the number of galaxies with redshifts in a magnitude bin centered around the galaxy, is calculated for each galaxy in the sample to correct for incompleteness. To ensure that the sample is not biased toward emission-line objects, galaxies with $W_r > 5$ are excluded. The remaining, magnitude-weighted sample is complete to about $M_r = -18.5 + 5 \log h$; galaxies less luminous than this limit are excluded from the sample.

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Fig. 1.—$W_3(O\ ii)$ as a function of clustercentric distance $R$, for the selected subsample. The points to the left of the dashed line are cluster galaxies, for which $R$ is the projected distance from the cluster center. There is one cluster galaxy, with $W_3(O\ ii) = 150$ Å, which is off the scale. The more distant points are field galaxies, for which $R$ is the Hubble flow distance determined from the redshift difference between the galaxy and the cluster mean. The solid line is the weighted mean in the field and three cluster radial bins. The sample error bar displayed is representative of the mean 1 $\sigma$ uncertainty in $W_3(O\ ii)$, 3.5 Å.
different richness, $R$ is normalized by $R_{200}$, the radius at which the cluster mass density is 200 times the critical density. For these clusters, $R_{200}$ is typically 1–1.5 h$^{-1}$ Mpc (Carlberg et al. 1996). There is an apparent absence of field galaxies in the sample at $3 < R/R_{200} < 20$, because of the fact that field galaxies at that redshift, projected in front of and behind the cluster, have a velocity offset from the BCG less than 3σ($r$) and are hence included in the cluster sample. Limited spatial coverage on the sky restricts the observed projected distance of galaxies in the sample to less than about $3R_{200}$. For statistical analysis, each galaxy is weighted by $W_m \times W_{\text{ring}}$, where $W_{\text{ring}}$ is a geometrical correction to account for the fact that the clusters are not uniformly sampled as a function of radius.

The restricted sample considered in this analysis consists of 727 cluster galaxies and 346 field galaxies, whereas $W_{\text{m}}(\text{O} \, \text{ii})$ measurements are available for a total of 1169 cluster and 783 field galaxies. The BCGs are considered atypical cluster members and are excluded from all analysis. Also, no attempt was made to identify active galactic nuclei (AGNs), as the H$\alpha$ and [O ii] λ5007 lines, which are common diagnostics, are usually redshifted out of the observed spectral range.

3. RESULTS

Figure 1 shows the distribution of $W_{\text{m}}(\text{O} \, \text{ii})$ as a function of $R/R_{200}$, where $R$ is defined in § 2. The dashed line separates the (inner) cluster galaxies from the field galaxies. As expected, emission-line galaxies are clearly less common in clusters than in the field. The weighted mean $W_{\text{m}}(\text{O} \, \text{ii})$ (and its uncertainty) in the field is $11.2 \pm 0.3$ A, compared with $3.5 \pm 0.4$ A in the outer cluster regions ($0.3 < R/R_{200} < 1$) and $0.3 \pm 0.4$ A in the central regions ($R/R_{200} < 0.3$). The mean error of an individual measurement, indicated by the sample error bar in the figure, is $3.5$ A. [Forty of the 1073 galaxies in the selected sample have (formal) uncertainties in $W_{\text{m}}(\text{O} \, \text{ii})$ greater than 10 A, and 117 have uncertainties less than 1 A.] There is no evidence of a population of cluster galaxies with excess emission relative to the field at any distance from the cluster center, out to $R \approx 2R_{200}$.

The difference between the cumulative $W_{\text{m}}(\text{O} \, \text{ii})$ distributions of the cluster and field is shown in the top panel of Figure 2. The cluster galaxies at $R \geq 0.3R_{200}$ are represented by the solid line, the inner cluster galaxies ($R < 0.3R_{200}$) by the long-dashed line, and the field galaxies by the dotted line. The cluster sample shows a clear deficiency in emission-line galaxies relative to the field in both the inner and outer cluster regions at all line strengths. There is no evidence of a population of cluster galaxies with stronger $W_{\text{m}}(\text{O} \, \text{ii})$ than is observed in field galaxies. Since the cluster sample is partially contaminated by field galaxies projected on the cluster, the measurements of the mean $W_{\text{m}}(\text{O} \, \text{ii})$ and SFR in the cluster are overestimates.

4. DISCUSSION

Star formation rates have been calculated from Kennicutt’s (1992) relation with his adopted extinction correction of $E$(H$\alpha$) = 1 mag:

$$\text{SFR} = 6.75 \times 10^{-12} \frac{L_{\text{H}\alpha}}{L_{\text{B}$(\text{O} \, \text{II})}} \ W_{\text{m}}(\text{O} \, \text{ii}),$$

where SFR is in $M_{\odot}$ yr$^{-1}$ and $L_{\text{H}\alpha}/L_{\text{B}$(\text{O} \, \text{II})} = 10^{0.4(5.48-M_{\odot})}$ depends

on the absolute B-band luminosity of the galaxy, which must be obtained from the available Gunn $g$ and $r$ photometry: $M_g = M_r + (g-r)_0 - (g-B)_0$. Rest-frame $(g-r)_0$ colors are computed from the color-redshift relations in Patton et al. (1997; their Fig. 7), which are fits to the color k-corrections of YEC, and the corresponding rest-frame $(g-B)_0$ color is found by linearly interpolating the published values in Fukugita, Shimasaku, & Ichikawa (1995; their Table 3f). The cumulative SFR distributions for the cluster and field populations are shown in the bottom panel of Figure 2.

For the inner cluster members, less than 35% have a SFR $>0.01$ h$^{-2}$ $M_{\odot}$ yr$^{-1}$, whereas the median SFR in the field is about $0.2$ h$^{-2}$ $M_{\odot}$ yr$^{-1}$. The SFR calculated in this manner is most useful as an indication of the relative difference between the cluster and field; Guzman et al. (1997) suggest that the coefficient in equation (1) may be about three times lower than is used here.

It has been clearly shown (see, e.g., Couch & Sharples 1987; Moss & Whittle 1993; Caldwell et al. 1996; Barger et al. 1996) that a significant fraction of cluster galaxies have undergone episodes of star formation in the past 2 Gyr. In particular, Barger et al. (1996) suggest that 30% have undergone a 0.1 Gyr burst in the past 2 Gyr, which implies that 1.5% of cluster galaxies should be in such a state at any one time. There are cluster galaxies in the present sample with nonzero $W_{\text{m}}(\text{O} \, \text{ii})$; however, they are less common than in the field population. For example, 4.3% of field galaxies have $W_{\text{m}}(\text{O} \, \text{ii}) > 40$ A, compared with only 1.4% of cluster galaxies. Thus, it seems unlikely that significant additional star formation activity in cluster galaxies is caused by the infall process or internal tides in the cluster. The weighted mean $W_{\text{m}}(\text{O} \, \text{ii})$ of the cluster galaxies with $W_{\text{m}}(\text{O} \, \text{ii}) > 40$ A is 59 A, which corresponds to an increase in
stellar mass of only 4% over 0.1 Gyr from equation (1), assuming a stellar mass-to-light ratio of unity. No galaxy anywhere in the sample is observed to have $W_{\text{d}}(\text{O} \text{II}) > 15 \AA$ or SFR $> 4 M_\odot \text{yr}^{-1}$, if there are galaxies with SFR $\approx 30 M_\odot \text{yr}^{-1}$, as suggested by Couch & Sharples (1987) and Barger et al. (1996), they may be located outside the sample, at $R > 2 R_{200}$.

It is instructive to compare the $W_{\text{d}}(\text{O} \text{II})$-radius relation with the well-known morphology-radius relation to determine whether or not they are consistent with one another. Unfortunately, morphological classifications are not yet available for the full CNOC sample. For now, the color-radius relation is considered, as galaxy morphology is expected to be correlated with color. The rest-frame $(g - r)_0$ colors, computed as described above, are used to divide the sample into four classes, which correspond roughly to E, Sbc, Scd, and Im morphological types, as in Patton et al. (1997). The fraction of field galaxies with $W_{\text{d}}(\text{O} \text{II}) > 10 \AA$ is $0.12 \pm 0.04$, $0.29 \pm 0.06$, $0.72 \pm 0.13$, and $0.78 \pm 0.17$ for the E, Sbc, Scd, and Im classes, respectively. From the color-radius relation of the cluster sample, the fraction of cluster galaxies with $W_{\text{d}}(\text{O} \text{II}) > 10 \AA$ in a given radial bin is predicted; this is shown as the long-dashed line in Figure 3. The observed fraction is shown as the solid line; it is significantly lower than expected from the color-radius relation alone, for $R < 2 R_{200}$. The fraction of galaxies with $W_{\text{d}}(\text{O} \text{II}) > 15 \AA$, however, is consistent with the color-radius relation; this may suggest that star formation is not truncated equally for all galaxy types, as already suggested by the results of Moss & Whittle (1993).

5. CONCLUSIONS

The mean $W_{\text{d}}(\text{O} \text{II})$ of cluster galaxies more luminous than $M_1 = -18.5 + 5 \log h$ in the CNOC spectroscopic sample of rich clusters at $0.2 < z < 0.55$ is $3.8 \pm 0.3$ Å, significantly less than the field galaxy mean of $11.2 \pm 0.3$ Å. The average SFR among cluster galaxies is less than the average in the field out to $2 R_{200}$, which implies that whatever mechanism is responsible for truncating star formation in cluster galaxies is taking place at a large distance from the cluster center. Cluster galaxies of a given color are less likely to show signs of significant star formation than their counterparts in the field at any distance from the cluster center. Of cluster members, 1.4% have $W_{\text{d}}(\text{O} \text{II}) > 40 \AA$, with a weighted mean of $59 \AA$, corresponding to an increase in stellar mass of less than 4% if the activity is due to a 0.1 Gyr burst. Many more (4.3%) field galaxies have $W_{\text{d}}(\text{O} \text{II}) > 40 \AA$, which suggests that star formation in cluster galaxies is likely not induced by the infall process or internal tides. This supports the conclusions of Abraham et al. (1996) that star formation is truncated in infalling field galaxies without an initial increase. The BO effect in these clusters may then be due to the increased rate of infall of bluer field galaxies at higher redshift.

We would like to thank the referee, J. A. Rose, for improving the clarity and focus of this work. M. L. B. would also like to thank C. J. Pritchet for helpful comments and discussions. M. L. B. is supported by the Natural Sciences and Engineering Research Council of Canada.

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