The Dependence of Cluster Galaxy Star Formation Rates on the Global Environment

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**ABSTRACT**

A comparison of star formation properties as a function of environment is made from the spectra of identically selected cluster and field galaxies in the CNOC 1 redshift survey of over 2000 galaxies in the fields of fifteen X-ray luminous clusters at \(0.18 < z < 0.55\). The ratio of bulge luminosity to total galaxy luminosity (B/T) is computed for galaxies in this sample, and this measure of morphology is compared with the galaxy star formation rate as determined from the [OII]\(\lambda3727\) emission line. The mean star formation rate of cluster galaxies brighter than \(M_r = -17.5 + 5 \log h\) is found to vary from \(0.17 \pm 0.02 h^{-2} M_{\odot} \text{yr}^{-1}\) at \(R_{200} (1.5–2 h^{-1} \text{Mpc})\) to zero in the cluster center, and is always less than the mean star formation rate of field galaxies, which is \(0.39 \pm 0.01 h^{-2} M_{\odot} \text{yr}^{-1}\). It is demonstrated that this significant difference is not due exclusively to the difference in morphological type, as parameterized by the B/T value, by correcting for the B/T–radius relation. The distribution of [OII] equivalent widths among cluster galaxies is skewed toward lower values relative to the distribution for field galaxies of comparable physical size, B/T and redshift, with a statistical significance of more than 99%. The cluster environment affects not only the morphological mix of the galaxy population, but also suppresses the star formation rate within those galaxies, relative to morphologically similar galaxies in the field.

**Subject headings:** galaxies: clusters: general — galaxies: emission lines — galaxies: structure

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1. Introduction

In the hierarchical cold dark matter model of structure formation, galaxy clusters form by the collapse of rare, highly overdense regions of the universe and continually accrete mass from the surrounding regions as they evolve. The cluster population may consist of galaxies that formed long ago within the high density region, as well as those that formed in the less dense field environment and were subsequently accreted. In either case, there is ample reason to suspect that galaxies within clusters will be quite different from those in the field. A galaxy that forms in a high density region of the universe may be subjected to harassment and distortion from nearby protogalaxies (Dressler 1980; Whitmore, Gilmore & Jones 1993; Shigeta et al. 1998), while one that forms in a low density environment and is subsequently accreted may be subjected to tidal forces due to the large gravitational potential, or interactions with other galaxies and the intra–cluster medium (Bothun & Dressler 1986; Gavazzi & Jaffe 1987; Byrd & Valtonen 1990; Barnes & Hernquist 1991; Moore et al. 1996; Shigeta et al. 1998; Moore, Lake & Katz 1998).

It is not surprising, then, that cluster galaxies are observed to differ from field galaxies in their morphologies, colors and star formation rates (e.g., Dressler 1980; Whitmore, Gilmore & Jones 1993; Abraham et al. 1996; Dressler et al. 1997; Balogh et al. 1997; Hashimoto et al. 1997; Fisher et al. 1998; Koopmann & Kenney 1998; Morris et al. 1998). Although it has been shown that the mean star formation rate (SFR) in cluster galaxies is always less than in field galaxies (Balogh et al. 1997), it is important to determine if this remains true when the different morphological composition of the two populations is accounted for, since SFR is known to be strongly correlated with morphological type (e.g., Kennicutt 1992). This will distinguish between two simple scenarios: 1) the cluster environment favors galaxies of a certain morphological type, in terms of their size and relative bulge and disk components, but the SFR of these galaxies is statistically equivalent to that of similar galaxies in the field; or, 2) the SFR of a galaxy depends on its environment as well as its morphology. The results of this work will provide strong support for the second hypothesis.

The plan of this paper is as follows. In § 2 the data sample is defined, selection effects are considered, and the measurement techniques are described. In § 3 the emission line properties and morphologies of cluster galaxies are compared with the field sample. Implications are discussed in § 4, and the conclusions are summarized in § 5. A cosmology of $q_0 = 0.1$ is assumed for distance dependent calculations, which are given in terms of $h = H_0/100$ throughout.

2. Sample Selection and Measurements

The CNOC 1 cluster sample$^6$ consists of fifteen X–ray luminous clusters, observed with MOS at CFHT, in the redshift range $0.18 < z < 0.55$. Redshifts were obtained for about 2500 galaxies, and observations extend as far out as 1–2 $R_{200}$ in projected distance for most clusters, where $R_{200}$ is the radius at which the mean interior mass density is equal to 200 times the critical density, and within which it is expected that the galaxies are in virial equilibrium (Gott & Gunn 1974; Crone, Evrard & Richstone 1994). The observational strategy and details of the survey are detailed in Yee, Ellingson & Carlberg (1996). Cluster members are considered to be those galaxies with velocity differences from the brightest cluster galaxy (BCG) less than $3 \sigma(r)$, where $\sigma(r)$ is the cluster velocity dispersion as a function of projected radius $r$, as determined from the mass models of Carlberg, Yee & Ellingson (1997). Field galaxies are selected to be those with velocities greater than $6 \sigma(r)$. The cluster–centric distance parameter $R$ is the projected distance from the cluster BCG, and will be normalized to $R_{200}$, since there is a small range in the mass and linear size of the clusters in this sample.

The equivalent width of the [OII]3727 emission line, $W_3(OII)$, was automatically computed by summing the observed 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 using weighted linear regression, with weights from the Poisson noise vector generated by optimally extracting the spectra with IRAF.$^7$ The error in $W_3(OII)$ is

$^6$The measured parameters discussed here, as well as others and the raw data itself, will soon be available from the CADC data archive.

$^7$Omitting cluster E0906+11, for which a velocity dispersion could not be computed (Carlberg et al. 1996).

$^8$Except for cluster MS 0451.5+0250, for which no redshift is available for the BCG. The velocities are measured relative to the mean for this cluster.

$^9$IRAF is distributed by the National Optical Astronomy Observatories which is operated by AURA Inc. under contract with
computed from equation A8 in Bohlin et al. (1983) and an average $W_\alpha(OII)$, weighted by this error, is adopted for multiply observed galaxies in the sample. The mean and median error in $W_\alpha(OII)$ is 5 Å and 3 Å, respectively, for the full sample. These error estimates were found to be reasonably representative of the reproducibility of multiple $W_\alpha(OII)$ measurements, as described in Balogh et al. (1997).

Morphological parameters for the Gunn r band MOS images were measured by fitting two dimensional models of exponential disk and $R^{1/4}$ law profiles to the symmetrized components of the light distribution, as described in Schade et al. (1996a, 1996b). The images are symmetrized to minimize the effects of nearby companions and asymmetric structure, and a $\chi^2$ minimization procedure is applied to the models, convolved with the image point spread function, to obtain best fit values of the galaxy size, surface brightness and fractional bulge luminosity (bulge–to–total, or B/T ratio). Simulations show that the B/T measurements are reliable within about 20% for images of this quality (Schade et al. 1996a).

The data are weighted by two factors: a magnitude weight $W_m$ which compensates for the fact that it is more difficult to obtain redshifts for faint galaxies, and $W_{ring}$, which corrects for non–uniform sampling as a function of distance from the cluster center (Yee et al. 1996). The latter weight is only important when global cluster properties are considered such that the properties of galaxies at large radii are averaged together with those at small radii. Good fits to the light profiles were obtained for 1143 (712 cluster, 373 field, 58 near–field) of the 1515 galaxies with $W_m \leq 5$ and errors in $W_\alpha(OII)$ of less than 10 Å, and these comprise the selected subsample. The emission line properties and relative abundance of the galaxy population with poorly fit luminosity profiles are not significantly correlated with radial distance or cluster membership, and thus the exclusion of these galaxies from the sample is unlikely to bias the results. The selected sample includes galaxies with absolute Gunn r magnitudes less than about $-17.5 + 5 \log h$, and is complete to $M_r = -18.5 + 5 \log h$. The absolute magnitude distribution of the cluster sample is not significantly different from that of field. Furthermore, the absolute magnitude distribution is similar for the low and high redshift galaxies, a result of the longer exposure times in the high redshift cluster images (Yee et al. 1996). Although a proper treatment of the redshift evolution is not the present focus, it is noted that there is no significant difference in the results of this investigation between the low and high redshift clusters in the sample.

The sample is divided into three classes (hereafter referred to as B/T classes) based on the measured B/T value. The bulge dominated class (B) consists of those galaxies with $B/T > 0.7$, the disk dominated class (D) those with $B/T < 0.4$, and intermediate galaxies are classified “Int”. These classes should not be confused with or forced to conform to more familiar Hubble types, which depend partly on star formation properties and the presence of spiral structure. The B/T ratio and the sizes of the disk and bulge components are more stable properties that reflect the true “morphology” of the galaxy and are less dependent on its star formation properties. However, the measured B/T may somewhat underestimate the “intrinsic” (i.e. representative of the mass distribution) value in star forming galaxies, as star formation takes place preferentially in the disk.

3. Results

The B/T–radius relation for the cluster sample is shown in the top panel of Figure 1. The fraction of field galaxies in each B/T class is shown at $R/R_{200} = 10$, strictly for display purposes. The radial bin sizes are equal in logarithmic intervals, except for the innermost bin, which represents all galaxies at $R < 0.16R_{200}$. The fraction of disk dominated galaxies, $f_D(r)$, decreases fairly steadily toward the center of the cluster, as expected, from about 70% in the field to 30% in the cluster center. The radial gradients of the B and Int populations ($f_B(r)$, $f_{int}(r)$) are nearly identical, and their proportions increase by about 15% between the outer and central cluster regions. The bottom panel of Figure 1 shows the mean $W_\alpha(OII)$ for galaxies in each B/T class as a function of radius. The field value, again shown at $R/R_{200} = 10$, for galaxies of class B, Int, and D is $\overline{W_\alpha(OII)}_B = 5.1 \pm 0.6$ Å, $\overline{W_\alpha(OII)}_{int} = 2.1 \pm 0.9$ Å, and $\overline{W_\alpha(OII)}_D = 15.8 \pm 0.3$ Å respectively. The non–
Fig. 1.— The top panel shows the fraction of galaxies in each B/T class as a function of cluster-centric radius. Open squares, connected by the solid line, represent the D class ($B/T < 0.4$). The solid squares (dotted line) represent the B class ($B/T > 0.7$), and the triangles (dashed line) the Int class. The field values are plotted at $R/R_{200} = 10$ for display purposes only. Shown in the bottom panel is the weighted observed $W_0(OII)$ for each class of galaxy as a function of radius, with the field values again plotted at $R/R_{200} = 10$.

Zero $W_0(OII)$ for the B class is significant at the 3σ level, and many B galaxies have quite strong emission lines (10% have $W_0(OII) > 14.0 \text{ Å}$). Thus, signs of significant star formation are found in galaxies with little or no disk component, though this may partly reflect the uncertainty in B/T. Within the cluster the $W_0(OII)$ for B and Int class galaxies is consistent with zero, and there is little variation with radius. The $W_0(OII)$ of D galaxies is only consistent with the field at $2R_{200}$; at smaller radii it is always less than the field value by at least 10 Å. The value of $W_0(OII)$ depends not only on the B/T parameter, but also on the environment, in the sense that it is lower for galaxies in clusters than for galaxies with the same B/T ratio in the field.

The actual SFR of a galaxy is directly related to the luminosity of the [OII] emission line (Gallagher et al. 1989; Kennicutt 1992; Barbaro & Poggianti 1997), although the constant of proportionality is somewhat uncertain. The relation proposed by Barbaro & Poggianti (1997) will be used here, but since the present concern is the relative SFR of cluster and field galaxies, the constant of proportionality is unimportant. The luminosity of the [OII] line is calculated from the equivalent width and the galaxy’s rest frame B magnitude following Kennicutt’s (1992) relation, with the suggested extinction at Hα of 1 magnitude. The mean SFR for field galaxies in each B/T class is $SFR_B = 0.14 \pm 0.02$, $SFR_{Int} = 0.10 \pm 0.02$ and $SFR_D = 0.52 \pm 0.02$, in units of $h^{-2} M_\odot \text{ yr}^{-1}$. If cluster galaxies of a given B/T type had identical SFRs to corresponding field galaxies, then the mean cluster SFR at radius $r$ could be determined from the relation $SFR(r) = f_B(r) \times SFR_B + f_{Int}(r) \times SFR_{Int} + f_D(r) \times SFR_D$. This “predicted” relation is shown as the solid line in Figure 2. The error bars displayed include both the error in the SFR values of each B/T class, and the uncertainty in the population fractions in each radial bin. The observed SFR is shown as the dotted line; it varies by $0.2h^{-2} M_\odot \text{ yr}^{-1}$ over the observed radial range, but for $R < R_{200}$ it is always less than the field value (corrected for the B/T-radius relation) by more than $3\sigma$. At $2R_{200}$ the cluster galaxies still have lower star formation by more than a factor of two, although the difference is only significant at the $1.9 \sigma$ level. This suggests that large changes in SFR may occur well outside the virial radius.
Fig. 2.— The weighted observed SFR (dotted line, open symbols) as a function of radius. The field value is represented as the large star at $R/R_{200} = 10$. The solid points (connected by the solid line) represent the SFR that would be observed at each radius if the SFR of galaxies in the B, Int and D classes was equal to its corresponding value in the field, $SFR_B = 0.14 \pm 0.02$, $SFR_{int} = 0.10 \pm 0.02$ and $SFR_D = 0.52 \pm 0.02$, in units of $h^{-2}M_\odot yr^{-1}$. (see §3 for details).

4. Discussion

It was shown in Balogh et al. (1997) that, on average, cluster galaxies have less star formation than field galaxies, and that there is no evidence for ongoing star formation in excess of the field at any radius. Figures 1 and 2 show that this result cannot be accounted for by assuming a universal dependence of SFR on B/T. The B/T measure, however, is not sufficient to characterize a galaxy’s physical structure, as there is a large range of physical bulge and disk sizes for a given B/T. To account for a dependence of $W_\odot(OII)$ on galaxy size, cluster galaxies are compared with an analogous field sample in the following manner. For every class D cluster galaxy, a corresponding field galaxy is found which has a similar redshift, B/T, and disk scale length. Only those galaxies for which a match exists are considered. Thus, a cluster and matched field sample are chosen such that the only significant difference in the selection of the two samples is the global environment of the galaxies. The $W_\odot(OII)$ distributions of the cluster and matching field disk sample are shown in the top panel of Figure 3.

A similar procedure is followed for the B class galaxies, where the field galaxies are chosen to match the cluster sample in redshift, B/T and physical bulge size; these distributions are shown in the bottom panel. For both B and D objects, the hypothesis that the cluster and field distributions of $W_\odot(OII)$ are drawn from the same population is rejected with more than 99% significance by a standard Kolmogorov–Smirnov test. For the B galaxies, the difference is due to an excess of field galaxies with weak emission lines ($W_\odot(OII) < 10 \AA$) relative to the cluster; few galaxies are seen in either the cluster or field with stronger lines. The D galaxies, on the other hand, show a significant excess of emission lines of all strengths in the field, relative to the cluster. In the mean, galaxies in clusters have lower SFRs than galaxies in the field, independent of their B/T ratio or physical size.

Figure 2 indicates that the mean star formation rate in cluster galaxies is still lower than that in the field around $2R_{200}$, which is approximately the virial radius in an $\Omega = 0.2$ universe. If cluster galaxies have undergone strong bursts of star formation in the past 1–2 Gyr, as suggested by several authors (e.g., Couch & Sharples 1987; Moss & Whittle 1993; Barger et al. 1996; Caldwell et al. 1996; Koo et al. 1997; Couch et al. 1998), then the elusive population of starburst-
ing galaxies may be present beyond this radius. Ram pressure or tidal stripping may still be viable mechanisms for reducing the star formation in these galaxies without a burst if they have already passed through the cluster center at least once, a scenario for which there is some support (Ghigna et al. 1998; Ramirez & de Souza).

Alternatively, the star formation properties of galaxies may have been altered before they became bound to the cluster. In particular, Hashimoto et al. (1997) and Couch et al. (1997) suggest that galaxy–galaxy interactions and mergers are responsible for inducing starbursts in lower density environments. Such interactions would be favored in galaxy groups, which have relatively low velocity dispersions. In the hierarchical model of structure formation, groups will merge to form clusters, and it may be that the reduced star formation observed among some cluster galaxies today is the result of their previous existence in a group environment. In this case, the population of strongly star forming galaxies may be found in such groups, and not within clusters at all.

5. Summary

The result of Balogh et al. (1997), that current star formation among cluster galaxies is suppressed relative to an identically selected field sample, is not simply a reflection of a different morphological composition of the two populations. Although the fraction of galaxies with a significant disk component decreases from about 70% in the field to 30% in the cluster center, the SFR of cluster galaxies is much less than can be explained by this correlation alone, significant at more than the 3σ level. Cluster galaxies have less star formation than field galaxies of similar physical size, fractional bulge luminosity and redshift. Even at the virial radius, around 2 $R_{200}$, the amount of star formation in cluster galaxies is less than that in the field, which suggests either that the global environment is affecting galaxy star formation at or beyond this radius (or within a group environment), or that a significant number of cluster galaxies near the virial radius have already passed through or near the cluster interior.

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