THE INFLUENCE OF ENVIRONMENT ON THE STAR FORMATION RATES OF GALAXIES

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ABSTRACT

We have used a sample of 15,749 galaxies taken from the Las Campanas Redshift Survey to investigate the effects of environment on the rate of star formation in galaxies. For each galaxy, we derive a measure of the star formation rate (SFR) based on the strength of the $\text{[O II]}$ emission line and a measure of galactic structure based on the central concentration of the galaxy’s light, which is used to decouple the effect of “morphology-environment” relation from the SFR. Galactic environment is characterized both by the three-space local density of galaxies and by membership in groups and clusters. The size and homogeneity of this data set allows us to sample, for the first time, the entire range of galactic environments, from the lowest density voids to the richest clusters, in a uniform manner. Thus, we could expand our research from the conventional cluster versus field comparison to a new “general” environmental investigation by decoupling the local galaxy density from the membership in associations. This decoupling is crucial for constraining the physical processes responsible for the observed environmental dependencies of star formation. On the other hand, the use of an automatic measure of galactic structure (concentration index) rather than Hubble type, which is a subjective and star formation–contaminated estimate of galactic morphology, allows us to separate cleanly the morphological component from the SFR–environment relationship. We find that, when a cluster/field comparison is made, cluster galaxies exhibit reduced star formation for the same concentration index. This result supports several previous studies based on Hubble type reporting similar suppression of star formation among cluster galaxies for the same Hubble type. We did not find any qualitatively different responses to environments between early- and late-type spirals, which were also previously reported. On the other hand, a further division of clusters by “richness” reveals a new possible excitation of starbursts in groups and poor clusters. Meanwhile, a more general environmental investigation shows that the star formation rate of galaxies with a given concentration index is sensitive to local galaxy density and shows a continuous correlation with the local density, in such a way that galaxies show higher levels of star formation in lower density environments. Interestingly, this trend is also observed both inside and outside of clusters, implying that physical processes responsible for this correlation might not operate intrinsically in the cluster environment. Furthermore, a more complex facet of the dependence of SFR on local density is also revealed; galaxies with differing levels of star formation appear to respond differently to the local density. Low levels of star formation, corresponding to those expected in normal members of the Hubble sequence, are more sensitive to environment inside than outside of clusters. In contrast, high levels of star formation, identified as “starbursts,” are at least as sensitive to local density in the field as in clusters. We conclude that at least two separate processes are responsible for the environmental sensitivity of the SFR and tentatively identify gas removal processes as responsible for the variation with density of the SFR of normal galaxies and galaxy–galaxy interactions as responsible for the prevalence of starbursts in intermediate density environments.

Subject headings: galaxies: clusters: general — galaxies: evolution — galaxies: interactions —
galaxies: starburst — galaxies: stellar content — galaxies: structure

1. INTRODUCTION

Many lines of evidence, accumulated over the past several decades, have made it abundantly clear that there has been substantial evolution of the properties and populations of galaxies during recent epochs ($z \leq 1.0$). Such evolution is seen both in clusters (Butcher & Oemler 1984; Dressler et al. 1994), in groups (Allington-Smith et al. 1993), and in the general “field” population (Lilly et al. 1996; Glazebrook et al. 1995). Although it is possible that some portion of the evolutionary changes observed are due to causes internal to the individual galaxies, there are reasons for suspecting that much of the evolution is driven by external forces in the galaxies’ environment.

Firstly, there is some evidence that suggests that the rate at which galaxies of a given type have evolved varies substantially with environment (Allington-Smith et al. 1993). Secondly, the profound changes in the global properties of galaxies that have occurred during recent epochs are difficult to understand using only the processes occurring within an undisturbed, isolated galaxy. Finally, the large
systematic variations in galaxy populations with environment require that environment affected the properties of galaxies no earlier than the epoch of their formation.

A number of modes of interaction of galaxies and their surroundings that can be expected to cause significant changes in the properties of galaxies over time are known, and at least some examples of such processes in action have been discovered in low- and intermediate-redshift galaxy populations. Among these processes are galaxy-galaxy mergers (see, e.g., Barnes & Hernquist 1991), tidal interactions between galaxies and surrounding masses (see, e.g., Byrd & Valtonen 1990), and gas phase interactions between the intragalactic and intergalactic media (see, e.g., Gunn & Gott 1972; van den Bergh 1976; Dressler & Gunn 1983). Unfortunately, however, easily one may enumerate processes to drive galaxy evolution, and however plausible such mechanisms may be, there exists little evidence demonstrating that any one of these processes is, in fact, responsible for driving galaxy evolution. Most of these processes act over an extended period of time, while observations of any population of galaxies give only a snapshot of one instant in its history. Also, observations at intermediate and high redshifts, which have provided most of the evidence for galaxy evolution, cannot easily provide the detailed information that is needed to elucidate subtle and complicated processes.

However, any means by which galaxies interact with their surroundings should operate today as well as at earlier times, and, therefore, observations of nearby populations should be an effective way of understanding them. In addition to direct evidence for the occurrence of interactions capable of driving galaxy evolution, the local universe holds clues about the nature of those phenomena in the form of variations of galaxy properties with environment, which must be the result of past interactions. The most well established of such variations is the morphology-density relation (Dressler 1980), which appears to hold not only in clusters, but also in the field (Bhavsar 1981; de Souza et al. 1982; Postman & Geller 1984; Giovanelli, Haynes, & Chincarini 1986; Tully 1988). However, another perhaps equally important clue for the understanding of the origin and the evolution of galaxies can be obtained by the study of the influence of environment on the star formation of galaxies, since star formation is both a fundamental galactic parameter and a driver of galaxy evolution.

There have been many studies investigating environmental influences on star formation. However, these previous studies have been limited to cluster versus field comparisons (or similar membership comparisons) that compare star formation in cluster galaxies to that in a field control sample. Unfortunately, these studies have produced conflicting results. Some have suggested a reduced star formation rate (SFR) in cluster galaxies with respect to field galaxies of the same morphological type (see, e.g., Gisler 1978; Kennicutt 1983; Dressler, Thompson, & Shectman 1985b). However, other studies suggest a similar or higher SFR in cluster spirals with respect to the field sample (see, e.g., Kennicutt, Bothun, & Schommer 1984; Gavazzi & Jaffe 1985). Others report qualitatively differential responses to environment between early- and late-type galaxies (see, e.g., Moss & Whittle 1993).

Some of the inconsistency between previous cluster/field studies can be traced to two facts. First, these studies use small samples for both cluster and field subsets (at most, on the order of 10^2 galaxies in each subset). With samples of this size, it is difficult to make a statistically sound comparison, particularly after binning galaxies by Hubble type. Also, the field samples are usually selected from existing bright galaxy catalogs or from “pencil beam” studies, which, despite a careful effort to select a fairly normal cross section of galaxies, may contain galaxies from a wide variety of environments. Thus “field” samples may contain galaxies within loose groups or on the periphery of clusters, galaxies that dilute the contrast with the cluster samples. Second, most of the previous cluster/field studies were forced to combine multiple data sets with heterogeneous characteristics, such as different Hubble classifications by different observers, varying image quality, different star formation measures with different sensitivities, and even different selection criteria for sample objects, all of which can cause spurious results.

It is clear that a new cluster/field comparison using a large number of galaxies studied in a consistent manner is very much needed. However, even a cluster versus field comparison free of these problems is not sufficient. The cluster/field studies (or any studies comparing subsets that are selected on the basis of membership in galaxy associations) have a fundamental limitation for understanding the mechanisms responsible for the environmental influences on star formation. In such studies, the inability to decouple very local environment, as characterized, for example, by local galaxy density, from more global environments, such as membership in a cluster, prevents us from differentiating between mechanisms specific to each of these classes of environment. The significance of the distinction between local and broader environments has been a matter of much contention in cluster studies (see, for example, Dressler 1980 vs. Whitmore & Gilmore 1991)

A further, equally serious, problem with previous studies comes from the nature of the Hubble type itself, which has been used for the normalization of star formation rates over the broad range of galaxy types. The Hubble type is determined by multiple characteristics of a galaxy, one being the resolution of spiral arms. However, the resolution of spiral arms is, in practice, determined largely by the star formation activity in the arms. Thus, systematic variations in the star formation rate may cause a systematic shift in the Hubble type. When Hubble type is used to normalize star formation rates, this shift results in a serious reduction in the sensitivity of the measurement of varying star formation rates. To avoid this, we need to characterize the galaxies not by Hubble type, but rather by a physical parameter that is more independent of star formation. (The problem of the Hubble system is further discussed in § 5.)

In this paper, we present our first attempt to answer questions about general environmental effects on the star-forming properties of galaxies in the local universe, taking advantage of the very large and homogeneous data set available from the Las Campanas Redshift Survey (LCRS: Shectman et al. 1996). This data set consists of a large number of galaxies inhabiting the entire range of galactic environments, from the sparsest field to the densest clusters, thus allowing us to study environmental variations without combing multiple data sets with inhomogeneous characteristics. Furthermore, we can also extend our research from the traditional cluster/field comparison to more “general” environmental study by, for the first time in investigations of star formation properties, decoupling the local galaxy
density from the membership in associations. Finally, to minimize the problems with the use of Hubble types mentioned above, we have used an automatically measured concentration index as a star formation baseline.

The outline of this paper is as follows. Section 2 briefly describes the data set used. In § 3 we describe the spectroscopic measures of star formation, and in § 4 we discuss the method of analysis. Results are in § 5.

2. DATA

Here we briefly describe our survey parameters; the reader is referred to Shectman et al. (1996) for further details. The LCRS consists of 26,418 galaxies, with a mean redshift $z = 0.1$ and a depth of about $z = 0.2$. The survey galaxies were selected, using isophotal and central magnitude criteria, from CCD-based photometry in a “hybrid” Kron-Cousin $R$-band. This photometry was obtained from driftscans on the Las Campanas 1 m Swope Telescope. The survey covers over 700 square degrees in six $1^\circ.5$ fields, each containing a maximum of 50 or 112 galaxies. The first 20% of the redshifts were obtained using a 50 object fiber-optic spectrograph. The nominal isophotal magnitude limits of the spectroscopic sample were $16.0 < R < 17.3$, and an additional central magnitude limit excluded the 20% of galaxies of lowest central surface brightnesses. The rest of the redshifts were obtained with a 112 object fiber system, with isophotal limits of $15.0 < R < 17.7$ and exclusion of the 5%–10% of galaxies with lowest central surface brightnesses. The shape of the luminosity function of the LCRS is consistent with that of other redshift surveys (Lin et al. 1996).

The spectra were obtained with the multifiber spectrograph and Reticon detector mounted on the du Pont 2.5 m telescope at Las Campanas Observatory. Each spectrum was flat fielded, wavelength calibrated, and sky subtracted. The spectra have a wavelength range of 3350–6750 Å, with a resolution of $\sim 5$ Å and a pixel scale of $\sim 3$ Å. The average signal-to-noise ratio in the continuum around the Balmer absorption lines is 8–9.

3. SPECTROSCOPIC MEASURES

In order to quantify the star formation properties of LCRS galaxies, we have measured the equivalent width (EW) of $[\text{O III}]$ $\lambda$3727, $[\text{O II}]$ $\lambda$5007, and $H\beta$ in LCRS spectra. Conventionally, $Hz$ has proved to be the best optical indicator of the massive star formation rate (see, e.g., Kennicutt 1983). However, $Hz$ is inaccessible in many of our spectroscopic samples because of the redshift range and spectral coverage of the survey. Several workers have used the EW of the $[\text{O III}]$ $\lambda$3727 doublet or of $H\beta$ as a star formation index for distant galaxies (see, e.g., Dressler & Gunn 1982; Dressler, Gunn, & Schneider 1985a; Peterson et al. 1986; Broadhurst, Ellis, & Shanks 1988; Lavery & Henry 1988; Colless et al. 1990). Gallagher, Bushouse, & Hunter (1989) have derived an approximate $[\text{O II}]$–versus–star formation rate (SFR) calibration from observations of $[\text{O II}]$ and $H\beta$ in nearby blue galaxies. A direct comparison to EW($Hz + N$ II) (Kennicutt 1992) showed that EW($H\beta$) and EW($O\ III$ $\lambda$5007) can serve as good substitutes for star-forming indicators in strong emission galaxies (those with EW($Hz + N$ II) $\geq 60$ Å, and EW($H\beta$) $\geq 5$ Å), while EW($O\ II$) is a good indicator of star formation for all emission strengths.

The equivalent widths are measured automatically by integrating the signal above or below the local continuum outward from the center of the line until reaching the continuum level. The local continuum is determined by fitting a third order polynomial over the 350 Å on either side of the line, excluding the line itself and nearby sky lines. The algorithm iterates the fitting 3 times while excluding the points outside $2 \sigma$ of the continuum. The equivalent width uncertainties are calculated using Poisson statistics, the local noise in the continuum, and standard propagation of errors. The mean errors in the measurements of EW($H\beta$), EW($O\ II$), and EW($O\ III$) are 1.8, 2.2, and 2.1 Å respectively. Those galaxies with continuum signal-to-noise ratios $(S/N) < 6$ within the 25 Å window centered on each line are excluded from the analysis. The number of galaxies remaining for EW measurements after this $S/N$ cut depends on the line measured; it is 18,875 for the $H\beta$ line, 16,377 for the $[O\ II]$ line, and 17,351 for the $[O\ III]$ line.

The fibers in the du Pont multiobject spectrograph subtend circles $3^\prime.5$ in diameter. For galaxies with recessional velocities between 15,000 and 40,000 km s$^{-1}$ (a velocity cut that was used for the analysis, as discussed below), this diameter corresponds to a projected circle of diameter $\sim 5$–10 kpc ($H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$, $q_0 = 0.5$). This is smaller than the total size of the typical galaxy but much larger than the nuclear regions and considerably larger than the bulges of all but the most bulge-dominated galaxies. The result of this undersampling of the disks will be a small systematic underestimate of star formation rates in the earliest spirals. However, such a systematic shift will have no affect on any of the analysis presented later in this paper.

4. ENVIRONMENTAL PARAMETERS

4.1. Local Galaxy Density

To characterize the environment of LCRS galaxies, we calculate the local galaxy density, $\rho$, around each of the 26,418 galaxies using a nearest-neighbor technique. For each galaxy, we take the local galaxy density to be

$$\rho = \frac{3}{4\pi D^3/3},$$

where $D$ is the three-dimensional redshift-space distance from the galaxy to its third nearest neighbor. Note that this measure of galaxy density uses a three-space distance to nearest neighbors. Since the radial component of this distance is derived from the galaxy’s redshift, the effect of the peculiar velocities will be to spread out the neighboring galaxies along the line of sight and thus to cause a systematic underestimate of the density in the densest regions. However, in even the densest regions of the LCRS sample, we calculate the underestimate of $\rho$ caused by the peculiar velocities to be typically less than $\sim 20\%$, which is smaller than the width of the bins of $\rho$ that we used for the analysis. Thus, the effect is negligible for the purpose of this study.

The effect of the variation of the survey selection function at different redshifts is removed by introducing a weight

$$w(z_i) = \frac{1}{S(z_i)}$$

for each galaxy $i$, where

[Note: The text continues with more detailed analysis and discussion.]
where \( M_1 \) and \( M_2 \) are the absolute magnitude limits in which we are interested and \( M_{\text{min}}(z_i) \) and \( M_{\text{abs}}(z_i) \) are the absolute magnitude limits, at the redshift of galaxy \( i \), corresponding to the apparent magnitude limits for the field containing galaxy \( i \). We describe the differential luminosity function \( \phi \) by a Schechter function with parameters \( \phi^* = 0.019 h^3 \text{ Mpc}^{-3}, M^*_i = -20.29 + 5 \log h, \) and \( \alpha = -0.70 \) (Lin et al. 1996), which we assume to be invariant with redshift.

In addition, another weight \( W_i \) is calculated for each galaxy \( i \) to take account of the field-to-field spectroscopic sampling variations. The spectroscopic completeness of a field decreases as the projected density of galaxies in the field increases, since each spectroscopic field is observed only once using a maximum of 50 or 112 fibers. Since galaxies in denser regions were selected randomly for spectroscopy from among all galaxies meeting the photometric criteria, this effect is corrected by setting \( W_i \) to be the inverse of the fraction of spectroscopically observed galaxies in the field containing galaxy \( i \). (Additionally, small effects from magnitude errors, apparent magnitude and surface brightness incompletenesses, and central surface brightness selection are also included in the calculated \( W_i \). Further detailed discussions of these weights and corrections are given in Lin et al. 1996.) Now, the corrected local galaxy density \( \rho \) around a galaxy \( i \) becomes

\[
\rho_i = \frac{\sum_{j=1}^{3} w(z_j) W_j}{4\pi D_i^2/3},
\]

where \( j \) represents the rank of the nearest neighbors from galaxy \( i \).

After removing objects too close to the LCRS survey spatial boundary, an additional conservative velocity boundary (from 15,000 to 40,000 km s\(^{-1}\)) was set in order to further minimize the uncertainties in the density estimate by allowing the use of only a relatively constant selection function. The number of galaxies remaining after the velocity and spatial boundary cuts is 10,536.

### 4.2. Membership

As a second environmental parameter, cluster or rich-group membership was determined for each galaxy in the LCRS. Cluster and rich group galaxies are defined by the three-dimensional “friends-of-friends” group identification algorithm (Huchra & Geller 1982). The algorithm finds all pairs within a projected separation \( D_L \) and within a line of sight velocity difference \( V_L \). Pairs with a member in common are linked into a single group. This linking makes the membership more sensitive to the environment of larger scale than the local density parameter defined in § 4.1. The selection parameters \( D_L \) and \( V_L \) are scaled to account for the magnitude limit of the LCRS survey and are defined as

\[
D_L = S_L D_0 \quad \text{and} \quad V_L = S_L V_0.
\]

Here the linking scale \( S_L \) is calculated as

\[
S_L = \left[ \frac{\rho'(d)}{\rho(d)} \right]^{1/3},
\]

where \( \rho'(d) \) is the galaxy number density, at the mean comoving distance \( d \) of the galaxy pair in question, for a homogeneous sample that has the same selection function as the LCRS. In other words, \( \rho'(d) \) is equivalent to the unnormalized galaxy selection function.

The distance \( d_f \) is the fiducial comoving distance at redshift \( z_f \) (we chose \( cz_f = 30,000 \text{ km s}^{-1} \)) at which we define \( D_0 \) and \( V_0 \). The density enhancement contour surrounding each group is related to \( D_0 \) by

\[
\frac{\Delta \rho}{\rho} = \frac{3}{4\pi D_0^2 \rho(d_f)} - 1.
\]

The values of \( D_0 \) (or \( \Delta \rho/\rho \)) and \( V_0 \) used are taken from the LCRS group catalog (Tucker 1994; Tucker et al. 1998) and are \( D_0 = 0.72 \text{ h}^{-1} \text{ Mpc} \) (or \( \Delta \rho/\rho = 80 \)) and \( V_0 = 500 \text{ km s}^{-1} \), which are determined by several semiquantitative constraints similar to those used in Huchra & Geller (1982), to avoid biasing the velocity dispersions of groups, and to optimize the number of interlopers.

### 5. Results

#### 5.1. Emission Properties of the Sample

Figure 1 presents the equivalent widths of \([\text{O II}] \lambda 3727\) and \(\text{H}\beta\) for 15,749 LCRS galaxies; emission is represented by positive values. The majority (13,951) of galaxies show negligible or weak emission, which we define to mean that \(\text{EW(}\text{O II}\text{)} < 20 \text{ \AA}\) and \(\text{EW(H}\beta) < 5 \text{ \AA}\). This is the range expected of normal galaxies of types E to Sc; &Kennicutt (1983) Romanishin (1990) have shown that such galaxies have \(\text{EW(}\text{H}\alpha + \text{N ii}\text{)} \leq 50 \text{ \AA}\), equivalent to \(\text{EW(}\text{O II}\text{)} \leq 20 \text{ \AA}\), assuming \(\text{EW(}\text{O II}\text{)} = 0.4 \text{ \text{EW(H}\alpha)} \) (Kennicutt 1992). However, a rather significant fraction (17/98 or \(> 10\% \)) of galaxies show strong \([\text{O II}]\) or \(\text{H}\beta\) emission \([\text{EW(}\text{O II}\text{)} \geq 20 \text{ \AA}\) or \(\text{EW(H}\beta) \geq 5 \text{ \AA}\)], with a pattern of line strengths consistent with strong star formation activity. A typical spectrum of a strong star-forming galaxy is shown in Figure 2a. It shows strong \([\text{O II}]\), \([\text{O III}]\), and Balmer emission lines but weak or undetectable \([\text{Ne v}]\) lines.

There is a small, fairly distinctive population (\(\sim 30\)) of galaxies with \([\text{O II}]\) emission that are weak compared to the strength of \(\text{H}\beta\); typically these have \(\text{EW(H}\beta) \approx 20 \text{ \AA}\) and \(\text{EW(}\text{O II}\text{)} < 10 \text{ \AA}\). An example of such a spectrum is presented in Figure 2b. These galaxies show strong broad Balmer emission lines, strong \([\text{O III}]\) emission, but weak emission in \([\text{O II}]\); most are Seyfert 1 galaxies (Kennicutt 1992).

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**Fig. 1.—**Distribution of equivalent widths of 15,749 LCRS galaxies in the \([\text{O II}] \lambda 3727\) versus \(\text{H}\beta\) plane, where the emission is represented by positive values.
galaxies are members of interacting systems (see, e.g., Heidmann & Kalloghlian 1973; Wasilewski 1983) and therefore that interactions of galaxies are one of the important triggering mechanisms for starbursts. If this is correct, and if starbursts predominate in the SEM class, the variation with environment of the fraction of SEM galaxies may reflect environmental variations in galaxy interaction rates.

5.1.2. AGNs

Using EW(O III) as an indicator of the SFR fails for galaxies with luminous active nuclei (AGNs; Kennicutt 1992). Thus, excluding AGNs is desirable, even if the total number of AGNs is minimal, particularly if AGN activity has a different dependence on environment than does star formation activity. AGN galaxies fall into two classes, those with abnormally strong [O III] emission, independent of Balmer line strength, and those with strong Balmer and [O III] emission but weak emission in [O II]. The former most often are Seyfert 2's or LINERs, and the latter tend to be Seyfert 1's, though there are exceptions to this rule (Kennicutt 1992).

Seyfert 1 galaxies are relatively easy to identify. With their weaker [O II] emission with respect to the Hβ emission and their broad Balmer lines, Seyfert 1 galaxies are a distinctive population among emission galaxies in the EW(O II) versus EW(Hβ) plane. We exclude 33 galaxies from the sample with EW(Hβ) ≥ 7 Å and EW(O II) ≤ 15 Å, all of which show broad Balmer emission lines. Identifying Seyfert 2's or LINERs is somewhat less reliable using the EW(O II) versus EW(Hβ) plane alone, without access to the Hα line. We did our best by additionally using EW(O III) and EW(Ne v λ3425) to exclude a larger subset of 45 galaxies that includes Seyfert 2/LINER galaxies but that also probably includes some non-AGNs, using the criteria EW(O III)/EW(Hβ) ≥ 2 or EW(Ne v λ3425) ≥ 7 Å.

5.2. Morphology

The goal of this paper is to investigate how star formation rates within galaxies vary with environment. However, the star formation rate in galaxies, in the weak star formation regime in particular, is generally correlated with their morphological type (Kennicutt & Kent 1983). Moreover, the distribution of morphological type itself is a function of environment (Dressler 1980). Thus, comparison of star formation rates among environmental subsets needs to account for any differences in the morphological distribution among the galaxy subsets.

Our task is, however, complicated by the fact that the star formation rate is one of the parameters that define the morphological type. In the Hubble System (Sandage 1961), morphological type is based on three characteristics: bulge-to-disk ratio (B/D), tightness of spiral arms, and the degree of resolution of spiral arms. It is widely believed that the tightness of spiral arms is related to the mass distribution within a galaxy and therefore to B/D. The degree of resolution of spiral arms is, on the other hand, strongly affected, even defined, by the star formation activity in the arms. Thus, two (rather than one) physical parameters, star formation rate and mass distribution, map into three parameters characterizing the Hubble System, and this star formation dependency of the Hubble System complicates our analysis.

The reason is straightforward to understand. If a particular environment reduces the SFR in a galaxy, this decrease
in SFR will shift its Hubble type toward an earlier type. Because the galaxy appears with an earlier Hubble type, we will expect a lower SFR and therefore underestimate the amount by which star formation has been diminished. The result is a lowered sensitivity to environmental changes in SFR. Van den Bergh (1976), who introduced the term “anemic” to refer to galaxies with weak star formation, in a way recognized this dangerous star formation dependence of the Hubble type. However, the better cure is using a measure of galaxy morphology that is independent of SFR. From the earlier discussion of the Hubble sequence, it is clear that the natural candidate is mass distribution, but that can be determined only from rotation curves and is, therefore, an impractical measure for any large sample of galaxies. A more practical measure is the light distribution.

We quantify the light distribution of the LCRS galaxies using the automatically determined concentration index \( C \) (Okamura, Kodaira, & Watanabe 1983; Doi, Fukugita, & Okamura 1993; Abraham et al. 1994), which measures the intensity-weighted second moment of the galaxies and compares the flux between the inner \((r < 0.3)\) and outer \((r < 1)\) isophote to indicate the degree of light concentration in the galaxy images. Here \( r \) is a normalized radius that is constant on an elliptical isophote and is normalized in such a way that \( r = \) unity when the area within the ellipse is equal to the detection area of a galaxy. (For further details of the definition, please see Abraham et al. 1994.)

The concentration index \( C \) has been developed as a substitute for Hubble type; however, we stress that \( C \) actually has a significant advantage over Hubble type for investigations of star formation. In other words, it is as a purer measure of one of the two physical parameters determining the Hubble type that we make use of it. Concentration not only suits our needs better than Hubble type, but it is also more robust against image degradation and easier to be measured automatically. It is thus ideal for a large galaxy survey, such as the LCRS, where the sample size is \( \sim 10^4 \) and most of the galaxies consist of on the order of \( 10^2 \) resolution elements. (Image parameters of LCRS galaxies are further discussed in Hashimoto, Oemler, & Tucker 1998.)

In Figure 3 we present the relation between \( C \) and mean \([\text{O II}]\) equivalent width of the galaxies in our sample. This figure shows a smooth increase in mean EW with decreasing \( C \) that parallels the relation between the Hubble type and EW(Ha) (see, e.g., Kennicutt & Kent 1983) or EW(O II) (Kennicutt 1992). This is the relationship that we shall use as a baseline for the comparison of the star formation rates. Figure 4 shows the distribution of \( C \) in each of the three emission classes. The distribution for the WEM class is more skewed toward late/irregular type galaxies (smaller \( C \)) than is that of the NEM class, as one would expect. The SEM class, on the other hand, shows a \( C \) distribution roughly identical to that of the WEM class, suggesting that the influence of mass distribution, or “galactic structure,” is minimal here. Thus, differences between the SEM and WEM classes must be due entirely to factors other than galactic structure.

### 5.3. Correlation with Local Density

#### 5.3.1. Density Effects in the Field

Figure 5 shows the SEM/WEM and WEM/NEM population ratios as a function of the local space density for the LCRS sample. Bars are root \( N \) error. The small difference in

![Fig. 3.—Relationship between the concentration index \( C \) (Abraham et al. 1994) and the mean equivalent width of \([\text{O II}]\) 3727 for 16,377 LCRS galaxies. It shows a smooth increase in the mean of EW with decreasing \( C \), which parallels the relation between the Hubble type and EW(Ha)(see, e.g., Kennicutt & Kent 1983) or EW(O II)(Kennicutt 1992)

![Fig. 4.—Distribution of the concentration index \( C \) in the three emission classes, as defined in § 5.1.1: SEM \([\text{EW(O ii)} \geq 20 \text{ \AA}]\), WEM \([5 \text{ \AA} \leq \text{EW(O ii)} < 20 \text{ \AA}]\), and NEM \([\text{EW(O ii)} < 5 \text{ \AA}]\)
However, to ensure that we have no EW biases with respect to redshift, we further remove any difference in the distributions of absolute \( R \) magnitudes between SEM and WEM, or between WEM and NEM, by assigning additional weights to WEM or NEM galaxies until the shapes of their absolute magnitude distributions match that of SEM or WEM galaxies, respectively. (Hereafter, whenever the correction using \( C \) is applied, it is always accompanied by an additional absolute magnitude correction.)

Figure 5 shows the correlation between the local density and the population ratios of different emission types. Figure 5a shows the population ratio of the SEM to the WEM emission class versus the local galaxy space density (\( \rho \)), while Figure 5b shows the corresponding ratios of WEM to NEM galaxies. Both Figures 5a and 5b show a decrease in emission line strength as density increases, although the trend is stronger in Figure 5b.

Figure 5 includes both cluster and field galaxies. Since different processes may be operating, with different effects, inside and outside of clusters, it is necessary to examine each population separately. We define “cluster galaxies” by the method outlined in § 4. Meanwhile, galaxies outside clusters, hereafter “field galaxies,” are identified by removing cluster galaxies from the entire sample, except that this

time, a lower \( \Delta \rho / \rho = 40 \) contour is used to ensure that galaxies in the outskirts of clusters are excluded from the field sample. Note that the “field” galaxies do not necessarily consist entirely of so called “isolated” galaxies, those without any physical associations to which the galaxy belongs. Some of our field galaxies may be members of low-density associations, such as loose groups.

Figure 6 shows the population ratios similar with Figure 5, but now for the field sample alone. Overall, Figure 6 still shows qualitatively the same correlation as Figure 5, namely, that galaxies with higher emission tend to be more abundant in less dense environments. However, unlike Figure 5, the SEM/WEM comparison (Fig. 6a) shows a stronger correlation than the WEM/NEM one (Fig. 6b). In particular, in Figure 6b, the slope is rather flat compared to Figure 6a (and Fig. 5b), except for the lowest density regime. Meanwhile, Figure 6a shows a clear trend of stronger emission galaxies becoming more prevalent in less dense environments.

### 5.3.2. Density Effects in Clusters

Figure 7 shows the same relation as Figure 6 for the cluster and rich group (hereafter “cluster”) sample alone. Overall, again, Figure 7 shows a qualitatively similar correlation as that in Figure 6: galaxies with stronger emission lines prefer less dense environments. Figure 7a, however, is less conclusive because of the small number of emission line
5.4. Comparison between Clusters and Field

Figure 8 shows the distribution of $C$ for cluster and field galaxies. The solid line represents cluster galaxies, while the dot-dashed line represents galaxies in the field. The $C$ distribution of the cluster galaxies is skewed toward early type (larger $C$), consistent with the well-established trend toward systems with larger bulges inside clusters.

Figure 9 includes galaxies of all “structural” types. Since the processes leading to the cluster/field differences exhibited here might operate differently on different type galaxies, we split the sample into three $C$ subclasses. Figure 10 shows the same plot as Figure 9 for the three separate $C$ bins, $0.35 < C \leq 0.5, 0.25 < C \leq 0.35,$ and $0.1 < C \leq 0.25$. (The field/cluster $C$ correction is applied within each subclass.) Though the effect is somewhat weaker than in Figure 9, all three bins of Figure 10 still show the same trend, namely that field galaxies tend to show higher [O II] emission than cluster galaxies. K-S probabilities for the three bins are $3 \times 10^{-9}, 1 \times 10^{-14},$ and $4 \times 10^{-3}$, respectively. We do not, however, find any strong qualitative differences among the three $C$ bins.

A different look at the same trends is presented in Table 1, which lists the percentiles of the various emission classes in different environments. The emission classes are defined in the same way as in §5.1, except that the SEM class is further subdivided into a low subset (LSEM) and a high subset (HSEM) at the border $EW(O\ II) = 50 \ \text{Å}$. The $C$ corrections have not been applied in Table 1. Cluster and field...
definitions are the same as in § 4.2 and § 5.3. Additionally, rich and poor cluster subsets are introduced and defined by their total luminosities $L_T$, which have been calculated as described in Tucker (1994). Rich clusters are defined as clusters with $L_T \geq 5 \times 10^{11} L_\odot$, while poor clusters are clusters with $L_T \leq 0.5 \times 10^{11} L_\odot$. Also included in Table 1 are 1σ uncertainties, calculated from Poisson statistics. The numbers in parentheses are the total number of galaxies in each environmental class.

Table 2 repeats the analysis of Table 1, but with $C$ corrections. The corrections were made using the same method as in § 5.3, now applied to match the $C$ distributions of the field, rich cluster, and all-cluster samples to the $C$ distribution of the poor cluster class. Although there are small differences between the numbers in the two tables, the same trends are apparent. As was evident from Figures 9 and 10, star formation rates are higher in the field than in clusters.

TABLE 1

| Class | Field (6051) | Cluster Poor (346) | Cluster All (3825) | Cluster Rich (394) |
|-------|-------------|-------------------|-------------------|-------------------|
| NEM   | 56.8 ± 0.6  | 43.6 ± 2.7        | 68.7 ± 0.8        | 80.5 ± 2.0        |
| WEM   | 33.1 ± 0.6  | 39.6 ± 2.6        | 24.6 ± 0.7        | 17.6 ± 1.9        |
| LSEM  | 9.1 ± 0.3   | 13.8 ± 1.8        | 5.9 ± 0.3         | 1.5 ± 0.6         |
| HSEM  | 0.9 ± 0.1   | 3.0 ± 0.8         | 0.8 ± 0.1         | 0.4 ± 0.3         |

Note.—See text for explanation of classes. Numbers in parentheses are numbers of galaxies in each category.

However, dividing clusters into rich and poor systems reveals some remarkable complexities underlying this general trend. Rich clusters show a somewhat depressed level of "normal" star formation, as counted by the WEM fraction: a factor of 2 relative to field galaxies, and a factor of 1.4 when $C$ corrections are made. However, the frequency of starbursts, as counted by the LSEM and HSEM fractions, is depressed by much more, a factor of about 5 relative to the field.

Most remarkable are the percentiles in the poor clusters. Poor clusters show higher levels of star formation than even the field. This enhanced star formation is particularly evident at the highest star formation rates: the HSEM galaxies are almost 4 times more abundant in poor clusters than in any other population. A $\chi^2$ test shows that the proportions for the poor cluster galaxies and the field galaxies are significantly different at significance level $\alpha = 2 \times 10^{-4}$ for the HSEM class.

6. DISCUSSION

The results of this study can be summarized as follows:

1. The correlation between the two fundamental physical parameters underlying the Hubble sequence, the star formation rate and the bulge-to-disk ratio, varies with environment.

2. Cluster galaxies exhibit reduced star formation compared to the field control sample of the same concentration index, or "galactic structure." We did not find any qualitatively different responses to environments between early- and late-type spirals, differences which some previous researches reported.

3. The star formation rates of galaxies of a given "galactic structure" are sensitive to local galaxy density and show a continuous correlation with the local density, in such a way that galaxies show higher levels of star formation in low-density than in high-density environments. Remarkably, this trend is observed both inside and outside of clusters, implying that physical processes responsible to this correlation might not be intrinsic to cluster environments.

4. Among field populations, the abundance of strong emission line galaxies, or "starburst" galaxies, is more sensitive to local density than the abundance of weak emission line galaxies, i.e., "normal star formation" galaxies. Among cluster populations, the opposite is true.

5. While rich clusters show lower levels of "normal star formation" and much lower levels of "starbursts" than the field, poor clusters show enhanced levels of both. The starburst level in poor clusters is a factor of four higher than that in either the field or rich clusters.

Reviewing these results, one might be tempted to conclude that star formation rates are higher in low-density
than in high-density environments and that the field/cluster difference is simply a manifestation of the variation of SFR with local density. However, a comparison of Figures 7 and 6 shows that things are not this simple. At low levels of star formation, the SFR is quite sensitive to density inside clusters but only weakly dependent on density in the field. However, this is not the case for galaxies with high levels of star formation, which appear to be at least as sensitive to local density in the field as in clusters. Even this description is an oversimplification. Table 2 demonstrates that the variation of SFR with environment is not monotonic. The highest levels of star formation are more prevalent in the intermediate environment of poor clusters than in either the field or rich clusters.

It is clear from these, as well as many earlier findings, that environment has a profound effect not only on the structure but also on the star formation rates within galaxies. Popular ideas about the effect of environment on galactic star formation envision at least two kinds of processes at work: those that lower the gas content, and therefore the potential star formation rate in galaxies, and those that precipitate bursts of star formation. Among the former are interactions between the intragalactic and intergalactic media, including stripping and evaporation (Gunn & Gott 1972; Cowie & Songaila 1977), tidal interactions that remove gas from disks (see, e.g., Spitzer & Baade 1951; Valluri & Jog 1990), and the suppression of infall of new gas-rich material from outside the galaxy (Larson, Tinsley, & Caldwell 1980). Among the latter are tidal shocks (see,1980), ram pressure–induced star formation (Dressler & Gunn 1983), and mergers with other systems (see, e.g., Barnes & Hernquist 1991).

Our understanding of all these processes is incomplete, and their effects may be complex. Tidal encounters and galaxy “harassment” (Moore et al. 1996) might either enhance or depress average star formation rates. More generally, short-term increases in star formation rate will deplete the gas supply at a higher rate, leading, perhaps, to longer term decreases in star formation. Nevertheless, there are some generalizations that it is probably safe to make. Ram pressure and evaporative stripping of gas are processes that depend on a dense and/or hot intergalactic medium and therefore works well only in rich clusters. Mergers of gas-rich systems, which probably produce starbursts, depend on the galaxy-galaxy encounter rate. Encounters between galaxies will be more prevalent in denser and higher velocity dispersion environments, but such encounters will lead to mergers only if the relative velocities of the galaxies are comparable to or lower than the characteristic velocities within the galaxies.

One can combine these generalizations with our previous inferences that the WEM galaxies are undergoing “normal” star formation and the SEM galaxies are undergoing starbursts to produce a picture that is facile and oversimplified but may be basically true. This picture predicts that the WEM/NEM ratio, measuring normal star formation, should decline with density, particularly in rich clusters, which it does. It also predicts that the SEM fraction, measuring starbursts, should increase with density until the local velocity dispersion exceeds internal galaxy velocities, after which it should drop. As a result, groups and poor clusters should have the highest proportion of SEM galaxies, which they do.

This may be too easy a solution. A rough correspondence of expectations and observed trends does not prove that gas stripping and encounter-driven starbursts are responsible for the environmental effects on star formation rates that we observe. However, whatever the real processes at work, we can confidently conclude that they number at least two: one that suppresses star formation in clusters, and one that precipitates starbursts in intermediate density environments. Thus, one of the two fundamental galactic parameters, the star formation rate, is profoundly affected by galaxies’ environments. To what extent the other fundamental parameter, structure, is also a product of environment will be the subject of following papers.

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