Cosmic Evolution and Galaxy Formation: Structure, Interactions, and Feedback
ASP Conference Series, Vol. 3×10^8, *2000*
J. Franco, E. Terlevich, O. López-Cruz, and I. Aretxaga, eds.

Star Formation and Galaxy Environment

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Abstract. The dependence of star formation rate on galaxian environment is a key issue in the understanding of galaxy formation and evolution. However, the study of this subject is complex and observationally challenging. This paper reviews some of the current results, drawing mostly from recent large redshift surveys such the LCRS, the MORPH collaboration, and the CNOC1 and CNOC2 redshift surveys.

1. Introduction

Tremendous strides have been made in the last few years in understanding the average star formation history of the universe from the present to as far back as 90% of the age of the universe (e.g., Steidel et al. 1999, Sawicki et al. 1997). However, the overall picture remains crude, and is still subject to many uncertainties and systematics. Most of the advances have been based on converting the UV luminosity density in different epochs into an average star formation rate (SFR). This requires averaging over volume and extrapolating over luminosity. The universe contains significant large scale structures even at epochs as early as $z \sim 3$ (Giavalisco et al. 1998), as galaxies formed initially in the most massive dark matter halos. Voids, filaments, and rich clusters mark very different environments in which galaxies reside. To come to a full physical understanding of galaxy formation and galaxy evolution, we need to have a more detailed picture, such as the history of star formation in different environments. This is an observationally challenging task, as currently, we have barely begun to study these issues in the relatively nearby universe.

There are two major observational questions that we ultimately would like to answer. First, how does the SFR depend on the environment? Second, how does this dependence evolve with time? Currently we have some idea of the answers to the first question, and little or no information on the second. Simple physical arguments provide some expectations on the influence of environments on SFR; however, these are not always clear cut. Processes that lower gas content of a galaxy are expected to decrease SFR; these include, e.g., ram-pressure stripping and evaporation in rich environments; tidal stripping from close encounters of galaxies; and the decrease of the accretion rate of new gas into a galaxy in rich environments. On the other hand, similar processes can also serve to *increase* the SFR: e.g., ram-pressure and tidal shocks, and mergers and harassment of galaxies in close encounters.

To obtain definitive and quantitative conclusions, well-controlled, large samples (in the thousands) of galaxies with redshift, multi-color photometry, and spectroscopic information are required. (Perhaps large, robust photometric redshift samples can provide some needed advancement also.) Examples of completed redshift surveys that meet these goals include the LCRS (e.g., Shectman et al. 1996) for $z \sim 0.1$, the CNOC1 cluster redshift survey (Yee et al. 1996) with 2600 redshifts in fields of galaxy clusters at $0.17 < z < 0.55$, and the CNOC2 field galaxy redshift survey (Yee et al. 2000) with 6000 redshifts at $0.1 < z < 0.6$.

In this review, which is not intended to be complete, I will look at three issues. The first is the star formation–environment dependence in the local universe. We will then survey the current knowledge of differential cluster-field evolution, mostly by looking at galaxy populations in rich galaxy clusters at moderate redshifts. Finally some conjectures and remarks are made regarding the evolution of SFR and its environmental dependence.

2. The Local Universe

In the local universe the SFR-environment relationship, in the sense that SFR is apparently smaller on average in denser environments, is well known, if not well understood. Indirect evidence supporting this correlation comes from the combination of the morphology-density relation of galaxies (e.g., Dressler 1981) and the correlation between Hα or [OII] equivalent widths and morphological types (e.g., Kennicutt 1983). However, the question that may be more important to our understanding of SFR and environment is the more complex issue of whether similar galaxies in different environments have similar SFRs. The complexity arises not only from having to take galaxy morphology, which is observationally difficult to quantify, into consideration, but also that apparent morphological classification is inherently intertwined with star formation rate. The latter issue has not been seriously considered in any of the investigations discussed below. It is parenthetically noted that the best course for correcting for morphological distribution will likely require excellent IR band images where episodic star formation will not skew the morphological classification as much.

2.1. Results from the LCRS

The 26,000 redshift LCRS (Shectman et al. 1996) provides a local ($z \sim 0.1$) galaxy sample sufficiently large to examine the SFR in different environments. However, the lack of color data in the LCRS is a drawback. Hashimoto et al. (1998) studied the dependence of SFR on environment using [OII] strengths in the LCRS. They quantified the environment using a local galaxy density parameter and attempted to account for the morphological dependence by classifying galaxies with a concentration parameter. They further divided their galaxies into "cluster" and "field". They found that in general galaxies considered in "clusters" have lower SFR, and that within the two respective global environments galaxies in higher density regions have a lower emission line fraction, even when both results are corrected for the concentration parameter distribution.

Allam et al. (1999) used the same data set but defined the environment as compact and loose groups, and field. They found a somewhat inconclusive result that while the fraction of strong star bursts are higher in the field by a factor of 2 over that in compact clusters/groups, the distributions of the equivalent width of [OII] are similar in all three environments. This, they concluded, may indicate that galaxy morphology accounts for most of the differences in SFR.

3. Differential Cluster-Field Evolution

Galaxy clusters offered one of the first direct observations of galaxy evolution (Butcher & Oemler 1984), in that more distant clusters evidently have higher blue galaxy fractions. Most of what we now know regarding differential evolution of galaxies in different environments stems from comparing the field and relatively rich clusters at different redshifts, given that measuring galaxy environment is even more difficult in the more distant universe. Differential cluster-field evolution is an important piece in the puzzle of the dependence of SFR on environment. Such information is not only pertinent in our understanding of galaxy formation and evolution, but is also vital in cosmology, e.g., in the determination of Ω_m using Oort's method (e.g., Carlberg, Yee, & Ellingson 1997).

3.1. The Butcher-Oemler Effect

The Butcher-Oemler (B-O) effect was verified by the spectroscopic work of Dressler et al. (1992, and references therein). They also found a significant percentage of a new spectroscopic class of galaxies in these intermediate redshift clusters – E+A (or the more recent and appropriate name K+A), which can be interpreted as post-starburst galaxies. Zabludoff et al. (1996) searched for K+A galaxies in the LCRS sample. They concluded that at low redshift, unlike the result obtained by Dressler et al. for the higher-z B-O clusters, the fractions of K+A galaxies are similar in the field and clusters and at the less than 1% level.

High-resolution imaging from HST of the B-O clusters appears to show a preponderance of spiral galaxies, leading to the conclusion by Dressler et al. (1997) that the blue galaxies found in the B-O clusters likely turn into the population of S0 galaxies that dominate the centers of low-z clusters. However, the process by which this occurs is not certain.

3.2. Recent Large Spectroscopic Surveys: CNOC1 and MORPH

The CNOC1 redshift survey (Yee et al. 1996), a large spectroscopic survey of EMSS clusters with a redshift range of 0.17 to 0.55, provides one of the best and largest data sets to investigate the differential evolution of field and clusters of galaxies. The survey contains 2600 redshifts, of which 1300 are cluster galaxies. The survey is also unique in that it covers galaxies out to cluster-centric radii of well over 2 h^{-1} Mpc. The field galaxy component has been augmented significantly by the recent completion of the CNOC2 field galaxy redshift survey (Yee et al. 2000) which contains about 6000 redshifts. These two sets of data provide self-consistent comparisons of the stellar populations in the two environments.

The CNOC1 data set has been investigated using two complementary approaches. One is the classical method of measuring line strengths and indices. The results are presented in a series of papers by Abraham et al. (1998), Morris et al. (1999), and Balogh et al. (1999). The CNOC data allow one to make comparisons of the cluster and field populations at the *same* redshift. The main conclusion from these investigations is that there is no significant excess star formation or burst activity over that of field galaxies at similar redshifts, despite the presence of the B-O effect. It is shown that the [OII] equivalent width, W_0([OII]), which is used as an indicator of SFR, smoothly increases with cluster-centric radius to the value found in the field. There is no excess of either the average W_0([OII]), or the number of galaxies with large W_0([OII]), at radii as large as 2.5 h^{-1} Mpc. Balogh et al. (1999) also found that the fractions of K+A galaxies (defined by $W_0(\mathrm{H}\delta) > 5$Å, and W_0([OII]) < 5Å) in clusters and field at $z \sim 0.3$ are similar (at about 1 to 2%), and show only a small, but statistically insignificant, change from that measured in the local universe from the LCRS by Zabludoff et al. (1996). The CNOC1 results suggest that as field galaxies fall into a rich cluster, their star formation is truncated in gradual processes, and they then evolve passively to become members of the red galaxy population.

The CNOC1 results, however, are apparently discrepant with those obtained by the MORPH collaboration (Dressler et al. 1999; Poggianti et al. 1999). The MORPH collaboration found a much higher fraction of K+A and starburst (A+em) galaxies in clusters compared to the field. For example, with a definition of $W_0(\mathrm{H}\delta) > 3$Å for K+A galaxies, they found fractions of 21% and 6% for clusters and field, respectively. The discrepancy with CNOC1 results remains very large after adjusting for the different definitions. Balogh et al. (1999) provide an extensive discussion for possible explanations for the differences, which include galaxy and cluster sample selections and measurement methods.

3.3. Principle Component Analysis of the CNOC1 Sample

A new approach in studying the populations and star formation in galaxies is using the technique of Principle Component Analysis (PCA, e.g., Connolly et al. 1995), which allows one to derive the relative fraction of the stellar populations in galaxies without making discrete individual measurements such as line indices. Preliminary results from the CNOC1 survey are reported in Ellingson et al. (1999). Using the PCA method, we can deproject the stellar populations of cluster galaxies into three components: "cluster-like", "field-like", and "post-star-formation" (psf). From the combined data of 15 clusters, Ellingson et al. found that the cluster-like component shows a strong positive gradient towards the center, while the field-like component shows a strong negative gradient. Furthermore, the components match onto the field values at about $2.5r_{200}$ (where r_{200} is the radius at which the interior average mass density of the cluster is $200\rho_c$), or about 3 h^{-1} Mpc,

The PCA decomposition also shows that the field-like and psf components have a larger spatial extent than that of the cluster-like component. Separating the CNOC1 sample into a $z > 0.3$ (median z of 0.42) and $z < 0.3$ (median z of 0.23) sample, it is found that the higher z sample has a larger field-like fraction outside of the central 0.25 r_{200}. This is simply a restatement of the B-O effect, but now using the field galaxies at the redshifts of the clusters as fiducials. Ellingson et al. also computed the average luminosity profiles of the cluster-like and field-like components for clusters in the two redshift bins. The interesting result is that the red (i.e., cluster-like) component essentially has an identical profile in the two epochs, while the blue (i.e., field-like) component for the higher-z subsample shows a drop relative to the lower-z clusters while retaining a similar profile shape. This suggests that the B-O effect can be explained most simply by a change in the field galaxy infall rate over the redshift range, rather than a change in the physical processes of converting blue field galaxies into red galaxies over these time scales (although such explanations are not ruled out).

4. Groups, Pairs, and Poor Environments

The dependence of galaxy evolution as a function of environment other than in rich cluster is an observationally challenging subject of study, and currently we basically know very little in this area. The primary obstacle is the difficulty in defining the environment of a galaxy even at moderate redshifts; e.g., producing a well-understood sample of galaxy groups of different richness.

Allington-Smith et al. (1993) used radio galaxies as markers for galaxy groups and clusters of varying richness. They compared the blue-galaxy fraction (f_B) of 14 groups of varying richness at $z \sim 0.3$ with a larger sample of groups at $z \sim 0.05$ from the CfA redshift survey. For the CfA groups, it was found that f_B increases from less than ~ 0.05 for the rich groups to ~ 0.3 over a richness range of about 20. For the higher z groups, they concluded that, although f_B increases in general, the color-environment relationship seen in the CfA sample no longer exists. However, it appears that their conclusion was dependent on only two poor, but apparently red, groups in their high-z sample. One can just as easily conclude that, based on their Figure 19, the f_B-richness relation for their high-z sample is entirely consistent with that of their low-z sample (their Figure 16) shifted blueward by the same amount for all environments.

The CNOC2 Field Redshift Survey (Yee et al. 2000) is currently the largest redshift sample at the intermediate redshift range of ~ 0.35. An initial report on the evolution of the LF of the galaxy sample (as a whole) has been given in Lin et al. (1999). More detailed analyses of the evolution of galaxies are underway and it is expected to offer some rudimentary clues on the evolution of galaxies in different environments. Very preliminary indications are that the relative evolution of galaxies in different environments may not be drastically different, at least for the more luminous galaxies. This is supported by an analysis of close spectroscopic pairs (Patton et al. 2000, in preparation; Carlberg et al. 2000a), in which the derived merger rate show very little evolution up to redshift of 1 (as opposed to a number of earlier studies). Furthermore, there appears to be little or no evolution in the clustering length of luminous galaxies over this redshift range, leading Carlberg et al. (2000b) to conclude that the evolution of M^* galaxies seen over the intermediate redshift range is not driven by a change in environment. Also, a very preliminary analysis of the SFR (as indicated by the spectral energy distribution) of the CNOC2 sample as a function of local galaxy space density (as measured by the richness parameter B_{gc} [see Yee & López-Cruz 1999]) shows that the changes over redshift are similar over a span of a factor of 10 in richness.

5. Summary Remarks

The interplay between galaxian environment and star formation is clearly a key issue in the understanding of galaxy formation and evolution. It is also a difficult and complex problem and requires extensive observational resources to make definitive progress. There are clear indications of the effect of the environment when we compare extreme cases of the cores of rich clusters and the field. However, the environmental effect on the rate of galaxy evolution may be subtle, in that over a less extreme range definitive differences in relative evolution have not been observed conclusively. Some of the most intriguing and useful work in this area may come from the direct observations of the effects of a changing environment on star formation and galaxy evolution as found in the infalling galaxies at the outskirts of rich clusters. A thorough investigation of the phenomenon covering a large span of cluster-centric radius and over a range of redshift may provide a crucial piece of the puzzle. More detailed investigations into the star formation properties of galaxies in clusters, such as those carried out by Moss & Whittle (2000, in these proceedings) using Hα narrow-band imaging, has the possibility of providing physical details on how the star formation process is affected when a galaxy falls into a cluster.

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