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Star-forming Galaxies in Clusters

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Abstract

Clusters are laboratories for studying the influence of environment on the evolution of the stellar content and structure of galaxies. In this article I shift the emphasis away from present-day clusters, where star formation has nearly ceased, to consider earlier times when the major components of clusters—elliptical and S0 galaxies—were in formation, and when rapidly star-forming disk galaxies were still infalling. During three distinct epochs—the birth of the giant spheroids at $z \gtrsim 2$, the accretion of active spirals into clusters at $z \approx 1$, and the trickle of decaying spirals into present-epoch clusters—the mechanisms of environmental influence on galaxy evolution have been very different.

Both observation and theory seem to be converging on the idea that most of the stars in E and S0 galaxies are old and that—especially in rich clusters—their assembly into mature galaxies occurred early as well, at $z \gtrsim 2$. Because giant spirals are the last such systems to form, this chronology suggests that elliptical galaxies and giant bulges are not likely to be the result of mergers of mature spiral galaxies—the prevalent picture of the last two decades. Rather, they are products of a time when the conditions for star formation and the dynamical interactions among stellar systems were far different from those that characterize present-day mergers of giant spirals. Likewise, the considerable age of most S0 galaxies, and the fact that most appear in lower-density field environments, belies the notion that S0s are produced by ram pressure stripping in rich clusters, another standard interpretation of recent decades. Rather, new observations of intermediate-redshift clusters point to the importance of weak and strong interactions, mergers, and accretions—manifestations of the group-environment stage in cluster building—as principle drivers of the conversion of spiral to S0 galaxies. Both the quenching of star formation through the removal of gas reservoirs, and the exhaustion of disk gas through bursts of star formation are implicated as important mechanisms.

1.1 Introduction

As one of the organizers of this Symposium, I should not be puzzled by the title I was given for this invited paper. At the time, Gus, John, and I imagined that we were dividing up cluster-land into two areas: elliptical/spheroidal galaxies with the emphasis on age and metallicity—reviewed by Marijn Franx (2004)—and the star-forming galaxies, presumably those disk systems that are responsible for the Butcher-Oemler effect, to be reviewed by me. As the time for this Symposium grew near, however, I became increasingly confused about my topic. Looking for star formation in today's clusters is a little bit like searching for the last cashew in a picked-over nut-cup, while at intermediate redshift there is still insufficient high-quality data to settle some very basic disagreements about what is being observed.

This confusion reached a catastrophic level on day one of our conference when we were shown the spectacular *N*-body simulation by Springel & Hernquist (2003a) of a Coma-like cluster being assembled at high redshift. Watching the clock run as gigayears flew by, with a semi-analytic formulation providing an educated guess of how star formation might track the assembly of dark matter halos (Springel & Hernquist 2003b), I awoke to the obvious—how utterly epoch-dependent the question of "star formation in clusters" actually is. What we see in clusters today is a faint echo of what once was, and even at intermediate redshifts what we observe is often a frosting upon a well-aged, massive spheroidal component. Clearly, what distinguishes a cluster population from the galaxies in groups and the field is the preponderance of old spheroidal systems—ellipticals and bulges. Observations have long indicated that the heyday for their assembly was $z \gtrsim 2$, and now theory seems to be catching up, as the fidelity of the simulations and the precision of the cosmological model are substantially improved. Again, I refer to the results of Springel & Hernquist's *N*-body simulations that show that not only the birth of the stars, but also their assembly into large spheroidal systems, occurred—for the cluster environment—at a medium epoch of $z = 3$. (Indeed, in these simulations half of *all* star formation, over all environments, occurred before $z = 2$.)

Ultimately, then, the topic of "star-forming galaxies in clusters" has most meaning when we imagine a fireworks of star formation compressed in time and in space unlike anything we see today—when the ellipticals and the big bulged disk systems were assembled. From that time on, the history of star-forming galaxies in clusters has been, in comparison, a tame accretion of infalling star-forming galaxies growing the cluster, a pale glow compared to what went before, and, by today, barely a glow at all.

1.2 Connecting Star Formation History and Morphology in Cluster Galaxies

The history of star formation cannot be separated from that of structure and morphology. From the very first, in the classification scheme proposed by Hubble (1936; see also Sandage 1961, 1981; cf. de Vaucouleurs, de Vaucouleurs, & Corwin 1976; van den Bergh 1976), there was an implied relationship: Hubble believed that spheroidal systems were an early stage of evolution and that as galaxies aged they would acquire arms, turning last into spirals. This is the origin of the "early-type" and "late-type" labels that often accompany a discussion of the Hubble sequence.

Clusters of galaxies are often cited as laboratories in which to study the formation of the Hubble sequence (Dressler 1984), and much of the discussion about cluster populations focuses on star formation rates and the effect of environment. In what follows I will consider this connection through three distinct epochs: (1) $z \gtrsim 2$, the time of elliptical and large bulge formation; (2) $z \approx 0.5 - 1.0$, the time of rapid cluster building through the infall of disk galaxies; and (3) $z \approx 0$, the present epoch when clusters are, in comparison with galaxies in loose groups or the field, nearly empty of significant star formation. Many lines of evidence point to the fact that elliptical galaxies, and to some extent the spheroids of large-bulge disk galaxies, were formed in this earliest period (see Trager 2004; Treu 2004), and that this time of intense star formation is in fact the place to start when describing star formation in clusters, rather than the present epoch, when activity has been slowed to a trickle, or even 5 Gyr ago, when rich clusters still contained substantial populations of star-forming galaxies.

1.2.1 A Blend of Old and New Paradigms of Elliptical Formation

Eggen, Lynden-Bell, & Sandage's (1962) notion of a monolithic collapse of the Milky Way halo long predated any more general notions of how structure formed in the Universe. Rather, the idea followed closely from observations that the majority of Galactic halo stars are old, including those in globular clusters, and that they exhibit particular correlations between kinematics and metal abundance. Metal-poor stars were found to have highly elliptical orbits that would characterize a system forming in freefall, while more metal-rich systems, presumably formed later, had progressively more disk-like distributions and kinematics, suggesting increasing levels of dissipation. In a subsequent, more detailed study of the abundances and kinematics of halo objects, Searle & Zinn (1978) suggested that the collapse had been more lumpy than monolithic, with the evolution of individual clumps of stars and gas relatively isolated until late in the game. Although no elliptical galaxies are nearby enough to perform the kind of star-by-star analysis made for the Milky Way *, spectrophotometric observations in integrated light of their metal abundance and kinematics had been (through the 1980s) reasonably interpreted as suggesting that ellipticals are analogous to the Galaxy's spheroid and halo, that is, formed from an early and more-or-less coherent collapse of cooling gas leading to a rapid phase of star formation. Nevertheless, even rather large bulges such as the one of the Sombrero galaxy are much more likely to have sustained some star formation into the recent past (Trager 2004).

With the 1980s came the popularity of hierarchical model of structure formation (White & Negroponte 1982; Primack et al. 1984; Davis et al. 1985; Frenk et al. 1988). The success of the cold dark matter (CDM) model in accounting for a variety of features in the large-scale structure—on scales of groups of galaxies and larger—was strong inducement to apply its methodology to the much smaller scale of galaxy formation itself. From the beginning, however, numerical simulations faced two difficult problems that clearly limited the fidelity of the models: (1) insufficient dynamic range to cover sub-galaxy scales within an evolving larger-scale structure, and (2) lack of a convincing model of star formation that could be linked to the behavior of the dark matter. Today's simulations are finally overcoming the first limitation, with perhaps hundreds of individual mass points representing a galaxy in supercluster or larger simulations (see, e.g., Jenkins et al. 1998; Pearce et al. 2001; Mihos 2004). For the second—a more challenging problem—semi-analytic models (Lacey & Cole 1993, 1994; Kauffmann, White, & Guiderdoni 1993; Cole et al. 2000) appear at present to be the most successful approach, but even these are not without problems (Navarro, Frenk, & White 1995), and most would concede that there is a long way to go before such simulations have a true predictive power. (Indeed, the necessity of "tuning" the many adjustable parameters in order to match some characteristics of real galaxies may be more revealing of star formation process than galaxy formation.)

Perhaps the most striking "prediction" of numerical simulations, as early as the 1980s but much more developed in the 1990s, related to the birth of elliptical galaxies. Going all the way back before Baade's time, and certainly since Larson & Tinsley's (1978) use of Sandage & Visvanathan's (1978) photometry, observers had concluded that elliptical galaxies are the oldest galactic systems, much like globulars are the oldest star clusters. However, in 1972 Toomre & Toomre suggested that major mergers were a likely mechanism of constructing

* It is, however, becoming possible with the new generation of large telescopes to make detailed observations of globular clusters in elliptical galaxies in the Local Supercluster out to the Virgo cluster.

spheroidal systems out of disk galaxies, and the idea became very popular, one might say *the* paradigm, ever since (see, e.g., Barnes 1988, 1992; Schweizer & Seitzer 1992; Mihos & Hernquist 1994, 1996; Schweizer 2000; see also Mihos 2004). Since merging is fundamental to hierarchical clustering, it was natural for those performing CDM N-body simulations to embrace this idea (Negroponte & White 1983): through the 1990s such simulations consistently showed that large spheroidal systems such as elliptical galaxies were relatively late arrivals in the galactic zoo, and that they achieved both spheroidal structure and large masses through hierarchical merging. Although details depend on the cosmology and resolution of the model, the prediction was universal that most ellipticals had formed since $z < 2$, with a sizeable fraction since $z < 1$. This topic is also discussed in Treu's (2004) review.

This was especially troubling to observational astronomers studying the populations of rich clusters of galaxies, our topic here. Colors, spectra, and number density in clusters with increasing look-back time all seemed to point to an advanced age for ellipticals; besides, two-body mergers should be strongly suppressed in the high-speed encounters occurring in the rich cluster environment.* Regardless of expectations, the various attempts to place better constraints on the ages of cluster ellipticals consistently yielded a typical formation epoch of $z = 2 - 3$, if not for the structures of these ellipticals, at least for the stars now contained within them (Bower, Lucey, & Ellis 1992; Ellis et al. 1997; Bower, Kodama, & Terlevich 1998; Kuntschner & Davies 1998; Stanford, Eisenhardt, & Dickinson 1998; Trager et al. 2000; Kelson et al. 2001; Treu et al. 2002, and references therein for a discussion of constraints based on the fundamental plane; Davies 2004; Trager 2004).

Further evidence comes from the analysis of the chemical composition of elliptical galaxies, which show marked differences from what would be expected of the late merger of two typical (Sc) spirals (Trager et al. 2000; Kelson et al. 2004). In addition, the general similarity of field and cluster ellipticals discourages the notion that only cluster ellipticals are old, although it is clear that star formation has continued at some level in many field ellipticals to a relatively recent epoch (Faber et al. 1999).

Fortunately for the harmony of theorists and observers, this disagreement seems to be coming to an end, at least for cluster ellipticals. The new high-resolution N-body simulations, particularly those with the now-standard Λ cosmology, no longer predict that ellipticals in rich clusters are late-comers. Indeed, the simulations by Springel & Hernquist that we were shown in this Symposium predict an average stellar age of $z \approx 3$ for ellipticals in rich clusters, with an average "assembly age" of $z \approx 2$. To my knowledge, these predictions are consistent with the considerable body of observational data that have been collected. Most ellipticals are old, in composition *and* assembly, especially in clusters.

Quite at odds with this is the heavily cited case of MS 1054–03 at $z = 0.83$ (van Dokkum et al. 2000), which shows $\sim$10 major mergers of early-type, luminous galaxies. Particularly puzzling about this case is that most of the mergers are between systems that are already early-type rather than late-type, star-forming galaxies. I am not aware of any other high-redshift clusters that show this behavior; until there are more examples, it is not sensible to take this one case as confirmation of a picture that has so much other evidence stacked against it.

* It is now recognized, however, that many clusters show strong subclustering; as these subclusters merge to make a richer cluster, their lower velocity dispersions would be more favorable to mergers. Still, in the rich environments of these subgroups (velocity dispersions ~ 500 km s^{-1}), mergers are much less likely than in poor groups or the field.

I believe that it is important to draw an even stronger conclusion from the evolution of *N*-body simulations—the demise of the paradigm of elliptical formation by mergers of spiral galaxies, at least for cluster ellipticals. At the time the cluster ellipticals were formed in rich clusters, there were simply few if any spirals to merge! It is clear from *N*-body simulations, as well as observations of the high-z Universe (Driver et al. 1998; Dickinson 2000; Rodighiero et al. 2000), that large spiral galaxies as we know them today were very rare at $z > 2$, although recent work suggests that some do exist (Dawson et al. 2003; Labbe et al. 2003; Trujillo et al. 2004).

This would be especially true in the dense environment of a proto-rich-cluster, where galaxies had too little time to form large disks from the accretion of high-angular momentum material, and likely experienced a too-violent bumper-car ride as they traversed the cluster. True spirals, with their remarkedly thin disks, require a much longer formation time with few or no major disturbances (Toth & Ostriker 1992). Support for this is evident in the images from *HST*'s Medium Deep Survey and Deep Fields: beyond $z = 1$ the number density of large, well-formed spirals begins to rapidly diminish in favor a smaller, chaotically arranged systems. Spiral galaxies are the true late-comers in the galactic club.

So, if cluster ellipticals should not be thought of as the result of mergers of spiral galaxies, which did not even exist at the right time and place, how were cluster ellipticals born? No one can give a unambiguous answer to this yet, but the *N*-body simulations, particularly those that try to add the evolution of the gas component explicitly, should become better and better at developing the picture. My impression from looking at the Springel & Hernquist simulations is that, at the $z = 2-3$ epoch, in the densest regions where the cores of rich clusters were born, the component parts for making an elliptical were more globule-like than disk-like, i.e., high-density transition objects with masses between giant H II regions such as 30 Doradus (or M33's NGC 504) and the Large Magellanic Cloud itself. Their typical masses were 10^{7-9} $M_{\odot}$, with velocity dispersions of some tens of kilometers per second. In some ways, I imagine the development of these fragments of elliptical assembly to be a giant version of the Searle-Zinn components of the formation of our own halo. Perhaps this is why the monolithic collapse model, even in its naive form, was so successful in accounting for the Galactic data—the true situation might have been much more like a spherical collapse than a model where the pieces are large disks that have undergone considerable dissipation.

By focusing on cluster ellipticals, I have skidded past an important puzzle concerning this picture of elliptical formation. That is the existence of present-day mergers that first caught the Toomres' attention and have been the worthy subjects of so many studies since, none more notable or refined than those of my Carnegie colleague Francois Schweizer. Francois argues persuasively that most (all?) of the features of ellipticals, including the induced formation of a increased number of globular clusters, are generated in the merger of two late-type galaxies (Whitmore & Schweizer 1995; Schweizer et al. 1996). If this is true, does it mean that these two different modes of elliptical formation lead to the same animal? This is possible, of course, but uncomfortable.

Put another way, the characteristics of field ellipticals are somewhat different than their rich-cluster counterparts (somewhat younger with episodes of recent stars formation, for example, as discussed in Trager's 2004 review), but unless you look closely, your first impression is that field ellipticals and cluster ellipticals are the same beast. For this reason, it is less than satisfying to propose that cluster ellipticals formed in one way and field ellipticals in another. I have for a long time suspected that even field ellipticals—the vast majority of ellipticals altogether—formed in nearly the same way as cluster ellipticals, that is, they are the remnants of small-mass but high-density regions in the early Universe: the elliptical represents the final state of all the available baryonic matter in that region, just as in the cluster case, but with only enough matter to form only a few large galaxies. We will learn the answers to such questions when we know the space density, masses, and stellar compositions of ellipticals all the way back to this putative time of formation, $z = 2-3$. Already the results are intriguing, but they allow a wide range of interpretations (see, e.g., McCarthy et al. 2001; Daddi et al. 2002; Roche et al. 2002; Treu 2004). Our understanding of these issues should rapidly improve.

I have taken the position, then, that the paradigm for elliptical formation should not be the merger of typical disk galaxies, since for the most part these did not exist at the time most ellipticals were formed. The weak form of this proposition applies only to cluster ellipticals; the strong form applies to all. What, then, do I say to my colleague Francois, who presents me with persuasive evidence of spirals in the act of merging to make a spheroid? I do not know—maybe most of these will become early-type disk galaxies, S0 or Sa, or maybe the elliptical population includes both types, and they are difficult to distinguish. We might expect, however, that if this is true, the new generation of large telescopes with their integral field spectrographs and polychromatic imagers might be able to find differences between ellipticals formed at very different epochs and under very different conditions.

1.2.2 Star Formation and Morphology

If the previous discussion contains any truth about the mechanism by which ellipticals are formed, then it is striking how much of a role the initial conditions, rather than the later influence on a galaxy of its environment, play in the development of the Hubble sequence. Again, through the popularity of CDM models of structure formation, the emphasis has been on the influence of later environment. Consider three general descriptions of how the Hubble sequence came about:

(1) Galaxy type is mutable and transient, so that a galaxy could well appear as a spiral as one part of its life, become part of an elliptical sometime later, perhaps returning to a spiral after that (see, e.g., Baugh, Cole, & Frenk 1996). This view, which became popular during the 1990s as CDM *N*-body simulations became larger and more sophisticated, emphasizes the role of happenstance—chance encounters with other galaxies—in determining the Hubble type during the lifetime of the galaxy.

(2) Galaxy type evolves steadily in one direction or the other, as Hubble originally proposed. A modern-day example of this is the first attempt to link hierarchical clustering with galaxy morphology that I describe above, where it is thought that all galaxies started out as spirals but, over time, mergers built larger spheroidal components in many of them, in some destroying their disks altogether, evolution in the opposite direction than Hubble had imagined. Another example is the proposal by Zhang (1999), who has developed the idea that secular evolution, the disturbance of disks by gravitational encounters with other galaxies (not requiring actual mergers) forces a spiral galaxy to evolve steadily toward a more spheroidal structure with steadily declining star formation rates (as the disk becomes more gas depleted and more puffed up—less conducive to continued star formation as perturbations in the disk are damped.

(3) Galaxy type is destiny. The idea here is that the environment *at birth* and soon after will be the main determinant of Hubble type. Sandage, Freeman, & Stokes (1970) and Faber

> & Gallagher (1976) were the first to suggest that initial conditions alone might be largely responsible for the Hubble type each galaxy would eventually assume. The distribution of angular momentum of halos and its transfer and dissipation by baryons could have been the key factor. In relatively dense environments such as protoclusters, nondissipative mergers of subgalactic units would produce spheroidal systems at an early epoch (Larson 1975, 1976; Fall 1979; Fall & Efstathiou 1980). Large spirals, particularly those with modest spheroids—take the Milky Way (the "modal type" of giant galaxies)—would evolve in regions of low density where they can accrete high-angular momentum material from large distances. Of course, a certain amount of serendipity may influence a galaxy's morphological type; for example, the processes of (2) are capable of moving the Hubble type, perhaps substantially, but in (3) these are seen as second-order processes.

I believe there is much merit in (2) and (3), and little or none in (1). It is difficult to point to any standard Hubble types that look like they have been through back-and-forth transformations. Indeed, when a spheroidal system tries to recapture a disk, the result looks odd and forced—like a dog wearing shoes—and not likely to settle down into a normal spiral (see the Hubble Heritage image of NGC 4650A). For my tastes, (3) provides a better foundation for describing how the Hubble sequence has formed. This preference began with my 1980 study of the correlation of local density with morphology in rich clusters, a relation that has been shown to extend down to the very modest enhancements in density that are found in loose groups and the field (Postman & Geller 1984; Giovanelli, Haynes, & Chincarini 1986). You might think at first that a correlation with local density is direct evidence for late environmental effects; indeed, the studies of present-epoch clusters have always focused on the transformation of spiral to S0 galaxies through ram pressure stripping, a mechanism exclusively connected with rich clusters. What made me conclude the opposite—that the morphology-density relationship was evidence that the environment at and soon after the galaxy's birth played the major role—was the extremely weak dependence of type on local density. The fraction of spiral galaxies changes by a factor of 2 over a change of 100 in projected density, equivalent to a factor of 1000 in space density! How could the correlation of Hubble type be such a weak function of density? This would, however, make perfect sense if the probability for Hubble type was set early on when these density differences were much more subtle, before the larger-scale perturbations grew and amplified the density contrasts.

What put people off from this explanation, indeed, from any idea that local density (past or present) could influence Hubble type, was the notion that galaxies could not "know" what environments they would enhabit in the future, so that any gradients would be very hard to explain—that is, the effects would be washed out as galaxies left their birth environment or the local density peaks they enhabit today as compared to 5 Gyr ago. *N*-body simulations have clearly shown that this is not a concern: those particles that are born in overdense regions spend all of their lives in more-or-less dense environments, and those born in lower-density regions remain so, by and large. (This is in contrast to the case of violent relaxation of a "top hat" density distribution where the positions of infalling bodies are truly scrambled—but this is not the way the Universe is put together.) The environment and later-encounter experiences of a $10^{11}\ M_{\odot}$ bound mass will be very different depending on where it is born, and this, I think, is probably to be the major contributor to its future form and star formation history—not the only, but the major one. In a sense, it *is* the initial conditions that determine galaxy morphology, by predetermining the influences that galaxy will experience for the rest of its life.

1.3 Today: The Cold Ashes of Today's Clusters

In the context of the idea that the heyday of galaxy clusters is long past, I would like to briefly review some of the aspects of star formation in rich clusters in today's Universe. There is quite an interesting history of this [see Biviano's (2000) informative and entertaining review], which tells us that, before there were observations of any clusters at earlier epochs, many astronomers believed that spirals—star-forming galaxies—were completely absent from rich clusters. Abell (1962) was skeptical that there were any spirals in rich clusters—I remember a plot he produced of the distribution of spirals galaxies in the field of Coma that showed no obvious concentration at all toward the center as defined by early-type galaxies. In response, Rood et al. (1972) went to some trouble to attribute cluster membership, by means of radial velocities, to a number of spirals in the field of Coma. By 1974, Gus Oemler had made a convincing case for spiral membership in many clusters in his seminal study of cluster properties. Contrasting with Oemler's categorization of "spiral rich" and "spiral poor" clusters, Melnick & Sargent (1977) parameterized the spiral population of X-ray luminous clusters as a smoothly increasing function of distance from the cluster core.

Of course, as less extreme clusters came under study, for example, Hercules and Virgo, and with the recognition that rich clusters are embedded in spiral-rich superclusters (Gregory & Thompson 1978), it became apparent that spiral galaxies *are* members of rich clusters, albeit at a much reduced fraction than the field. Realizing that spiral galaxies must be infalling into rich clusters, and mindful of Baade & Spitzer's (1951) suggestion that spirals might be stripped of their gas—becoming S0s—by galaxy-galaxy collisions, Gunn & Gott (1972) proposed that ram pressure stripping would be an effective means of promoting conversion of spiral to S0 galaxies (see Balsara, Livio, & O'Dea 1994 and Quilis, Moore, & Bower 2000 for contemporary treatments). Removing disk gas would presumably end star formation, provided sufficient gas did not reaccumulate through further infall and the return of gas through stellar evolution. In the same year, substantial arguments were made by Rood et al. that most S0 galaxies in the Coma cluster, let alone the S0 galaxies in the field, were not likely to be the result of ram pressure stripping of typical spirals. Nevertheless, although many additional objections have been raised since (see Dressler 1984 for a review), the ram pressure stripping paradigm is still today the most-cited environmental mechanism for turning spiral galaxies into S0s.

In their classic work on the subject of H I deficiency in cluster spirals using the Arecibo telescope, Giovanelli & Haynes (1983) were careful not to draw "sweeping" conclusions about the ability of the cluster environment—specifically the hot, X-ray-emitting gas first seen so clearly in *Einstein* X-ray images (see the review by Forman & Jones 1982)—to affect transformation of galaxy morphological type. Nevertheless, they did find clear evidence that cluster spirals of given Hubble type are deficient in H I gas in comparison to their field counterparts, and that this deficiency correlates with cluster X-ray luminosity, which is in turn a sensitive probe of gas density. Their work (see Haynes, Giovanelli, & Chincarini 1984 for a review) confirmed the notion of "anemia" in star formation that van den Bergh had noted earlier (1976). I myself found a correlation of orbits with H I deficiency that bolstered the idea (Dressler 1986). These studies had no purchase on the colder molecular gas; subsequent work by Young & Scoville 1991) has shown that the higher-density gas of molecular clouds is usually confined to the inner few kiloparsecs of a spiral galaxy. Theoretical work suggests that this component is more difficult to strip (Kundić, Spergel, & Hernquist 1993; Quilis et al. 2000).

In recent years, Jacqueline van Gorkom (1996, 2004) has made beautifully detailed, spatially resolved H I maps with the VLA that show how H I disks in spirals galaxies shrink systematically with proximity to the cluster center—clearly, the effect on the galaxy's interstellar medium can be substantial. If these galaxies had survived as normal, vigorous spirals until their plunge into the center, this might be evidence that at least *some* spirals were doomed to S0-dom by the stripping of their gas. My colleagues and I—the Morphs—believe that our observations of intermediate-redshift galaxies suggest that most of the damage has already been done on the way in, that the ram pressure stripping that occurs is a shot to the heart of a galaxy that was about beaten to death—already.

The modern work by Solanes et al. (2001) has further strengthened the case that the high-density environment, plausibly the hot plasma itself, has extracted a penalty from all spirals that make it close to the center of a cluster. The trends are clear, but remarkably weak, and the effect is really only seen in the inner 1 Mpc (see, e.g., Fig. 4 of Solanes et al.). Given that gas density rises so rapidly in cluster centers, and the fact that the orbits of these infalling galaxies, which originate far from the cluster core, cannot be purely radial, there seems to be little chance that many spiral galaxies in full flower could suffer a violent stripping of their gas that could turn them into S0 galaxies.

Adding to this circumstantial evidence of H I deficiency is "smoking gun" evidence that ram pressure stripping certainly is at work (see, e.g., Irwin et al. 1987; Kenney & Koopmann 1999); however, there is no real evidence that this has much to do with the prevalence of S0 galaxies in clusters (Abadi, Moore, & Bower 1999). Although Quilis et al. claim to demonstrate that ram pressure stripping is sufficient to completely remove the H I gas from a cluster spiral, they do not consider how often spirals reach the high-density core where such thorough stripping can occur. Furthermore, as I discuss in the next section, it is clear from the work on intermediate-redshift clusters that the effect of environment on an infalling spirals manifests itself far out in the cluster, at much lower gas densities than those at which ram pressure stripping is effective. Furthermore, ram pressure stripping is far less effective in poorer clusters such as Virgo, yet S0s are common even in these clusters. Finally, as Quilis et al. concede, the similarity of cluster and field S0 galaxies must be taken as a coincidence in this picture, since ram pressure stripping is of no consequence outside of rich cluster cores. Rather, it seems to me that the contribution to ram pressure stripping in producing S0 galaxies might be to hasten spirals to become and remain gas free in rich clusters, a nonunique, possibly redundant role. The power of the model was that it was supposed to explain the dearth of spirals and prevalence of S0 galaxies in rich clusters: there seems to me to be no evidence that is even persuasive, let alone compelling, that ram pressure stripping is the principle explanation of this phenomenon.

Star formation in rich clusters *today* is, then, a pretty sad affair. Infall is low and rapidly diminishing, if you believe we live in a Λ-dominated Universe. Spirals themselves are "running down" compared to half-a-Hubble time ago. The spirals that will be drawn into rich clusters in the future will die the death of a thousand cuts—in the rich group environment into which they have for so long been entrained, they are likely already to have had their fates sealed long ago.

1.4 5 Gyr Ago: Flameouts of Dying Galaxies

Against this bleak backdrop, it is perhaps easier to appreciate the surprise (and disbelief) that accompanied Butcher & Oemler's (1978a, b) discovery of a population of blue galaxies in rich clusters at $z \approx 0.5$. Presciently, they suggested that these were actively star-forming *spiral* galaxies (without benefit of morphological information), which were joining an already ancient population of elliptical and S0 galaxies. If spirals are so effectively extinguished in clusters today, why were they not in clusters 5 Gyr ago? This puzzle was itself projected against a dominant view in the late 1970s that the basic characteristics of galaxies were set long ago, well before this "late" 5 Gyr-ago epoch.

Indeed, there is general agreement that most clusters show a marked increase in the fraction of blue, star-forming galaxies by $z = 0.5$, but the question of "why" remains unanswered. An opposing view has been advanced by De Propris et al. (2003), who argue that K-band limited samples of distant clusters show little color evolution. We should not find that surprising, since selecting in the infrared is closer to a mass-limited sample, and, of course, giant elliptical and S0 galaxies dominate the bright end of cluster luminosity functions at $z = 0.5$ and today. But, this does not contradict observations that show clearly that—in contrast to today's clusters—L^* galaxies with strong star formation do appear in $z = 0.5$ clusters. But, are these M^* galaxies or, as De Propris et al. suggest, more dwarfish galaxies much inflamed. Mass-to-light ratios that come from optical colors suggest that this cannot be the case, but dust remains a troubling caveat. This question will be resolved soon with studies such as those of Metevier, Koo, & Simard (2002) and Ziegler et al. (2002), which use rotation curves to determine the mass of these systems—so far, the evidence suggests that these are massive systems. Undoubtedly related to this is Caldwell & Rose's (1997) finding of significant populations of star-forming *dwarf* galaxies in the outskirts of the Coma cluster; this suggests that the Butcher-Oemler effect can be seen as an evolution that depends on mass, in the sense that at higher redshift many luminous disk galaxies are still forming stars vigorously, while today this activity persists only for low-mass systems. Perhaps none of this seems surprising in light of hierarchical clustering, a different situation than in 1974. Nevertheless, the fact that does still need explaining is why this evolution is so rapid over the last 5 Gyr. I will come back to this.

There are five major groups working on intermediate-redshift cluster populations; their studies all include morphology with *HST*, photometry and spectroscopy with ground-based telescopes. Oemler, Poggianti, and I are the active members of the Morphs group at the moment, which has included Smail, Ellis, Couch, Butcher, and Sharples. A well-known study called CNOC1 was done by Yee, Ellingson, Morris, Carlberg, Balogh, and collaborators, and this group is continuing with new samples. The group of Franx, Illingworth, van Dokkum, Kelson, and collaborators has done only five clusters, but these cover the widest redshift range; the ACSCS group, Postman, Lubin, and Oke, has published results for two high-redshift clusters, with many more scheduled to be observed with *HST*+ACS. The newest entry, the EDisCS team of White, Aragón-Salamanca, Saglia, Dalcanton, Poggianti, and Kauffmann has a large amount of VLT time to study an optically selected sample of 10 clusters at $z \approx 0.4$ and 10 at $z \approx 0.8$. Put together, these account for a sample of perhaps 40 clusters of $0.3 < z < 1.0$, but for many of these the data are just being gathered. Except for the Morphs and EDisCS, X-ray luminosity has been the principal selection criteria of these samples (see Donahue et al. 2002 and Rosati 2004)—this results in a well-controlled, but strongly biased sample.

What have been the main results of morphological studies using *HST* images? For one, the Morphs group claims that the fractional population of S0 galaxies grow with time, from the epoch of $z = 0.5$ until today (Dressler et al. 1999). Fabricant, Franx, & van Dokkum (2000) are not so sure, and Andreon (1998) is *certain* the Morphs are wrong, but no more certain than I am that he is in error. Rather than restate the Morphs case (see Dressler et al. 1997), I will leave this subject by saying that with the new generation of large telescopes with multislit spectrographs, it will be straightforward to measure rotations of early-type galaxies to distinguish between ellipticals and S0s, the main point of contention and concern.

The second result is that those star-forming galaxies that are found in intermediate-redshift clusters are noted by all to be more irregular, distorted, or contorted versions of disk galaxies today (Oemler, Dressler, & Butcher 1997; Smail et al. 1998). It is very likely that environment has played a role in this: some may be mergers or accretion events, others may have been rocked by strong but temporary gravitational interactions. A complication of deciphering what exactly can be blamed on the cluster environment is that, in general, disk galaxies in the field at intermediate redshift also look more disheveled than today's examples (Griffiths et al. 1994; Driver, Windhorst, & Griffiths 1995), although it is difficult to be quantitative. Perhaps future kinematical studies with integral-field spectrographs on big telescopes will be able to distinguish true two-body mergers from other events.

As I have said, photometry leads all these groups to conclude that there is a Butcher-Oemler effect, with some disagreement about whether some clusters at intermediate redshift are immune. Spectroscopic results are more varied and interesting. The Franx et al. group has concentrated on spectroscopy of early types, both for studying the evolution of the fundamental plane (Kelson et al. 2000; see also Jørgensen et al. 1999), and—a related issue—evidence from spectral lines that stellar populations are different in early-type galaxies in intermediate-redshift clusters (Kelson et al. 2001).

Concerning the star-forming galaxies, CNOC1 and the Morphs have weighed in most heavily up until now, with somewhat different conclusions and emphasis. The Morphs group reports high fractions, $\sim$30%, of Balmer-strong galaxies, which they associate with starbursting or post-starburst systems (Dressler et al. 1999; Poggianti et al. 1999). Other groups see some of these but generally with lower frequency, sometimes significantly so. If the difference is real, there are many possible causes—X-ray versus optical selection, magnitude limits, quality of spectra—that have not been adequately investigated. Perhaps the dispersion in the frequency of Balmer-strong galaxies is larger than the Morphs group has found for their sample, and modulated by stages in cluster evolution.

I now return to the question of why these star-forming galaxies are seen in $z = 0.5$ clusters but rarely today. We now know that infall into clusters has begun to slow dramatically due to the effects of the acceleration of the Universe. We also know that the star formation rates of field spirals show a factor of several decline since $z = 1$ (Lilly et al. 1996). Do the combination of these two effects alone account for the factor of 10 decrease in star-forming galaxies in rich clusters in only 5 billion years?

To answer this question it will be necessary to finally determine which are the dominant mechanisms through which the cluster environment influences the evolution of spiral galaxies. Despite decades of work, there is no consensus on the importance of different effects. I have already discussed ram pressure stripping and made some arguments that suggest to me that this plays only a secondary role. Evaporative gas removal (Cowie & Songaila 1976; Nulsen 1982) is not usually cited as a possible mechanism for significantly altering the evolution of a spiral galaxy, but is probably an important cause of a variety of more subtle differences of galaxies in dense environments (Burstein & Blumenthal 2002). The hydrodynamics of cold gas clouds bathed in a much hotter gas is complex: contemporary studies benefit from the increased power of numerical simulations (see, e.g., Henser & Vieser 2002). A full understanding of the effects of the intracluster medium on infalling galaxies will certainly include both ram pressure stripping and the evaporative process.

In denser environments there are obviously more opportunities for mergers, accretions, and strong interactions, and therefore reason to suspect that these could be driving galaxy evolution in groups and clusters. If *N*-body simulations evolve to accurately track star formation, we might be in a good position to judge how important these events are. As I mentioned earlier, such processes should be particularly effective in the subclusters we expect to see in higher-redshift clusters, due to the lower *local* velocity dispersions in these yet-unrelaxed clusters. The "harassment" mechanism of Moore et al. (1996), which combines both global (galaxy-cluster) and local (galaxy-galaxy) tidal effects, and particularly includes the contribution of *rapid* encounters, predicts that infalling galaxies will be substantially whittled down—unfortunately, this does not seem to throw much light on the star-forming disk galaxies that are observed.

The "mechanism *du jour*" is starvation (or strangulation, if you prefer, which I do not), of Bekki, Couch, & Shioya (2002). This derives from Larson, Tinsley, & Caldwell's (1980) idea that, if galaxies are continually refueled by extended gas reservoirs, these would be easily stripped as the galaxy enters a dense environment, resulting in the choking off of subsequent star formation. I digress to mention that this mechanism, originally to account for the Butcher-Oemler effect, was also offered as a way around the observation that most spirals should run out of gas in less than a Hubble time at present gas-consumption rates of their disk gas. From today's perspective, this seems like *a fact* rather than something to find a way out of. Imagine the papers that must have been written 6 billion years ago when some creature realized that the (now) S0 galaxies could not sustain star formation at their present rates. Although no gas reservoirs of the kind proposed are known to exist, they might in fact be difficult to detect (Benson et al. 2000). The starvation mechanism might have particular importance in intermediate-redshift clusters where galaxies still have a "full tank" compared to today's infalling spirals.

The starvation mechanism, much in vogue, is particularly touted by the CNOC1 group, who believe that the decline in star formation rates (measured from [O II] line strengths) as star-forming galaxies fall into clusters can be completely understood as a result of such a starvation mechanism. Ellingson et al. (2001) have produced detailed models of the structural evolution of clusters that match the CNOC1 observations well. By considering the population fractions as a continuous function of radius, they are able to predict the star formation rates of succeeding generations of field galaxies as they "turn around" and migrate toward the cluster center. This is an important new direction for cluster studies in the future—to fully map the range of star formation histories with epoch and radial distance from the cluster center.

Returning, then, to the question of the rapid decay of star-forming galaxies over the last 5 billion years, if these two mechanisms—galaxy-galaxy interactions and starvation—-are the ones most influencing the evolution of spiral galaxies, it is interesting to ask if either would be more effective in the past than it is today. As far as removing gas reservoirs, it is not obvious why this would be less effective in intermediate-redshift clusters than today.

However, the difference might be that the group environment in rich clusters has changed substantially over this epoch, as pointed out by Kauffmann (1995): the epoch $z \approx 0.5$ may represent a peak in the importance of groups in the building of clusters. For the infalling galaxies that are building today's clusters the protracted time they have spent in the group phase may have already succeeded in exhausting their gas through star formation and perhaps through starvation. Combining this with the normal decline in star formation seen for field galaxies over this epoch, and the effect of Λ in shutting down infall, the different histories of galaxies in groups could account for the rapid decline in star-forming galaxies that is the Butcher-Oemler effect.

Back to the past, do these spiral galaxies go quietly as they enter the apparently hostile environment of a rich cluster at $z \approx 0.5$? Here is where the Morphs and CNOC1 stories diverge: the CNOC1 group sees infalling spirals as victims of starvation and other mechanisms that simply truncate star formation; the Morphs sees these galaxies jostled and shocked into great bursts of star formation that hasten their demise, in dramatic fashion. The Morphs group emphasizes that the CNOC1 survey, for reasons yet to be determined, does not have a representative sample of galaxies with strong Balmer lines—*starbursts*. Despite the large number of CNOC1 clusters, only four overlap the redshift range covered by the 10 Morph's clusters (most are below $z = 0.3$), so this may be just small number statistics. Balogh et al.'s (1999) search for Balmer-strong galaxies in the CNOC1 sample turns up only a few percent of galaxies with strong Balmer lines, but even their analysis of the Morphs data shows a strong enhancement over the intermediate-redshift field (see Balogh et al., Fig. 29). New, deeper, better data on more clusters will soon answer the question of why the two groups get different results (the other groups seem to report intermediate results—higher fractions than CNOC1, but less than the Morphs). Rather than embarking a lengthy and ultimately inconclusive discussion, I will instead show what we believe is incontrovertible evidence that the Morphs data do show a strong starburst/post-starburst signal, i.e., this is not a matter of data quality or analysis technique. Our group has been experimenting with forming *composite spectra* in each cluster by coadding luminosity-weighted spectra. This avoids a major problem in comparing different studies by producing high-S/N spectra for which Balmer lines can be measured robustly: no complex statistical analysis of the kind performed by Balogh et al. is required. In Dressler et al. (2004) we present different combinations of these composite spectra, including simply adding all cluster members together: this produces the diagram Figure 1.1, which shows the trend of [O II] versus Hδ *cluster by cluster* with epoch.

Here I also show as Figure 1.2 the "recipe" for a intermediate-redshift (Morphs) cluster: by adding together all the spectra of all our clusters along categories of our spectral classifications, template spectra are produced that show clearly the different kinds of galaxies found in these clusters, including the large population of those with strong Balmer lines. These spectra demonstrate that the Morphs spectra are correctly interpreted as having strong Balmer lines—the whole of the Balmer sequence is now clearly seen. I hope that forming such composite spectra will become a common practice in future studies, since comparing one or a few excellent composite spectra per cluster is far better than comparing variously defined categories of hundreds of spectra of mixed quality. Integrated spectra will also provide a straightforward way to make Madau-like diagrams of star formation rates as a function of redshift for clusters (see Fig. 15 of Postman et al. 2001) and eventually for the full range of environments.

As Poggianti (2004) discusses, Dressler & Gunn (1983) and later Couch & Sharples

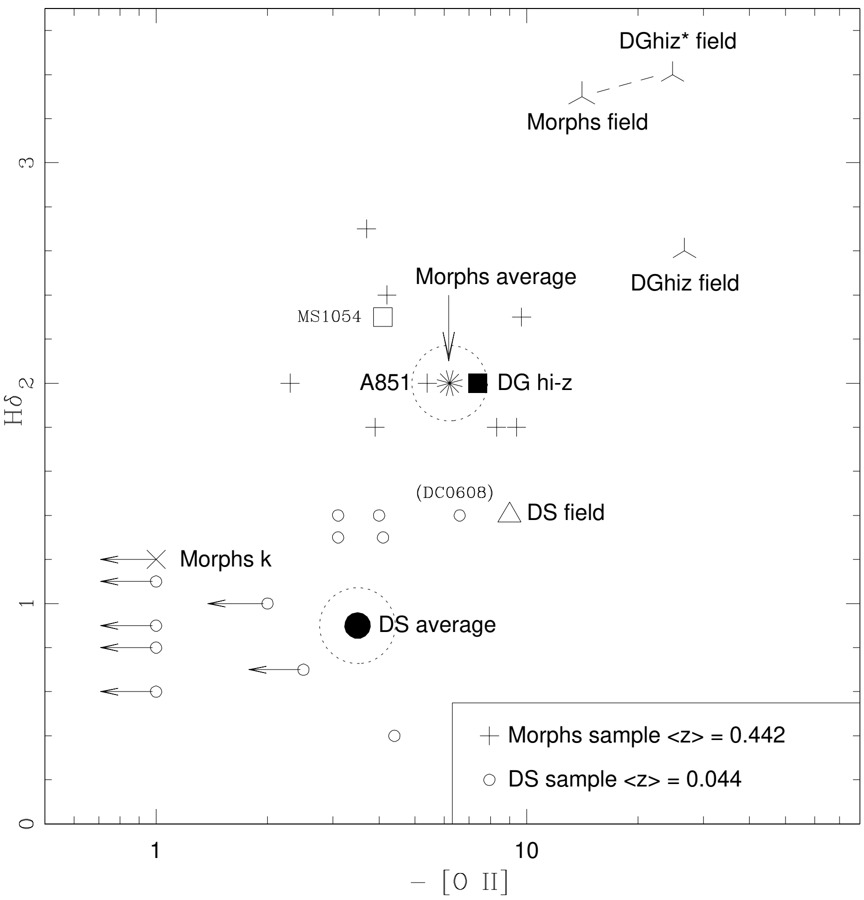

Fig. 1.1. Measurements of [O II] and Hδ for the various field and cluster samples of the Morphs study and the Dressler/Shectman low-redshift sample. There is a clear separation of the "mean" values for the Morphs and Dressler/Shectman samples, but there is also no overlap in the individual measurements for the clusters involved, i.e., there is a clean separation. Even higher-redshift clusters share the properties of the Morphs sample, with no obvious further increase in activity from $z \approx 0.5$ to $z \approx 0.8$. The field relation parallels that for the cluster galaxies, but is shifted toward stronger [O II] and Hδ at each redshift.

(1987) correctly associated the presence of strong Balmer lines with starbursts, past or present. The Morphs interpretation of the distribution of star-forming galaxies in intermediate-redshift clusters is consistent with the picture advocated by the CNOC1 group in the sense that both attribute such changes to the effects of the denser cluster environment. However, the Morphs data lead us to add a strong emphasis on understanding why *starbursts* are prevalent in (at least) many of these clusters, but not in present-epoch clusters. If the field population itself contained a sufficiently large fraction of starbursts, perhaps the sim-

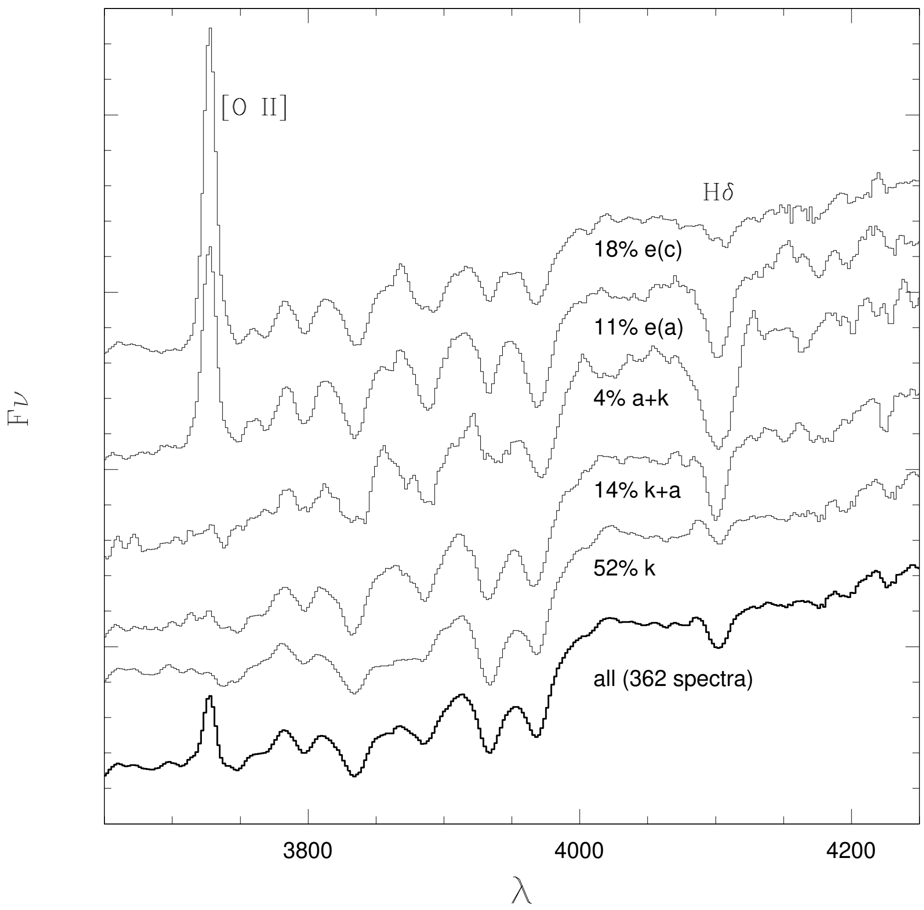

Fig. 1.2. The composite spectra for galaxies in eight clusters of the Morphs sample at $z \approx 0.5$ showing a "recipe" for a typical intermediate-redshift cluster. For the spectra shown above, the individual spectra were sorted according to their spectral classifications (Poggianti et al. 1999) and then coadded, weighted by luminosity. Galaxies with strong Hδ make up 28% of the Morphs sample. For spectra that were classified as k+a, a+k, and e(a), not only Hδ used in this classification, but also the higher-order Balmer lines, are clearly seen. This demonstrates the robustness of these classifications despite the lower S/N and greater variation of quality of the individual spectra.

ple infall/starvation picture of Ellingson et al. would suffice—this seems to be true for the CNOC1 sample with its lower fraction of starbursts—but there are a factor of 2–3 too few field starbursts to explain the populations of the Morphs clusters, and this is even without explaining how starbursts with moderate-to-low duty cycles would fall in at the proper time (see Poggianti et al. 1999). This leads the Morphs to conclude that the cluster environment does more than truncate star formation, but also *stimulates* star formation in many infalling disk galaxies, often with spectacular results. In a new study Milvang-Hensen et al. (2003)

come to the same conclusion about stimulated star formation for infalling spirals for a cluster at $z = 0.83$. Galaxy-galaxy interactions in infalling groups seems to be a likely mechanism, as discussed below.

Why is it important to see if stimulated starbursts are an important part of galaxy cluster evolution? The Morphs think that this phenomenon might be representative of the even higher-redshift Universe in a general way. Perhaps the dominant mode of star formation for spiral galaxies at $z \gtrsim 1$ is the starburst, even for massive, giant systems. If true, this is clearly an important feature of how galaxies evolve; the association with the cluster environment is, once again, an important clue as to the mechanism and how it works. As a final thought about this, once again it appears that what we see may be an evolution through mass with epoch. Consider the growing body of work on local dwarf galaxies where the fossil record of star formation can be read, for example, in the study by Gallart et al. (1999). Many dwarf galaxies appear to have evolved by bursts, unlike the modulated but generally continuous star formation of present-epoch giant spirals. The presence of large numbers of bursting galaxies in both cluster and field at $z > 0.4$ could signal a sensitivity to this kind of behavior for giant galaxies that dominated over their lifetimes, but now has abated—an important insight if true.

Finally, to further pursue this possibility that starbursts are an important result of the cluster environment on their galaxies, the Morphs are beginning to study galaxies much further out in these clusters. The idea is to separate the effects of global processes, such as harassment or ram pressure stripping, both of which are only effective within the inner Mpc (Treu et al. 2003), from galaxy-galaxy processes such as tidal interactions, which may dominate because of the way clusters are built from infalling groups in the supercluster environment. In Abell 851, in particular, we have obtained spectra of 50 additional cluster members in the range 2 Mpc $< R <$ 3.5 Mpc (Oemler et al. 2004). More than 50% of these are starbursts according to the definitions of Poggianti et al. Even if this remarkably high fraction is not common in intermediate-redshift clusters (if, for example, Abell 851 is caught at an unusually favorable epoch of assembly), the ability of the cluster environment to trigger such a display is *prima facia* evidence that local processes, most effective in modest-density enhancement, and not global processes are governing the last stages of star formation of these galaxies. Treu et al. (2003) have reached a similar conclusion about the dominance of local processes over the global influences of the high-density cluster core for the cluster CL 0024+16, based not on spectra but morphological considerations.

SIRTF will play a crucial role in this area, because, as Poggianti et al. have shown, the starbursts in these clusters are very dusty (see also Poggiant & Wu 2000)—substantial amounts of ongoing star formation hidden in optical (rest frame) observations. VLA observations by Morrison et al. (2002) and *ISO* observations by Fadda et al. (2000) demonstrate the importance of pursuing this issue with wavelengths that penetrate the dusty regions of starbursting galaxies.

As with the Ellingson et al. (2001) study, we believe that the tracking of star formation history with epoch and radius is a crucial next step in this kind of research. Our intention is to use the wide field of IMACS on Magellan to follow the star formation history of infalling galaxies in representative rich clusters of the Red Galaxy Survey (Gladders & Yee 2001) over different epochs out into the cluster periphery.

The idea that the evolution of star-forming galaxies is affected at modest density enhancements over the field, as opposed to the extreme environment of cluster cores, seems to be gaining support. We have heard from others at this conference other evidence for a "critical local density" that seems to mark changes in galaxy properties. Kodama et al. (2001) actually have used the same cluster discussed above, Abell 851, in their study of the colors of galaxies out into the supercluster environment. They report an abrupt change in the colors of *low-luminosity galaxies* at a projected density of 100 galaxies Mpc^{-2}, 2–3 orders of magnitude below that of the dense cluster core. In related studies, the first data release from the Sloan Digital Sky Survey analyzed by Gómez et al. (2003) shows a dramatic decrease in strongly star-forming Sc galaxies at a projected density of 1 Mpc^{-2}, which they identify as the boundary of the infall regions of clusters, and Bower & Balogh (2004) also find a similar effect in the CNOC2 survey. However, it is important to remember that these latter studies deal with present-day, luminous field galaxies and so are not directly comparable with the Kodama et al. results. Nevertheless, both results point to the effectiveness of some environmental process, probably associated with galaxy-galaxy interacts and mergers, that occurs at relatively low density.

1.5 One Billion Years ABB: A Cluster is Born

As I began, I conclude that the subject of "star formation in clusters" is a very epoch-dependent question. The work in this subject started, of course, with the study of present-epoch clusters, which show very weak ongoing star formation, most of it in low-luminosity galaxies. Despite early attempts to associate environmental influences such as ram pressure stripping with fundamental aspects of galaxy morphology or star formation, the preponderance of the evidence is that these characteristics derive from earlier epochs and very different conditions in clusters than we see today. In particular, the large population of elliptical galaxies that anchor today's clusters are very old—theory and observation both seem to be on the same side of this now—and this means that a spectacular epoch of star formation at $z \approx 2-3$ must have marked the beginning of cluster evolution. Probably because they are rare, no such protocluster of the mass of Coma has yet been found, but studies of Lyman-break galaxies or SCUBA sources, to give two examples, will probably turn up a few as the volume of surveyed space rapidly increases.

The properties of galaxies in intermediate-redshift clusters, particularly those back at $z \approx 1$ that are as yet little explored, will of course link the two epochs, telling us how the mostly old S0 galaxies evolved and how and when giant spirals were formed and, in some cases, destroyed. Connecting the galaxies in these clusters to their counterparts in the field at that epoch will be, as it has been at low redshift, essential to understanding the role of environment in shaping the galaxies of the modern Universe.

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