Outskirts of Galaxy Clusters: Intense Life in the Suburbs
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Infall and starbursts in z ∼ 0.5 clusters

Alan Dressler

Carnegie Observatories, 813 Santa Barbara Street, Pasadena, CA 91101

Abstract. In this paper I address three topics. The first regards the use of composite spectra as a tool to study the spectral evolution of galaxies in intermediate-redshift clusters. This technique is used to demonstrate the robustness of measurements of strong Hδ absorption, indicative of mild-to-moderate starbursts, in a significant fraction of galaxies in these clusters. Second, I present some spectroscopic data on Abell 851 ($z = 0.41$) that suggests that the starbursts in this cluster have been triggered by tidal encounters in infalling groups in the cluster. Third, I briefly describe the IMACS imaging-spectrograph, which has been built for the Magellan-Baade telescope, and, following the idea that the outskirts of clusters are "where the action is," describe a large spectroscopic program to study "cluster building" using IMACS.

The results reported here are the work of many people, and are described in detail in Dressler *et al.* (2004) and Oemler *et al.*(2004). The author would appreciate citations to these papers, with the addition, if appropriate, of "as reported in Dressler (2004)" – this conference.

1. Introduction

Butcher & Oemler's (1978) report of a significant number of star forming galaxies in intermediate-redshift clusters, in contrast to the largely dormant cluster galaxies of the present era, was quite a surprise given the relatively small lookback time of only 4-5 Gyr. They speculated, correctly it now seems, that the star formation they were seeing was associated with disk galaxies, rather than ellipticals, which they postulated were already long residents of these clusters. Further, they suggested that these disk galaxies were likely infalling spirals whose fate was to add to the large S0 population. The mechanism most frequently (almost exclusively) credited with this conversion was ram-pressure stripping Gunn & Gott (1972), a process that would connect strongly to the very core of the cluster — a global process, as opposed to a local one involving interactions between galaxies. Perhaps equally surprising then, was the discovery by Gunn and myself (Dressler & Gunn 1983) that the spectra of these star forming galaxies were typically those of starbursts and post-starbursts, rather than spectra typical of spirals undergoing continuous, relatively constant star formation. Of course, the spectra of a truncated star formation history is qualitatively similar to a post-starburst spectrum, but quantitative estimates of the strength of the bursts suggested that these were significant enhancements in the star formation rates and that most (all?) of the infalling, starforming galaxies seem to be involved.

The Morphs group greatly expanded the spectroscopy of galaxies in a collection of 10 clusters at $0.35 < z < 0.55$, and found, in support of the early work, a $\sim 20 - 30\%$ fraction of cluster galaxies that have strong Hδ indicative of subsiding or recent starbursts (Dressler *et al.* 1997). However, particularly puzzling was the absence of bright ongoing starbursts that could account for the later-stage examples. A solution to this problem, proposed by Poggianti *et al.* (1999), is that one class of these galaxies, those with strong Hδ and some [O II], are in fact dusty starbursts whose true burst strength is hidden. A variety of evidence now supports this view, including data from the ISO satellite discussed

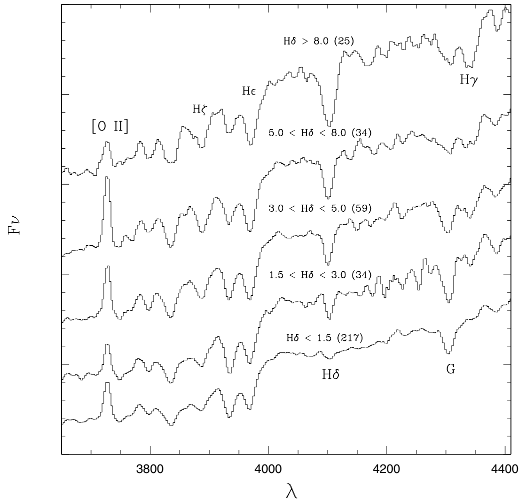

Figure 1. Composite spectra for Morphs sample galaxies with Hδ absorption recorded in 5 ranges of strength. The clear trend of increasing Hδ strength and corresponding other members of the Balmer series (note, in particular, Hγ, Hϵ, and Hζ marked on top spectrum) shows the reality of the Hδ measurement, even in the presence of substantial noise in the continuum in individual spectra.

at this conference and the detection of these many sources in the radio continuum (e.g., Glenn Morrison's PhD thesis).

2. Using composite spectra to compare stellar populations

Also in 1999, however, came a challenge to the Morphs claim of a large fraction of starbursts from Balogh *et al.* (1999) whose analysis of the CNOC cluster sample failed to show a large fraction of galaxies with strong Hδ. From the perspective of several years on, it is easy to see a number of reasons for this difference, which are discussed in Dressler *et al.* (2004, hereinafter D04). Regardless, a consequence of the attempts to reconcile these two studies was a realization by the Morphs that the relatively low S/N of spectra in their and the CNOC study, typically ∼10 per resolution element, makes the comparison of results problematical, especially when different studies adopt different schemes of spectral classification, as was the case here. As a remedy, we decided to form composite spectra of each of our clusters, and to compare them with composite spectra of a present-epoch cluster sample assembled by Shectman and myself in the mid-1980s. As described in D04, we coadded the spectra after normalizing them and weighting them by luminosity (by their photometric magnitudes), so as to similulate as closely as possible a composite stellar population for the whole cluster.

As expected, the S/N of these spectra is vastly improved over individual spectra. This allowed us to answer one question raised by Balogh *et al.*, whether a significant number of the detections of Hδ in the Morphs study might be the result of the high noise level. As shown in Figure 1, by forming composites of the different spectra as a function of Hδ strength, the resulting spectra show a clear sequence of increasing contribution from A stars. In particular, not just Hδ, but the other Balmer absorption lines, are evident in the spectra. The Morphs measurements of Hδ, though often noisy, are robust.

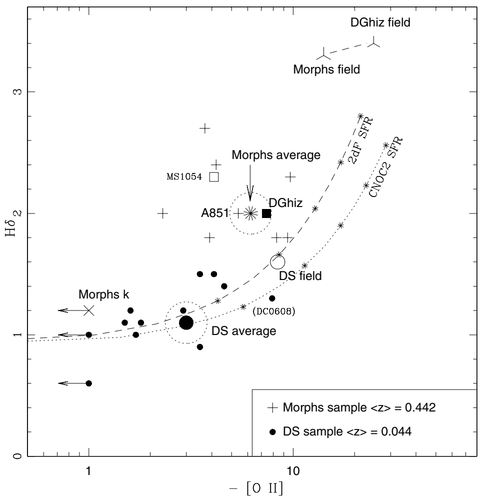

Figure 2. Measurements of EW([O II]) and EW(Hδ) for field and cluster samples There is a clear separation of the "mean" values of Hδ for the Morphs and the DS (low-redshift) samples, but there is also no overlap in the individual measurements for the clusters studied. As discussed in Dressler *et al.* (2004), the two lines represent different mixes of passive galaxies and continuously star–forming galaxies with [O II] distributions from the 2dF Survey (dashed line) and the CNOC survey (dotted line). Although such mixes adequately describe the low–redshift DS clusters and field, they fail to match any of the higher–redshift cluster or field samples, demonstrating the importance of starbursts in these galaxy populations.

With such composite spectra, cluster-by-cluster, we compare the stellar populations, as characterized by [O II] and Hδ, in Figure 2. The intermediate–redshift clusters all average Hδ strengths of ∼2.0Å and have substantial [O II] emission varying between -3Å and -10Å equivalent width; both are indicative of substantial ongoing star formation. In contrast, each of the low–redshift clusters shows much weaker EW(Hδ) ∼ 1.3Å— this is not just 35% weaker, but typical of a population with no significant star formation for several Gyr — and much weaker EW([O II]) = -2Å to -5Å. This difference in spectral characteristics appears to be primarily dependent on epoch rather than a function of cluster properties, but of course, the sample is still too small to be sure.

Figure 2 also plots two curves representing the locus of galaxies with histories of continuous star formation, added in different amounts to passively-evolving galaxies, formed as explained in D04. These two curves, which represent a stronger (CNOC "field") and weaker (2dF "group") star formation rate, describe the $z = 0$ local sample of field and cluster galaxies very well, but fail to account the location of points representing the $z > 0.35$ clusters and field. We take this as strong evidence that these intermediate-redshift populations contain a significant fraction of starburst galaxies not common today (among luminous galaxies), and that this represents an important departure in the mode of star formation in the earlier universe. We note that higher gas fractions in the star forming galaxies, and greater interactions in an earlier epoch of a lambda-dominated universe, may contribute to this difference.

The starburst galaxies observed in the Morphs sample have the morphology of disk galaxies, albeit disturbed disk galaxies, in 80-90% of the cases. It is reasonable, then, to imagine that the starburst is involved in the conversion of a spiral galaxy to an S0, although whether a starburst can be strong enough to accomplish this by itself is unknown at this time. What does seem clear, though, is that a simple truncation of star formation, the picture favored by the CNOC collaboration in their modeling of [O II] strengths as a function of radius from the cluster center (Ellingson *et al.* 2001) doesn't tell the whole story with respect to the Morphs observations. This highlights the value of collecting high S/N spectra with sufficient resolution to measure absorption as well as emission lines.

3. Spectroscopic results for Abell 851: early evidence that the triggering of starbursts happens in the cluster outskirts

These results from the Morphs studies, for the most part, come from the inner parts of these clusters, roughly out to $R \sim 1$ Mpc. To identify the mechanism(s) responsible for the starbursts it is sensible to push such observations as far out into the cluster environment as possible, due to the different environmental dependences of these proposed processes (Treu *et al.* 2003). Abell 851 is a very rich clusteri with several distinct centers in both optical and X-ray images, evidence which points to a propitious moment in its history when subclumps are merging to form a much larger, relaxed cluster. Also, as shown by Kodama *et al.* (2001), and much exhibited at this meeting, A851 has an obvious structure of infalling groups along what appears to be a rather filametary structure.

With new spectroscopic observations obtained with COSMIC on the 200-inch Hale telescope over the last few years, we have pushed into the outskirts of this cluster. In Figure 3 we abstract those results by showing the distribution of different spectral classes reaching out to $R \sim 3$ Mpc from the cluster core. For the region covered by our mosaic of 3×3 HST-WFPC2 frames, we find a complete mix of the different spectral types, which is to say, there is no decline in the percentage of starburst galaxies as we move further from the strongest central concentration (and principal X-ray center) of the cluster. Given the chaotic state of this cluster, and the substantial distances from the cluster center where these starbursts are found, it becomes increasingly less likely that global processes — associated with the cluster's dark matter or gas distribution, for example (i.e., ram-pressure stripping or harassment) — have triggered these starbursts.

The smoking gun, so to speak, of this argument, is the nature of the furthest cluster members found out in filaments to the north-west, which lie almost 3 Mpc from the cluster center, seen clearly in the Kodama *et al.* map. As can be seen from the coding in Figure 3, 7 out of 9 members of the top filament are starburst galaxies, a remarkable result. (Just below is another apparent structure with 4/6 starbursts.) Note that most of these are e(a) galaxies, the kind that the Morphs identify as the active, highly obscured starbursts *in progress*, which would be exactly as expected if the triggering is happening here, far from the cluster core. Our tentative conclusion, based on this limited but significant example, is that tidal interactions on these galaxies, from their neighbors and from "in situ" cluster galaxies, are triggering these gas-rich spirals to undergo substantial bursts of star formation.

The details of these observations for A851, and our interpretation, are discussed in Oemler *et al.* (2004).

4. ICBS: using IMACS to study the outskirts of distant galaxy clusters

These results on A851 are encouraging in regard to finally identifying a major cause of galaxy transformation due to environment. Gus Oemler, Mike Gladders, Bianca Poggianti, and myself, are collaborating to make much more extensive observations (in radial

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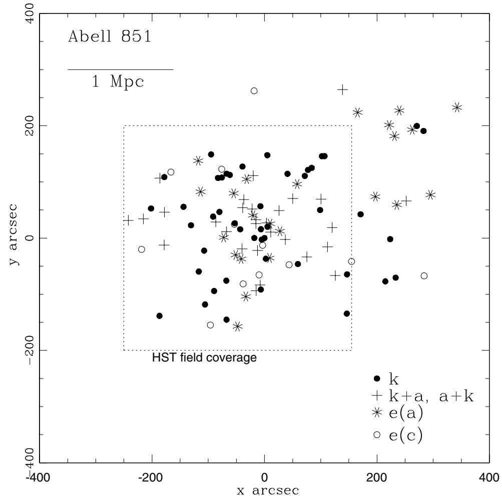

Figure 3. Distribution of the spectral types of 113 cluster members in the field of Abell 851. Within the area covered by the HST WFPC2 mosaic, shown by the dotted line, passive galaxies – k, continuously star-forming galaxies – e(c), and active- and post-starbursts – e(a) & k+a, a+k, are well mixed. There is no decline in the fraction of starbursts with cluster radius. For the filamentary structures to the northwest (upper right), active starbursts are the most common spectral type that has been detected, suggesting that the triggering mechanism of starbursts has occurred at least this far from the center of Abell 851.

distance and in numbers of cluster galaxies recovered) for a statistically significant number of intermediate-redshift clusters.

We are fortunate to have an excellent tool for this job. The Inamori-Magellan Areal Camera and Spectrograph has recently gone into routine operation on the Magellan-Baade 6.5-m telescope. IMACS is a re-imaging camera/spectrograph with a huge field, by big-telescope standards, of almost 1/2-degree in diameter, and the capacity to place multislits on hundreds of targets per exposure. This makes feasible an ambitious program of gathering a thousand or more cluster members in fields of these clusters, which we call the IMACS Cluster Building Survey.

Our strategy for this survey is, of course, to push as far out in the clusters as possible: the IMACS field covers typically out to $R \sim 5$ Mpc for $0.35 < R < 1.2$, which will be our target redshift range. However, we want to do more than study the behavior of individual clusters, but also follow the process of galaxy accretion and possible interactions over the principal epochs of cluster growth, eventually out to (at least) $z \sim 1.2$. Cluster simulations by Gladders, using the Hydra Consortium code, suggest that the galaxies that end up well-concentrated in clusters at $z = 0.3$ cover the full volume $R < 5$ Mpc at $z = 1.2$. To follow the cluster-building process, moreover, we must ensure that we are making an "apples to apples" comparison, that is, we must choose clusters at $z = 1.2$ that are progenitors of the clusters we will study at $z \sim 0.8$ and $z \sim 0.4$. We do this by selecting from equal volumes of the universe and selecting the most massive clusters at each epoch, making sure that the volume is not too large such that one-of-a-kind clusters are likely to creep into the sample.

The clusters will be chosen from the Red Sequence Cluster Survey (Gladders & Yee 2004) and Sloan Digital Sky Survey. Our initial goal is 5 clusters at $0.35 < z < 0.50$ and 5 clusters at $0.75 < z < 0.85$. With the intensive effort that we think will be necessary

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to flush out the infalling galaxies far from the inner cluster, we expect this program to take 60-70 nights on the Magellan telescope, to be spread over about 3 years. The first observations were made in 2004 January, with a couple of hundred redshifts collected in fields containing three clusters.

5. Summary

We have formed composite spectra of galaxies in intermediate redshift clusters to increase the reliability of measurements of absorption and emission lines that characterize their star formation histories. These spectra also facilitate the comparison of different investigations, and allow better study of classes of objects chosen by, for example, morphology, location, or color. The composite spectra confirm a high incidence of starbursts in galaxies in many (most? all?) intermediate-redshift clusters, a situation quite different from the populations of clusters today. Combined with morphologies of galaxies in the intermediate-redshift clusters, the evidence suggests that starbursts and structural disturbance are steps along the way to converting spiral galaxies into S0 galaxies. There is preliminary evidence that this process begins far from the cluster core and is associated with tidal interactions, accretions, and mergers that occur as infalling galaxies, many of them in groups, are incorporated into the cluster.

A new spectrograph, IMACS, on the Magellan-Baade telescope is particularly well suited for studying the outskirts of cluster galaxies, due to its wide field and large multiplexing capability. The IMACS Cluster Building Survey will target intermediate-redshift clusters to assemble a representative sample of the infalling galaxies that build clusters in their growth years.

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