Evolution in the Fast Lane: Evolution in Massive Galaxy Clusters

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Abstract
Evolution in galaxy clusters has long been shown to proceed differently than in the field, but recent results have also shown that galaxy evolution is accelerated in the most massive structures. We present results from a survey of galaxy populations in the most massive galaxy clusters in the Universe. Out to z=1, red sequence galaxies in these clusters appear already in place down to relatively faint magnitudes (M_B~−18). The deficit of faint, red galaxies seen in the field and in lower mass systems is not present in these clusters. For star-forming systems, the results are far more dramatic. Star-forming galaxies are abundant in the outskirts of these clusters and show signs for enhanced star formation. Furthermore, the number density of luminous, blue, compact galaxies (LCBGs)--a rapidly evolving field population--appear to be enhanced in intermediate clusters, and their properties indicate an even more extreme sample of galaxies. How these, and other star-forming galaxies travel across the green valley to reach their final fate on the red sequence will be critical to understanding galaxy evolution in clusters.

Introduction
Some of the first evidence for galaxy evolution came from the observations of blue galaxies in galaxy clusters (Butcher & Oemler 1984), but since then, a number of different studies have shown that galaxies evolve differently in clusters (Dressler et al. 1997). Different processes are believed to drive the evolution of cluster galaxies (Boselli & Gavazzi 2006) and mapping when these processes are dominate is an important question to answer.

In the nearby universe, galaxy clusters are dominated by early-type galaxies (Dressler 1980) along the so-called red sequence. The red sequence was in place at very early redshifts (Stanford et al. 2005), but recent observations of some clusters indicate that faint galaxies are a recent addition to it (de Lucia et al. 2006), but there have been conflicting studies (Andreon 2006).

Unlike at z=0, star-forming galaxies are a ubiquitous population of clusters at int-z. This includes luminous, compact, blue galaxies (LCBGs), an extreme class of star-forming galaxies. Star-forming galaxies only seen at intermediate redshifts (Koo et al. 1997, Guzman et al. 1997, Crawford et al. 2006). How these galaxies evolve will affect what clusters look like today.

Cluster Sample
Our selection of clusters sampled the most massive clusters at intermediate redshifts, (Ld=0.0). The clusters red sequence for each cluster can be seen in the next figure (in the right hand column). In the blue panel, the filled circle indicates a bright, blue object identified with a red, green, blue objects in photometric redshifts. Right As compared to other samples, we build a larger sample of clusters, for the growth of halos from Westfall et al. (2009) represent clusters as dashed lines.

Observations and Data Analysis
WIYN Observations
WIYN 3.5m UBRIz observations were made of the clusters between Oct 1999-May 2004. Custom narrow band observations were made of five cluster to detect [OII]3727 emission from star forming galaxies. Further information about the data reduction and analysis can be found in Crawford et al. (2009).

KECK Observations
Keck DEIMOS observations were made of a sample of star-forming galaxies selected from the [OII]3727 imaging in two z~0.5 clusters. The R0 line grating was used with 1° slits that provided a resolution of FWHM~2.86 Å and wavelength coverage from 5000-8600 Å. The data were reduced using the DEEP pipeline (Cooper et al. 2008). Further details of the observations will be published in Wirth et al. (2010).

Conclusion
We have studied the galaxy populations in a sample of very massive, intermediate redshift, galaxy clusters.

• In these clusters, the red sequence is in place to M_B~−18 and no deficit of sources is evident
• The star forming galaxies show an enhancement over field densities and are dominated by infalling, lower mass, star-bursting galaxies.

Acknowledgments
We would like to thank the organizers of the meeting for the opportunity to present our work and the attendees for the encouragement that the very graphic reduced role that the authors of these papers have in the proceedings.

References
Wirth et al. 2010, in prep

[Figure 1: Evolution of Red Galaxies]

Evolution of Red Galaxies
We measure the red sequence luminosity function using the deep WIYN imaging. We classify the cluster red sequence following Wirth et al. (2008) and identify potential cluster members from their photometric redshifts (top left panel). The luminosity function and errors for each cluster are shown on the right. In addition to measuring the luminosity function for our intermediate redshift sample, we also selected Abell clusters (Abell et al. 1989) that had SDSS imaging and then measured the luminosity function for these clusters in a similar manner as in our sample. We limit the LF in these clusters to the same absolute magnitude limit as our higher redshift sample.

[Figure 2: Measuring the Red Sequence Luminosity Function]

Measuring the Red Sequence Luminosity Function
The RSLF for our five massive clusters is presented on the left from Crawford et al. (2009). The 45 down to M_B~−18 is already in place in these clusters and the first infalling galaxies appear. Very little room exists at the bright end for the addition of a large number of galaxies.

[Figure 3: Example of cluster star forming galaxies from MS0541 and COS016. The sample can be split into standards star forming galaxies and very compact sources with extreme star formation.]

Example of cluster star forming galaxies from MS0541 and COS016. The sample can be split into standards star forming galaxies and very compact sources with extreme star formation.