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The Environmental Dependencies of Star-Formation and the Origin of the Bimodality in Galaxy Properties

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Abstract. We examine the origins of the bimodality observed in the global properties of galaxies by comparing the environmental dependencies of star-formation for giant and dwarf galaxy populations. Using Sloan Digital Sky Survey (SDSS) DR4 spectroscopic data to create a volume-limited sample complete to $M^{\star}+3$, we find that the environmental dependences of giant and dwarf galaxies are quite different, implying fundamental differences in their evolution. Whereas the star-formation histories of giant galaxies are determined primarily by their merger history, resulting in passively-evolving giant galaxies being found in all environments, we show that this is not the case for dwarf galaxies. In particular, we find that old or passive dwarf galaxies are *only* found as satellites within massive halos (clusters, groups or giant galaxies), with none in the lowest density regions. This implies that star-formation in dwarf galaxies must be much more resilient to the effects of mergers, and that the evolution of dwarf galaxies is primarily driven by the mass of their host halo, through effects such as suffocation, ram-pressure stripping or galaxy harassment.

1. Introduction

The global properties of galaxies have been found to be bimodally distributed about a stellar mass $\sim 3\times10^{10}M_{\odot}$ ($M^{\star}+1$), with more massive galaxies predominately passive, red spheroids dominated by old stellar populations, and less massive galaxies tending to be blue, star-forming disk galaxies whose light is dominated by young stars (e.g. Kauffmann et al. 2003). This implies fundamental differences in the formation and evolution of giant and dwarf galaxies. What causes this bimodality? If galaxies grow hierarchically through merging and accretion, why do they only become passive once they reach $\sim 3\times10^{10}M_{\odot}$?

One approach to this problem is to look at the environmental trends of galaxies, as the trends with mass are paralleled by those with environment. In particular, passively-evolving spheroids dominate cluster cores whereas galaxies in field regions are typically star-forming disk galaxies, giving rise to the classic morphology-density and star formation-density relations. Are these environmental trends : (i) the direct result of the initial conditions in which the galaxy forms, whereby cluster galaxies could form earlier and evolve more rapidly through a more active merger history, than those in the smoother lower density regions; or (ii) produced later by the direct interaction of galaxies with one or more aspects of their environment through processes such as galaxy harassment, suffocation or ram-pressure stripping? This is the so-called nature versus nurture problem.

Studies of the most massive galaxies find little or no difference in the mass-to-light ratios or mean stellar ages between cluster and field early-type galaxies, implying that environmental processes are not important (e.g. van Dokkum & van der Marel 2007). However, at fainter magnitudes large variations with local density are seen in the ages, colours and the shape of the luminosity function, implying that environmental process are much more important for low-mass galaxies (e.g. Haines et al. 2006a; Mercurio et al. 2006). By examining when, where and how galaxies are being transformed, we can gain information as to the nature of the physical mechanisms responsible for the transformation. By in addition, seeing how these environmental dependences vary with mass, we can hope to understand the causes of the bimodality.

We have examined the origins of the bimodality by comparing the environmental dependencies of giant and dwarf galaxy populations in the vicinity of the supercluster centred on the rich cluster A 2199 at $z = 0.0309$. This is the richest low-redshift ($z < 0.04$) structure covered by SDSS DR4, producing a spectroscopic sample of $\sim 2\,000$ galaxies that is $\sim 90\%$ complete to a magnitude limit of $M_r = -17.8$ or $M^{\star} + 3.3$, i.e. well into the dwarf regime. From these we measured global trends with environment (using the adaptive kernel estimator to estimate the local galaxy density on scales of the host halo) for both giant ($M_r < -20$) and dwarf ($-19 < M_r < -17.8$) subsamples using the r-band luminosity-weighted mean stellar age and Hα emission as two independent measures of star-formation history (for details see Haines et al. 2006b).

2. Results

One example of the global bimodality in galaxy properties is seen in the relation between mean stellar age and the r-band absolute magnitude (M_r), with a population of bright ($\sim L^{\star}$) galaxies $\sim$10 Gyr old, and a distinct population of fainter galaxies dominated by young (< 3 Gyr) stars (see Fig. 1 of Haines et al. 2006b). Examining the environmental trends of mean stellar age, we find that both giant and dwarf galaxy populations get steadily older with density, and in all environments giant galaxies are at least 1 Gyr older on average than dwarf galaxies. In high-density regions corresponding to cluster cores, galaxies are predominately old ($\gtrsim$8 Gyr), independent of their luminosity. Moreover, while the age distribution of massive galaxies extends to include ever younger ages with decreasing density, that of dwarf galaxies gets younger but also narrows, so that at the lowest-densities found in the rarefied field only young ($\lesssim$2 Gyr) galaxies are found. Equally, examining the environmental dependence of the fraction of old ($>$7 Gyr) galaxies, we find that in the highest density regions, $\sim 75\%$ of both giant and dwarf galaxies are old. Whereas the fraction of giant galaxies with old stellar populations declines gradually with decreasing density to the global field value of $\sim 50\%$, that of dwarf galaxies drops rapidly to $\sim 20\%$ by the cluster virial radius, and continues to decrease, tending to *zero* for the lowest density bins. Identical trends are independently observed when considering passive galaxies with EW(Hα) < 4Å.

To relate the differences in environmental trends directly to the effect of the supercluster, Figure 1 shows the spatial distribution of passively-evolving (red solid circles) and star-forming (light-blue circles) galaxies, for the dwarf

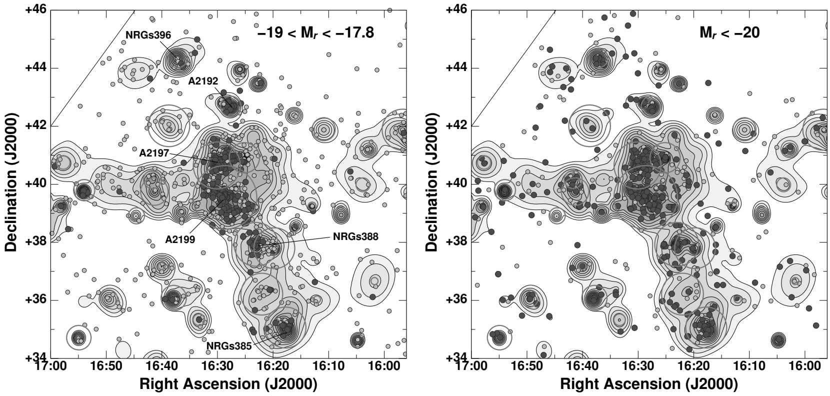

Figure 1. The distribution of galaxies with (solid light/blue circles) and without (EW[Hα] ≤ 4Å; solid dark/red circles) Hα emission in the A2199 supercluster environment, for dwarf ($-19 < \mathrm{M}_r < -18$; left) and giant ($\mathrm{M}_r < -20$; right) galaxies. The black contours represent the local luminosity-weighted surface density of galaxies with redshifts within $2\,000\,\mathrm{km\,s^{-1}}$ of A2199. The grey/green open circles indicate the virial radii of the galaxy groups/clusters associated with the A2199 supercluster.

($-19 < \mathrm{M}_r < -17.8$; left panel) and giant ($\mathrm{M}_r < -20$; right panel) galaxy subsamples, with relation to the supercluster as represented by the grey-scale isodensity contours. Although the passively-evolving giant galaxies are more concentrated towards the centres of the rich clusters in the supercluster than their star-forming counterparts, they are found throughout the region covered. In the low-density regions there is an equal interspersed mixture of passive/old and star-forming/young galaxies. This indicates that their evolution is driven primarily by internal mechanisms and their merging history rather than by direct interactions with their large-scale environment; the gradual overall trends of star-formation with environment reflect the increasing probability with density that a galaxy with have undergone a major merger during its lifetime.

In contrast, the star-formation history of dwarf galaxies are strongly correlated with their environment. While the cores of clusters are still dominated by passively-evolving dwarf galaxies, elsewhere almost all of the dwarf galaxies are currently actively star-forming, and of the few remaining passively-evolving galaxies outside a cluster, *all* are found in either poor groups or within $\sim 200\,\mathrm{kpc}$ of an old, massive galaxy. None are found to be isolated.

Extending the study to the entire SDSS DR4 dataset, we consider a volume-limited sample of $\sim 30\,000$ galaxies in the redshift range $0.005 < z < 0.037$, complete to $\mathrm{M}_r = -18.0$. Examining the fraction of passively-evolving galaxies as a function of both their luminosity/stellar mass and local environment, we find that in high-density regions passively-evolving galaxies dominate independent of luminosity, making up $\approx$70% of the population. In the rarefied field however, the fraction of passively-evolving galaxies is a strong function of luminosity, dropping from 50% for $\mathrm{M}_r \lesssim -21$, to *zero* by $\mathrm{M}_r = -18$ or a stellar mass $\sim 10^{9.2}\mathrm{M}_\odot$. Indeed, in the lowest-luminosity range covered ($-18 < \mathrm{M}_r < -16$) *none* of the

$\simeq 600$ galaxies in the lowest density quartile are passive. These results confirm and extend the well known observation that dwarf ellipticals in the local Group are found only near massive galaxies (e.g. Binggeli, Tarenghi, & Sandage 1990; Ferguson & Binggeli 1994), or in more massive structures such as the Virgo and Coma clusters (e.g. Conselice et al. 2003), and imply that processes *internal* to the galaxy cannot completely shut down star-formation in dwarf galaxies, and instead they only become passive once they become a satellite within a more massive halo.

3. Discussion

The relationship between star-formation and environment for giant and dwarf galaxies are quite different. Whereas the star-formation histories of giant galaxies are primarily determined by their merger history, star-formation in dwarf galaxies appears much more resilient to the effects of mergers. Instead dwarf galaxies become passive only once they become satellites within a more massive halo, by losing their halo gas reservoir to the host halo ("suffocation") or other environment-related processes such as galaxy harassment and/or ram-pressure stripping. These differences can be understood in the context of the hot and cold gas infall (Dekel & Birnboim 2006) or AGN feedback models of galaxy evolution. When two massive gas-rich galaxies merge, tidal forces trigger a star-burst and fuel the rapid growth of the central black hole, until outflows from the AGN drive out the remaining cold gas from the galaxy, rapidly terminating the starburst (Springel, di Matteo, & Hernquist 2005). In massive galaxies, the halo gas is also heated by stable virial shocks, and is prevented from cooling by feedback from the quiescent accretion of the hot gas onto the black hole, effectively permanently shutting down star-formation (Croton et al. 2006). Because black-hole growth is strongly dependent on galaxy mass, AGN feedback in low-mass galaxies is much less efficient at expelling cold gas or affecting star-formation. Low-mass galaxies also regulate their star-formation through supernovae feedback preventing starbursts that exhaust the cold gas, which is in turn constantly replenished by filamentary cold streams from the halo, so that their ability to maintain star-formation over many Gyr is much less affected by their merger history. Thus the characteristic mass-scale of the bimodality represents the point at which galaxies can become passive through internal processes.

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