Low-Mass Cluster Galaxies: A Cornerstone of Galaxy Evolution

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Abstract. Low-mass cluster galaxies are the most common galaxy type in the universe and are at a cornerstone of our understanding of galaxy formation, cluster luminosity functions, dark matter and the formation of large scale structure. I describe in this summary recent observational results concerning the properties and likely origins of low-mass galaxies in clusters and the implications of these findings in broader galaxy formation issues.

1. Low-Mass Cluster Galaxies

Although they are the faintest and lowest mass galaxies in the universe, low-mass cluster galaxies (LMCGs), especially dwarf ellipticals, hold clues for the ultimate understanding of galaxy formation, dark matter and structure formation. The reason for this is quite simple: low-mass galaxies, and particularly low-mass galaxies in clusters (Conselice et al. 2001) are the most common galaxies in the nearby universe (Ferguson & Binggeli 1994). Any ultimate galaxy evolution/formation scenario must be able to predict and accurately describe the properties of these objects. In galaxy formation models, such as hierarchical assembly (e.g., Cole et al. 2000), massive dark halos form by the mergers of lower mass ones early in the universe. By understanding these LMCGs, we are potentially studying the very first galaxies to form. On the other hand, observations reveal that no low-mass galaxies formed all of their stars early in the universe at $z > 7$, with considerable evidence for star formation occurring in the last few Gyrs (e.g., Grebel 1997; Conselice et al. 2003).

While low-mass galaxies are traditionally studied in low density environments, such as in the Local Group, it is now clear that a large population of these low-mass galaxies exist in clusters, whose nature is only recently becoming clear (Conselice et al. 2001; 2003). A comparison with the Local Group demonstrates that the ratio of low-mass to large mass galaxies in clusters is roughly five to ten times higher than in low density environments. This over density of LMCGs, and the fact that some Local Group dwarf spheroidals (Klyena et al. 2002) have large dark matter halos, hints that potentially a large amount of mass in clusters is associated with low-mass galaxies. New observational results also suggest that early-type LMCGs are not a homogeneous population, but consist of at least two distinct types, that are morphologically similar, but with different physical properties.

2. New Observational Results

There are several observations, listed below, that suggest low-mass cluster galaxies have unique dynamical, kinematic and stellar population properties that differ from properties of Local Group low-mass galaxies (see e.g., Conselice, Gallagher & Wyse 2001, 2002, 2003; Rakos et al. 2001; Pedraz et al. 2002).

1. **Spatial Position:** While Local Group dwarf galaxies, particularly dwarf ellipticals, are strongly clustered around the giant galaxies in the Local Group (van den Bergh 2000), the opposite is found for low-mass galaxies in clusters, where most are neither clustered around, nor distributed globally similar to, the giant elliptical galaxies (Conselice et al. 2001).

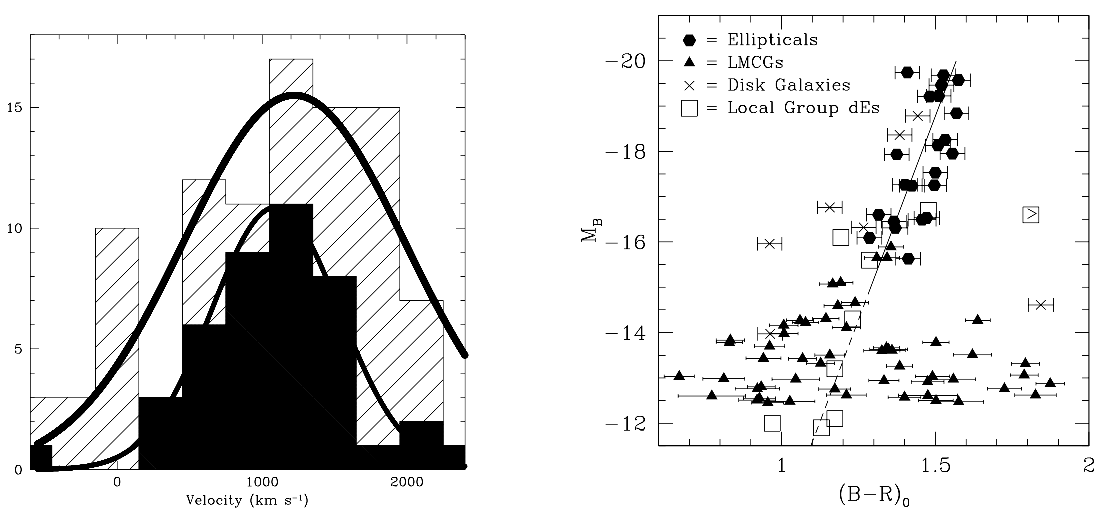

Figure 1. (a) Velocity histograms for giant ellipticals (solid) and dwarf ellipticals (shaded) in the Virgo cluster (Conselice et al. 2001) (b) Color magnitude diagram for galaxies in the Perseus cluster, demonstrating the large color scatter for systems with $M_B > -15$. The solid boxes are where Local Group dEs/dSphs would fit on this plot.

2. **Radial Velocities:** The radial velocities of low-mass cluster galaxies, including S0s, spirals, dwarf irregulars and dwarf ellipticals are more widely distributed than the ellipticals (see Figure 1a). For example, Virgo cluster elliptical galaxies have a narrow Gaussian velocity distribution, with $\sigma = 462$ km s^{-1}, concentrated at the mean radial velocity of the cluster. The other populations, including the over 100 classified dwarf ellipticals in Virgo with radial velocities, have much broader, and non-Gaussian, velocity distributions ($\sigma \sim 700$ km s^{-1}), all with velocity dispersion ratios with the ellipticals consistent with their being accreted (e.g., Conselice et al. 2001).

3. **Stellar Populations:** Faint LMCGs, with $\mathrm{M_B} > -15$, have a large color scatter at a given magnitude (e.g., Rakos et al. 2001; Conselice et al. 2003) produced by galaxies that are both bluer and redder than the extrapolated color-magnitude relationship, as defined by the giant elliptical galaxies (Figure 1b). This is found in several nearby clusters, including Fornax, Coma and Perseus, and can be explained by the stellar populations in LMCGs having a mixture of ages and metallicities (e.g., Rakos et al. 2001; Conselice et al. 2003). Stromgren and broad-band photometry reveals that the red LMCGs are metal enriched systems. These red LMCGs steepen the luminosity function (LF) of clusters, and are responsible for differences in faint end LF slopes seen in clusters and in the field (Conselice 2002).

4. **Internal Kinematics:** Some LMCGs show evidence for rotation when observed out to at least one scale radii (e.g., Pedraz et al. 2002). Rotation is however not present in Local Group dEs, such as NGC 205 and NGC 185 (e.g., van den Bergh 2000).

3. LMCG Origins

Based on the observational results presented above it appears that some LMCGs are fundamentally different than low-mass galaxies in groups, although bright LMCGs have similar photometric properties to Local Group dEs (e.g., Conselice et al. 2003).

Several possible physical mechanisms can potentially explain the origin of LMCG populations. In the simple collapse + feedback scenario (Dekel & Silk 1986), LMCGs are formed when gas collapses and forms stars. These stars produce winds that expels gas from these systems, halting any future star formation. In this formation scenario LMCGs formed before the cluster ellipticals, or at least formed within groups that later merged to form clusters. Faint LMCGs however, cannot all be born in groups which later accreted into clusters along with the massive galaxies, due to the high LMCG to giant galaxy ratio found in clusters (Conselice et al. 2001, 2003). The above evidence suggests that simple low-mass galaxy formation scenarios can be safely ruled out for some LMCGs.

One alternative idea is that present day LMCGs formed after the cluster itself was in place by collapsing out of enriched intracluster gas. Another is that the intracluster medium (ICM) is able to retain enriched gas that in the Dekel and Silk (1986) paradigm would be ejected by feedback, but remains due to the confinement pressure of the ICM (Babul & Rees 1992). This scenario would explain the higher metallicities of some of the fainter LMCGs.

An alternative scenario is that LMCGs form in the cluster through a tidal origin. Two main possibilities for this are tidal dwarfs (Duc & Mirabel 1994), and as the remnants of stripped disks or dwarf irregulars (Conselice et al. 2003). The velocity and spatial distributions of LMCGs suggest that they must have been accreted into the cluster during the last few Gyrs (Conselice et al. 2001). This, combined with the high metallicities of these LMCGs, and the fact that their stellar populations are fundamentally different than field dwarfs (e.g., Conselice 2003; Figure 1b) suggests that the cluster environment has morphologically transformed accreted galaxies into LMCGs. This is consistent with the internal rotation found for some LMCGs (Moore et al. 1998). Ongoing and future observations of the HI, dynamical and dark properties of LMCGs will soon allow for a more complete observational description of these objects.

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