How ‘heredity’ and ‘environment’ shape galaxy properties

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Abstract. In this review, I give a brief summary of galaxy evolution processes in hierarchical cosmologies and of their relative importance at different masses, times, and environments. I remind the reader of the processes that are commonly included in modern semi-analytic models of galaxy formation, and I comment on recent results and open issues.

1. Introduction

It has been known for a long time that the local and large–scale environment play an important role in determining many galaxy properties\footnote{First indications of a correlation between the galaxy type and the environment can be found in the \textit{The Realm of Nebulae} by E. Hubble (1936).}. Disentangling the processes responsible for the observed correlations has proved difficult and it remains unclear whether the observed relations are imprinted during formation or by physical processes at work in dense environments. In recent years, the subject has received much impetus from the completion of large spectroscopic and photometric surveys at different redshifts (e.g. Kauffmann et al. 2004; Cucciati et al. 2006; Cooper et al. 2006). Historically, however, theoretical and observational studies trying to assess the role of environment on galaxy evolution have been focused mainly on galaxy clusters. The primary reason for this is the practical advantage of having many galaxies in a relatively small region of the sky and all approximately at the same redshift. This allows efficient observations to be carried out, even with modest fields of view and modest amounts of telescope time. It should be noted, however, that in order to establish that physical processes related to the cluster environment are indeed playing a role, it is necessary to compare the evolution of similar galaxies in different environments (i.e. in the clusters and in the ‘field’). In addition, it is worth reminding that galaxy clusters represent a \textit{biased} environment for evolutionary studies. In the current standard cosmogony, clusters originate from the gravitational collapse of the highest peaks of primordial density perturbations, and evolutionary processes in these regions occur at an accelerated pace with respect to regions of the Universe with ‘average density’. Clusters do have another related important drawback: they are \textit{rare} (they only contain about 10 per cent of the cosmic galaxy population at the present day, and even a lower fraction at higher redshift). Finally, there is one element that is often overlooked in classical discussions about environment: according to the current paradigm for structure formation, dark matter collapses
into haloes in a bottom-up fashion. Small systems form first and subsequently merge to form progressively larger systems. As structure grows, galaxies join more and more massive systems, therefore experiencing different ‘environments’ during their life-times. In this context, it is clear that both ‘heredity’ (i.e. the initial conditions) and ‘environment’ (i.e. subsequent physical processes that galaxies experience during their life-times) do play a role in shaping the observed galaxy properties and in determining the observed environmental trends.

2. Physical processes

A comprehensive review of early and recent theoretical work on galaxy evolution and environment would easily fill an entire volume. In the following, I will therefore limit myself to an overview of the various physical processes, and of their relative importance at different masses, times, and environments. I will remind the reader of the processes that are commonly included in modern semi-analytic models of galaxy formation, and comment on recent results.

**Mergers**: Galaxy mergers and more generally strong galaxy-galaxy interactions, are commonly viewed as a rarity in massive clusters because of the large velocity dispersion of the system. They are certainly more efficient in the infalling group environment and may therefore represent an important ‘preprocessing’ step in the evolution of cluster galaxies. In this perspective, mergers are important over the entire life of a galaxy cluster: at early times when the cluster is first collapsing, and still at later times in the outskirts of the cluster, as it accretes groups from the field. Numerical simulations (see Mihos 2004, and references therein) have shown that close interactions can lead to a strong internal dynamical response driving the formation of spiral arms and, in some cases, of strong bar modes. The axisymmetry of these structures leads to the compression of the gas that can fuel starburst/AGN activity. Simulations have also shown that sufficiently close encounters can completely destroy the disc, leaving a kinematically hot remnant with photometric and structural properties that resemble those of elliptical galaxies.

Mergers are intrinsically included in standard semi-analytic models of galaxy formation and represent the main channel for the formation of bulges. In the hierarchical galaxy formation scenario, more massive galaxies form through the mergers of smaller units and larger systems are expected to be made up by a larger number of progenitor galaxies. It is therefore interesting to ask how the number of progenitors varies as a function of galaxy mass. In our recent work (De Lucia et al. 2006), we have investigated this issue by defining for each galaxy an *effective number of stellar progenitors*. This essentially represents a mass-weighted counting of the stellar systems that make up the final galaxy (see original paper for more details) and therefore provides a good proxy for the number of significant mergers required to assemble a galaxy.

The left panel of Fig. 1 shows how the effective number of progenitors varies as a function of galaxy mass for model ellipticals. Filled circles show results from our ‘standard’ model which includes a disc instability channel for the formation of bulges. Empty symbols indicate results from a model in which this channel is switched off. The vertical dashed line indicates the threshold above which our morphology classification can be considered ‘robust’ (see original paper for more
details). As expected, more massive galaxies are made up of more pieces. The number of effective progenitors is, however, less than 2 up to stellar masses of \( \approx 10^{11} \, M_\odot \), indicating that the formation of these systems typically involves only a small number of major mergers. Only more massive galaxies are built through a larger number of mergers, reaching up to \( \approx 5 \) for the most massive systems. The right panel of Fig. 1 shows the distribution of ‘formation’ (top panel) and ‘assembly’ redshifts (bottom panel) of model ellipticals. The formation redshift is defined here as the redshift when 50 per cent of the stars that end up in ellipticals today are already formed, while the assembly redshift is defined as the redshift when 50 per cent of the stars that end up in ellipticals today are already assembled in a single object. The right panel of Fig. 1 shows that more massive galaxies are older, albeit with a large scatter, but assemble later than their lower mass counterparts. The assembly history of ellipticals hence parallels the hierarchical growth of dark matter haloes, in contrast to the formation history of the stars themselves. Data shown in the right panel of Fig. 1 imply that a significant fraction of present elliptical galaxies has assembled relatively recently through purely stellar mergers, in agreement with recent observational results (e.g. van Dokkum 2005).

**Harassment:** Galaxy harassment is a process that is not usually included in semi-analytic models of galaxy formation. The process has been discussed in early work on dynamical evolution of cluster galaxies (e.g. Richstone 1976), and has been explored in some detail using numerical simulations by Farouki & Shapiro (1981). These early studies showed that repeated fast en-

Figure 1. **Left:** Effective number of progenitors as a function of galaxy stellar mass for model elliptical galaxies. Symbols show the median of the distribution, while error bars indicate the upper and lower quartiles. Filled and empty symbols refer to a model with and without a disc instability channel for the formation of the bulge. **Right:** Distribution of formation (top panel) and assembly redshifts (bottom panel). The shaded histogram is for elliptical galaxies with stellar mass larger than \( 10^{11} \, M_\odot \), while the open histogram is for all the galaxies with mass larger than \( 4 \times 10^9 \, M_\odot \). Arrows indicate the medians of the distributions, with the thick arrows referring to the shaded histograms. (From De Lucia et al. 2006)
counters coupled with the effects of the global tidal field of the cluster, can drive a strong response in cluster galaxies - results that were confirmed by later and better simulations (Moore et al. 1998). Numerical simulations indicate that the efficiency of this process is largely limited to low-luminosity hosts, due to their slowly rising rotation curves and their low-density cores. For this reason, it is believed that harassment might have an important role in the formation of dwarf ellipticals or in the destruction of low-surface brightness galaxies in clusters, but it is less able to explain the evolution of luminous cluster galaxies.

**Gas stripping**: Galaxies travelling through a dense intra-cluster medium suffer a strong ram-pressure stripping that sweeps cold gas out of the stellar disc (Gunn & Gott 1972). Although the gas is tenuous, a large pressure front builds up in front of the galaxy because of its rapid motion. Depending on the binding energy of the gas in the galaxy, the intra-cluster medium will either be forced to flow around the galaxy or will blow through it removing some of the diffuse interstellar medium. Related mechanisms are thermal evaporation (Cowie & Songaila 1977) and viscous stripping of galaxy discs (Nulsen 1982), that occur when ram-pressure is not effective. In this case, turbulence in the gas flowing around the galaxy entrains the interstellar medium resulting in its depletion. Unlike the physical mechanism discussed before, gas stripping does not affect galaxy morphology. At least not directly. But once star formation is halted in a disc, this can fade significantly, the bulge-to-disc relative importance can change, and therefore the galaxy morphology can appear different. The effect of ram-pressure stripping has been discussed only in a couple of studies using semi-analytic techniques (Okamoto & Nagashima 2003; Lanzoni et al. 2005). These conclude that the inclusion of this additional physical process causes only mild variations in galaxy colours and star formation rates. This happens because the stripping of the hot gas from galactic haloes (see below) suppresses the star formation so efficiently that the effect of ram-pressure is only marginal.

**Strangulation**: Current theories of galaxy formation suggest that when a galaxy is accreted onto a larger structure, the gas supply can no longer be replenished by cooling that is suppressed (Larson et al. 1980). This process has been given the quite violent name of ‘strangulation’ (or ‘starvation’ or ‘suffocation’) and it represents one important element of semi-analytic models of galaxy formation. It is common to read in discussions related to these physical mechanisms that strangulation is expected to affect a galaxy star formation history on a quite long timescale and therefore to cause a slow declining activity. This is not what happens in practice. If this process is combined with a relatively efficient supernovae feedback (and this is the case in many recent models), galaxies that fall into a larger system consume their cold gas very rapidly, moving onto the red-sequence on quite short time-scales. The left panel of Fig. 2 shows the u-r vs r colour-magnitude relation for such a model. The right panel shows the colour distribution of model galaxies in the magnitude bin \([-19.7, -19.8]\). The figure clearly shows that the ‘transition’ region does not appear to be as well populated as observed. It also appears that there is a clear excess of faint red satellites with respect to observational data (see also Balogh, this volume).

**AGN heating**: Since the milestone paper by White & Frenk (1991), it has been realized that some physical process is needed to suppress cooling flows
that otherwise would produce too many massive and luminous galaxies at odds with observational results. Early semi-analytic models introduced ad-hoc prescriptions to suppress cooling flows in haloes above a critical mass. Modern models have included more accurate and physically motivated prescriptions and have confirmed that AGN heating is indeed important to reproduce the exponential cut-off at the bright end of the galaxy luminosity function (e.g., Croton et al. 2006; Bower et al. 2006, and many others). These prescriptions are necessarily very schematic and not well grounded in observation. Still much work needs to be done in order to understand exactly how and when AGN feedback is important.

**Cannibalism** : Early theoretical studies have discussed the role of cannibalism due to the dynamical friction in the formation of brightest cluster galaxies (Ostriker & Tremaine 1975; White 1976). This early work was however not successful due to the use of a simplified cluster model (this relates to my discussion in Sec. 1). In the now standard paradigm of structure formation, clusters assembled quite late, through the merging of smaller systems. In this perspective, cooling flows are the main fuel for galaxy formation at high redshift, in dense and lower mass haloes. This source is removed at lower redshift, possibly due to AGN feedback. Galaxy-galaxy mergers, as discussed above, are most efficient within small haloes with low velocity dispersion. They are indeed driven by dynamical friction, but it is the accretion rate of the galaxies into the proto-cluster, along with the cluster growth itself that regulates and sets the conditions for galaxy merging. This is illustrated very nicely in Fig. 3 which shows the merger tree of a central galaxy of a cluster-sized halo (for details and for a colour version of the figure, see De Lucia & Blaizot 2006). Fig. 3 shows another important point: in the context of the hierarchical paradigm for structure formation, the full history of a galaxy is described by its complete merger tree. Whereas in the monolithic approximation the history of a galaxy

![Figure 2](image-url)
can be described by a set of functions of time, hierarchical histories are difficult to summarise in a simple form, because even the identity of a galaxy is ill-defined. A galaxy is no more a single object when viewed at different times but the ensemble of its progenitors, all of which need to be taken into account for a correct characterisation of the stellar population of the final object. It is also interesting to note that although the merger trees of these central galaxies have a very large number of branches, only a few of these contribute significantly to the final mass of the system (those shown as symbols which have mass larger than $10^{10} \, M_\odot \, h^{-1}$) - this relates back to the discussion about the left panel of Fig. 1.

![Figure 3. Merger tree of a central galaxy of a cluster-sized halo. The area of the symbols scales with the stellar mass. Only progenitors more massive than $10^{10} \, M_\odot \, h^{-1}$ are shown with symbols. Circles are used for galaxies that reside in the FOF group inhabited by the main branch. Triangles show galaxies that have not yet joined this FOF group. (From De Lucia & Blaizot 2006).](image)

3. Heredity

As discussed in the introduction, a simple distinction between ‘heredity’ and ‘environment’ is difficult to accommodate within the current standard paradigm for structure formation. Although early numerical studies found little dependence of halo properties on environment (e.g. Lemson & Kauffmann 1999), more recent studies have come to different conclusions. Taking advantage of high resolution simulations of structure formation, recent studies have demonstrated that halo properties like concentration, spin, shape, and internal angular momentum show clear environmental trends (e.g. Avila-Reese et al. 2005). Haloes in high density regions form statistically earlier and a higher fraction of their mass is assembled in major mergers compared to similar mass haloes in lower density
regions (Gao et al. 2005; Maulbetsch et al. 2006). Clearly, this is bound to leave an ‘imprinting’ on the galaxies that inhabit different regions today.

Figure 4 shows the median properties of model elliptical galaxies as a function of distance from the cluster centre. Data in Fig. 4 show that galaxies closer to the centre are on average older, more metal rich, and redder than galaxies at the outskirts of these clusters. Data in panel (d) show that this trend is partly driven by mass segregation. A radial dependence of galaxy properties is, however, also a natural consequence of the fact that mixing of the galaxy population is incomplete during cluster assembly. This implies that the cluster-centric distance of the galaxies is correlated with the time they were accreted onto a larger structure, with galaxies closer to the centre being accreted earlier than those residing at the outskirts (Diaferio et al. 2001; Gao et al. 2004). If the accretion in a larger system is associated with suppression of star formation, the longer a galaxy is a satellite, the older its stellar population is.

The assembly history of dark matter haloes plays therefore some role in determining the observed environmental trends. Little work, however, has been devoted to quantify explicitly this dependence (see Maulbetsch et al. 2006 for a first attempt in this direction).

4. Conclusions

Are the observed environmental trends of galaxy properties determined very early on (‘heredity’ or ‘nature’ hypothesis) or the result of processes that have operated during the galaxies life-times (‘environment’ or ‘nurture’ hypothesis)? The perhaps unsurprising answer to this question is that both necessarily play a role. Only a few of the physical processes that I have discussed in Sec. 2 are
explicitly included in modern semi-analytic models of galaxy formation. Models based on merger trees extracted from numerical simulations represent an interesting tool to be used in this context, because they intrinsically take into account the dependencies of halo assembly history and properties on environment. A combination of data from the new generation of large surveys, both in the local Universe and at high redshift, with insight gained from modern numerical simulations of structure formation will provide an important key to deciphering the relative importance of heredity and environment in determining the observed environmental trends of galaxy properties.

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