Observing Massive Galaxy Formation

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Abstract. A major goal of contemporary astrophysics is understanding the origin of the most massive galaxies in the universe, particularly near ellipticals and spirals. Theoretical models of galaxy formation have existed for many decades, although low and high redshift observations are only beginning to put constraints on different ideas. We briefly describe these observations and how they are revealing the methods by which galaxies form by contrasting and comparing fiducial rapid collapse and hierarchical formation model predictions. The available data show that cluster ellipticals must have rapidly formed at $z > 2$, and that up to 50% of all massive galaxies at $z \sim 2.5$ are involved in major mergers. While the former is consistent with the monolithic collapse picture, we argue that hierarchical formation is the only model that can reproduce all the available observations.

1. Introduction

Massive galaxies, typically those with stellar masses $> 10^{10} \, M_\odot$, are the best studied galaxies at all distances due to their high luminosities. Because we can study these galaxies in detail, nearly all galaxy formation ideas, models, and scenarios are geared towards constraining the properties of these systems (Tinsley & Gunn 1976; Cole et al. 2000). A persistent unanswered question is however: how did these galaxies form? There are currently no lack of theoretical answers, although observations are only just beginning to constrain different ideas.

It is very popular to divide major galaxy formation scenarios into two different classes: the so-called monolithic collapse (Tinsley & Gunn 1976) and hierarchical formation, usually in the milieu of the Cold Dark Matter (CDM) paradigm (Cole et al. 2000). If we accept that galaxies are embedded in dark matter halos then we have an additional, and perhaps more fundamental, problem of determining how dark halos assembled, and how galaxy formation occurred in concert with this.

Monolithic collapse models assume that early in the universe’s history ($z > 2$) baryonic gas in galaxies collapsed to form stars within a very short period of time ($\sim 100$ Myr) with star formation rates of $10^2 - 10^3 \, M_\odot \, yr^{-1}$, creating massive galaxies that thereafter passively evolve in luminosity. In hierarchical models, galaxies form through mergers of pre-existing smaller systems. With these two major ideas as guidelines, we will describe observational properties of the most massive galaxies in the nearby and distant universe and how these observations currently favor the hierarchical idea.
Currently we believe that giant elliptical galaxies in clusters formed their stellar mass early in the universe at $z > 2$ (e.g., Ellis et al. 1997) and most galaxy formation studies also try to answer when these objects formed. This review is focused on answering the other fundamental origin question of how this formation occurred. Three basic pieces of evidence are discussed: 1. The fact that nearby giant ellipticals contain old ($> 8$ Gyr) stellar populations, 2. The well-defined scaling relations for ellipticals (i.e., fundamental plane) seen out to $z \sim 1$, and 3. The structural appearances of high-$z$ galaxies. While monolithic collapse models can account for the first two through a rapid early formation, the spatial structures of high-$z$ galaxies at $z \sim 2.5$ can only be reconciled with the hierarchical model.

2. Properties of Nearby Massive Galaxies

Massive galaxies in the local universe include ellipticals, and spiral galaxies with large central bulges. Most galaxy formation models are designed to reproduce the properties of these systems, which is a natural approach towards understanding galaxy formation as nearby systems are the only ones which we can study in great detail (see Conselice et al. 2002 for a recent overview of low-mass galaxy formation which must be dealt with in a different manner.) We examine below the properties of nearby giant ellipticals and why most giant ellipticals in clusters must have formed early.

Ellipticals contain mostly old stellar populations; this is particularly true for those in dense areas (Trager et al. 2000). The existence of these old stellar populations indicate that the bulk of the stars in massive galaxies must have formed long ago. This is also true to a lesser extent for the bulges of early type spiral galaxies and ellipticals found in regions of lower density (Trager et al. 2000). It appears likely that the oldest stars in the universe are in cluster elliptical galaxies.

To determine the origin of these galaxies, it would be very useful to know whether or not the stellar populations in ellipticals formed all at once (within a 100 Myr or so), as in the monolithic collapse model, or if the stars were formed in discrete episodes. Unfortunately, determining the ages of individual stars in these galaxies, which is currently impossible, would not help us resolve this issue, as current techniques for dating old $> 5$ Gyr stellar populations are uncertain by at least several Gyrs.

Other important clues for understanding the origin of elliptical galaxies are the very strong correlations between photometric and spectroscopic parameters. These include the color-magnitude relationship, the correlation of velocity dispersion and luminosity, the correlation of
3. Properties of High Redshift Galaxies

3.1. The Galaxy Population at $z > 2$

The census of massive high redshift galaxies is likely still incomplete, but a suitable fraction of the massive high-$z$ population has likely been uncovered (e.g., Giavalisco 2002). These include Lyman break galaxies (LBGs), extremely red objects (EROs), sub-mm SCUBA sources, and quasars. These systems are likely the progenitors of the most massive galaxies in the nearby universe, based on their clustering properties and stellar masses (e.g., Papovich et al. 2001; Giavalisco 2002).

The best characterized of these are the Lyman break galaxies which are high redshift $z \sim 2 - 4$ starburst galaxies. EROs are currently thought to be a combination of dusty starbursts or systems with old stellar populations, with total masses $> 10^{12} M_\odot$ (Moustakas & Somerville 2002). SCUBA sources are likely dusty starbursts, analogs of nearby ULIRGs, that also potentially evolve into the large galaxies we see
in the nearby universe. Not surprisingly, many of these galaxies are undergoing, or recently underwent, intense star formation, essentially forming galaxies. Studying these high-\(z\) populations is an extremely active research area, although we still only understand their basic properties such as current star formation rates and stellar masses (Papovich et al. 2001). These measurements also only reveal when, as opposed to how, these galaxies formed.

### 3.2. Structures of High Redshift Galaxies

A major, and hereto largely unexplored, technique for solving the origin problem is through the use of structural features, including the sizes, shapes and morphologies of high redshift galaxies. One difference between young and modern massive galaxies, besides the intensive amounts of star formation at high-\(z\), is the rarely commented on morphological properties of \(z \sim 2 - 3\) galaxies as imaged by the Hubble Space Telescope (HST) (Figure 1). These are galaxies that would be considered peculiars in most morphology systems, and often mergers from the presence of multiple components and tidal tails. One must however be careful about making this connection as the appearances of these galaxies is dominated by intensive star formation at all wavelengths. However, recent advances in image analysis (e.g., Conselice et al. 2000a; Conselice 2003) now allow for objective morphological methods of identifying galaxies undergoing mergers.
Figure 3. The inferred merger fractions of HDF galaxies derived through the asymmetry method (Conselice et al. 2003). The solid large circles are merger fractions at different magnitude cuts (shown above each panel) as a function of redshift. The other points on the plots are the corresponding merger fractions derived by Patton et al. (1997), LeFèvre et al. (2000) and Carlberg et al. (2000). The dark blue lines show fits to only the asymmetry points, while the light blue lines shows similar fits while holding the $z \sim 0$ fraction constant at 0.02. The red line shows merger fraction predictions chosen in exactly the same way they are observationally, from a semi-analytic CDM model (Benson et al. 2002). The shaded region is the $\pm 1\sigma$ random error on the merger fractions computations.

Most nearby bright galaxies (> 95%) are relaxed and can be placed on the Hubble sequence, appearing as simple normal ellipticals and spirals. There are however some nearby galaxies that appear peculiar,
which cannot be placed into standard classification systems. A subset of these are galaxies undergoing mergers, such as the Ultra Luminous Infrared Galaxies (ULIRGs). While the process of morphologically classifying galaxies as mergers is difficult, and subjective, the process is removed of ambiguity by using a computerized approach (Conselice 2003; Figure 2).

The stellar light distribution of galaxies holds significant information about the formation histories of galaxies, including whether or not they recently underwent a major merger (Conselice et al. 2000b; Conselice 2003; Figure 2). Galaxy mergers can be identified through the use of the asymmetry index (Conselice et al. 2000a), where the most asymmetric galaxies are those that have undergone a major merger in the last Gyr (Conselice 2003). The criteria for choosing a galaxy as a merger has been found empirically through studies of nearby mergers such as ULIRGs (Figure 2) and through N-body models (Conselice et al. 2003). Few galaxies, including those seen at different viewing angles, that are not involved in a recent major merger have asymmetry values $> 0.35$. The only nearby galaxies with high asymmetries are starbursts and ULIRGs involved in major mergers (Figure 2).

It is still unknown whether the application of this criteria at high redshifts is valid. Based on the understanding of how asymmetry behaves for nearby galaxies, it is a criteria with as much basis as any other, including kinematic measurements, as all are based on a priori assumptions of what is a merger.

![Figure 4](image-url)

*Figure 4.* The fraction of stellar mass involved in major mergers as a function of redshift, selected by stellar mass and absolute magnitude limits. The most massive $M_{\text{stellar}} > 10^{10} M_\odot$ and brightest systems $M_B < -21$ have the highest fraction (50%) of their mass involved in mergers at $z \sim 2.5$, although this fraction decreases steeply with redshift.

What do we find when we measure the asymmetries of high redshift galaxies in their rest-frame B-band using WFPC2 and NICMOS
observations of the Hubble Deep Field North? As we would expect in
the hierarchical model, there are more galaxies consistent with mergers
at high redshift than at lower redshifts (Figure 3). We find that the
fraction of galaxies undergoing major mergers significantly increases
for brighter and more massive systems (Conselice et al. 2003). The
fraction of stellar mass involved in major mergers also increases steeply
with redshift for the most massive and brightest systems (Figure 4). For
bright and massive LBGs at $z > 2.5$ with $M_B < -21$ and $M_{\text{stellar}} > 10^{10}
M_\odot$, approximately half of all galaxies are involved in major mergers
with an evolution of $(1 + z)^{3.7\pm0.3}$ (Conselice et al. 2003).

Lower mass and fainter galaxies are not undergoing mergers at the
same high rate (Figure 3) with an almost constant merger fraction
history that only slightly increases at higher redshifts. The peak merger
fraction for lower mass systems is $\sim 20\%$ at $z \sim 1$. Our analysis
indicates that these merger fraction computations are not biased by
selection effects or systematic errors (Conselice et al. 2003).

4. Testing Models

4.1. Evidence for Monolithic Collapse

There are several observations used to argue that massive galaxies
formed through a monolithic collapse, or rather that they did not form
through hierarchical merging. The main argument in favor of an early
collapse has to do with what we will call “smart” stars that inhabit
massive galaxies. Elliptical galaxy stars are smart because they seem to
know the global properties of the galaxy they inhabit, namely its total
luminosity and velocity dispersion ($\S2$) which likely correlate with total
mass. The strong correlation between various parameters like [$\alpha$/Fe]
ratios and velocity dispersion, such that more massive systems are $\alpha$
element enhanced, imply that the giant ellipticals formed very rapidly,
removing gas from these systems before significant amounts of Fe from
Type Ia supernovae can pollute material that future generations of
stars form from. Rapid monolithic collapse models nicely reproduce
these features (e.g., Chiosi & Carrao 2002).

Additionally, if all galaxies form as single systems of the same low
mass and then merge, the stars inside these galaxies should all be
roughly homogeneous, if simple feedback scenarios are implicated for
understanding star formation (e.g., Dekel & Silk 1986), and no further
star formation occurs and environmental effects are ignored. This is
obviously an over idealized situation, but the seemingly uniformly old
stellar populations of massive galaxies in clusters at low and high red-
shifts (e.g., Bower et al. 1992; Ellis et al. 1997) demands an explanation,
especially since hierarchical models predict that ellipticals should still
be forming up until and later than \( z \sim 1 \) (Kauffmann, Charlot & White 1996). However, the morphologies of high-z galaxies (Figure 1 and 3) and the fact that they are not homogeneous in color, but have bluer (and presumably younger) cores (Moth & Elston 2002; Menanteau et al. 2001) are strong arguments against a single monolithic collapse.

4.2. **Evidence for Hierarchical Formation**

As discussed in the introduction, the formation of galaxies through hierarchical formation is complicated by dark halo formation which may or may not be occurring at the same time. To state this another way, dark halos could be merging early in the universe, as demanded by CDM models, without any cooling of baryons to form stars until most halo merging is finished. If this is the case then galaxies form in effectively the same way in monolithic and hierarchical models. The question to answer is then whether or not massive galaxies formed through mergers of extant galaxies, that is halos with stars.

4.2.1. **Clues at Low Redshift**

Observationally, the hierarchical formation of giant galaxies has been argued based on their steep \( r^{1/4} \) surface brightness profiles which are seen in ongoing mergers such as Arp 220, and are predicted in models to be the natural outcome of major mergers (Barnes & Hernquist 1992). Perhaps more convincing is the visible signs of past merging activity around giant elliptical galaxies, such as the so-called shells or ripples found around 10% of all massive galaxies (e.g., Schweizer & Seizer 1988). A significant number of central cluster galaxies also show evidence for recent merger activity in the form of multiple nuclei and tidal features (e.g., Conselice et al. 2001). Another piece of evidence for merger activity are decoupled cores found in the centers of up to half of all ellipticals (e.g., de Zeeuw et al. 2002). This evidence is however not yet strong enough to show convincingly that all massive spheroidal galaxies form by merging, as not every nearby elliptical has these properties. Most tell-tale structural signatures of merging would also be erased by now, particularly in dense areas such as clusters.

4.2.2. **Clues at High Redshift**

One method of determining how massive galaxies formed is to measure the mass or luminosity function of galaxies as a function of redshift. There should be more low-mass galaxies and fewer massive galaxies at high redshift, if mergers occurred, than we see in the nearby universe. At later times the number of massive galaxies should increase, while the number of lower mass galaxies should decline assuming no new galaxy/star formation.
Another more direct approach is to identify galaxies at high redshift which are undergoing mergers and to use this to determine the past history of merging. Unfortunately, it is very difficult to demonstrate with certainty that a given galaxy is undergoing a merger. One can use identifiable aspects of nearby major mergers, such as massive star formation, to identify mergers, but massive starbursts can be triggered by a variety of methods (e.g., Conselice et al. 2000b).

As we argued in §3.2, at least 50% of galaxies at $z > 2.5$ are morphologically consistent with undergoing a merger. Other methods of finding mergers through galaxy pair counts, either kinematic or spatially projected (Patton et al. 1997; LeFèvre et al. 2000; Carlberg et al. 2000), agree with our results out to $z \sim 1$ (Figure 3). As briefly mentioned, there are stellar population gradients inside Lyman break galaxies seen in the Hubble Deep Field North such that the centers of LBGs are bluer than their outer parts (Moth & Elston 2002). This cannot result from a monolithic collapse of gas, and suggests an origin from preexisting galaxies in merger driven central starbursts (Mihos & Hernquist 1996).

Massive starbursts induced by mergers also solves the smart star problem. When two dark matter halos merge with galaxies in them, those galaxies will appear as distinct objects until they merge due to dynamical friction, although they both occupy effectively the same dark halo. Star formation can be induced by the interaction/merger between these two systems if they contain cold gas. New stars forming within this massive dark halo will have properties and characteristics that mimic those of massive galaxies, producing the required smart stars. At present we do not directly know if the most massive nearby galaxies in clusters underwent multiple early episodes of star formation, although field ellipticals at $z \sim 1$ show a clear diversity of recent star formation properties (Menanteau et al. 2001). In any case, if a significant fraction of star formation occurs in a massive galaxy forming through a merger, the resulting star formation will produce smart stars.

5. Final Comments

The implications of these results, with the caveat that the Hubble Deep Field North is a small area, is that most massive galaxies formed through the mergers of preexisting galaxies. If anything, we are likely underestimating the fraction of galaxies undergoing mergers at $z \sim 3$ with the asymmetry method, as fainter and nosier images give systematically lower asymmetry values (Conselice et al. 2000a). A similar analysis of the Hubble Deep Field South reveals a similar large
merger fraction at high redshifts, despite the claim that there exist more evolved galaxies at $z \sim 2.5$ (e.g., Labbé et al. 2002). Note that although hierarchical formation does seem to be occurring, the agreement with semi-analytical CDM models is relatively poor, except for the brightest and most massive systems (Figure 3).

In the future, deep observations with SIRTF will help constrain the properties and stellar masses of the underlying older stellar populations in these high redshift star forming system. Kinematic measurements using IFUs on 8 meter telescopes will also soon reveal the kinematic properties of these forming galaxies. Ongoing and future observations with the Advanced Camera for Surveys on HST will also allow for a more thorough search and characterization of the merger process through galaxy structures.

I thank Richard Ellis, Kevin Bundy, Matt Bershady, Mark Dickinson, Casey Papovich and Mike Santos for valuable conversations on these topics, and permission to discuss and cite unpublished results.

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