Galaxy Mergers and Interactions at High Redshift

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Abstract. In this review we discuss the evidence for galaxy interactions and mergers in the distant universe and the role of mergers in forming galaxies. Observations show that the fraction of massive ($M > M_*$) galaxies involved in major mergers is roughly 5–10% at $z \sim 1$. The merger fraction however increases steeply for the most massive galaxies up to $z \sim 3$, where the merger fraction is $50 \pm 20\%$. Using N-body models of the galaxy merger process at a variety of merger conditions, merger mass ratios, and viewing angles this merger fraction can be converted into a merger rate, and mass accretion rate due to mergers. A simple integration of the merger rate shows that a typical massive galaxy at $z \sim 3$ will undergo 4–5 major mergers between $z \sim 3$ and $z \sim 0$, with most of this activity, and resulting mass assembly, occurring at $z > 1.5$.

1. Introduction

Do galaxies merge? Does the formation of galaxies rely on merging? The answer to the first question is undoubtedly yes. There are undeniable and famous ongoing galaxy mergers in the nearby universe, such as the Antennae, as well as accretion of galaxy satellites into our own galaxy. Perhaps mergers are rare however, and perhaps the low level merging seen in our own galaxy is a minor contributor to its mass and evolution.

On the other hand, merging may be the dominate method whereby galaxies acquire their mass, and this activity may drive the evolution we see in distant galaxies (e.g., Hopkins *et al.* 2006). It is furthermore possible that galaxy merging is not only the driving force behind galaxy formation, but may also induce star formation and black hole growth, and has been conjectured to be the link between galaxies and quasars. We are just beginning to explore observationally the idea that merging is the dominate method whereby galaxies form, and understanding its role in a cosmological context will likely be one of the major debates in extragalactic astrophysics in the coming years.

There are many reasons to expect that galaxies form through mergers. Perhaps the most overwhelming is that the largely accepted cosmological model – a Λ dominated Cold Dark Matter (CDM) based universe – explicitly predicts that galaxies should form in the merger process. If mergers are not responsible for the majority of massive galaxy formation, it would require a reevaluation of our assumptions concerning dark matter and the nature of baryonic physics. More likely, observational studies of the merger history will allow us to test galaxy formation models on a very fundamental level.

Despite the importance of understanding the history of galaxy merging, there is very little known about its history, and the available results still contain large uncertainties. Despite this, it is worth reviewing the evidence for the role of mergers in the formation of galaxies. We argue that the available evidence suggests that mergers are the dominate process in forming at least the most massive galaxies in the universe.
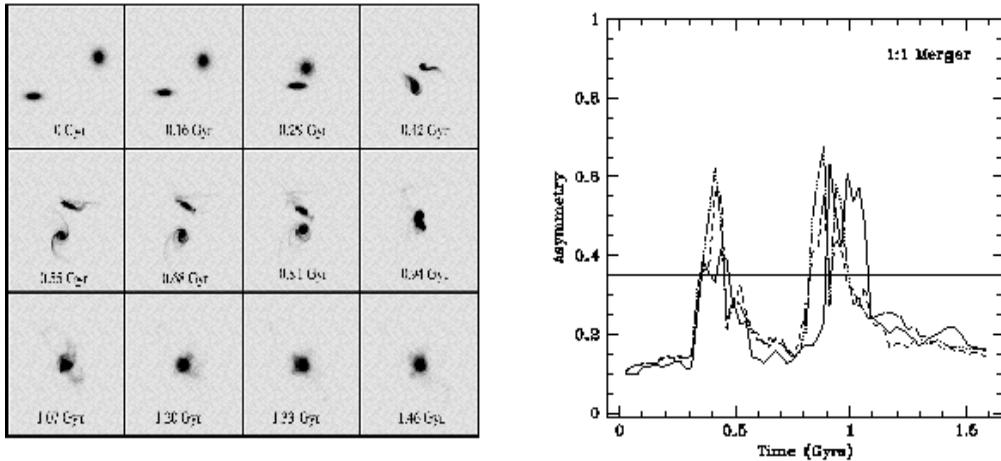
Figure 1. N-body model of two disk galaxies with the same mass merging. The number on the bottom of each simulated image shows the time in the simulation. The resulting measured asymmetry for each galaxy is shown on the right hand panel (Conselice 2006).

2. Observed Merger History

2.1. *Merger Fractions*

The measurements of the history of galaxy merging is sometimes thought to be ambiguous. However this often results from comparing measured galaxy merger fractions (f_{gm}) and merger rates ($\Re$) using different techniques to identify the total number of galaxies involved in mergers (N_{gm}) at various wavelengths (λ), as well as at different luminosity (M_B), and stellar mass (M_*) ranges. Alter any of these properties, and the measured merger fraction will change. The observed merger fraction is the number of galaxies determined to be a merger by a technique within a given set of observables divided by the total number of galaxies within that observable range.:

$$f_{gm}(M_*, M_B, z, \lambda) = \frac{N_{gm}(M_*, M_B, z, \lambda)}{N_T(M_*, M_B, z, \lambda)}.$$

Very different merger fractions for the same population of galaxies can be uncovered by using techniques that differ in merger sensitivity. Normalising the merger fraction by its time-scale sensitivity gives the merger rate, and normalising the merger rate by the mass sensitivity gives the mass accretion rate. The merger rate and the mass accretion rate are the preferred measured quantities. These quantities are hard to measure, but early attempts to measure them are promising (Conselice 2006).

There are only a few methods for measuring the merger fraction, all of which have their limitations and advantages. The oldest and perhaps most straightforward observational method is to look for galaxies in pairs (e.g., Lin *et al.* 2004). However, pair studies require spectroscopy of complete samples of field galaxies, and have only successfully been applied up to $z \sim 1.4$. The pair fraction, and resulting merger fraction based on pairs of similar luminosities, increases slightly up to $z \sim 1$ (see Bridge *et al.* 2006). The other method, particularly useful at $z > 1$, is to look for galaxies that are peculiar in their morphology or kinematics, and to use this as a measure of the merger fraction (Conselice *et al.* 2003; Lavery *et al.* 2004; Papovich *et al.* 2005; Conselice *et al.* 2005; Lotz *et al.* 2006). For example, studies utilising the asymmetry index (Conselice *et al.* 2000; Conselice 2003) show that the merger fraction is very high at $z \sim 2.5$, with the $M_* > 10^{10}$ $M_\odot$ merger fraction at $\sim 50\%$, and steeply declining as $(1+z)^{3\pm0.3}$.
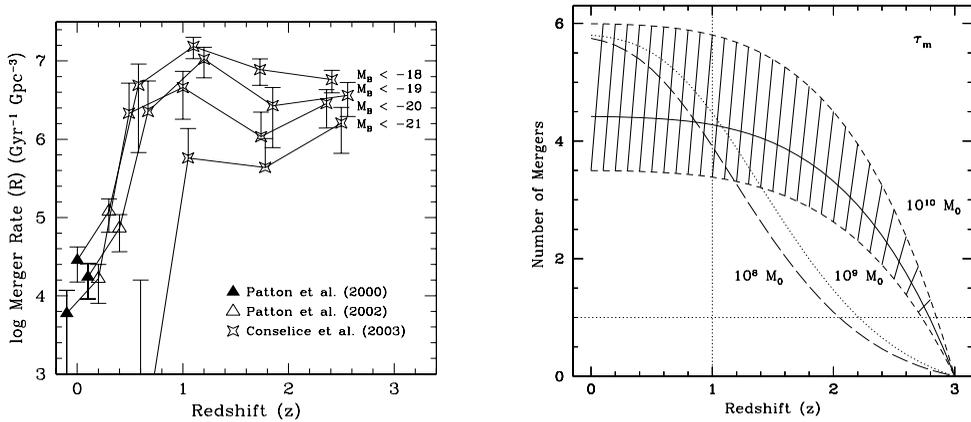
Figure 2. Evolution of the merger rate, in units of Gyr and co-moving Gpc^3, as a function of redshift and observed magnitude (left panel), and the empirically determined integrated number of major mergers since $z \sim 3$. These merger rates and histories are taken from merger fraction data in Conselice *et al.* (2003) and Patton *et al.* (2002, 2000).

Determining the history of galaxy interactions, as opposed to active mergers, is more difficult. In some sense, looking for galaxies in pairs (Patton *et al.* 2002) gives us a good idea for the likely interaction history, as close galaxies will be interacting without necessarily merging. While some increase in the star formation rate is seen for galaxies in close pairs (e.g., Barton *et al.* 2003), it is not clear what the global role interactions play in the increase of stellar mass in galaxies. Recent investigations suggest that the merger and interaction history together contribute a large fraction of the star formation at $z < 1$ (Bridge *et al.* 2006).

2.2. *Galaxy Merger Rates*

The measurements of galaxy merger rates, and mass accretion rates due to the merger process, are the ultimate goal of galaxy merger studies. Observationally, it is not trivial to determine the merger rate, and very often it is necessary to utilise models in some regard. The basic problem is understanding how long during a merger your particular method of finding mergers is sensitive. This quantity is in principle easy to measure for systems in pairs using dynamical friction arguments; yet it is impossible to constrain the relative velocities between galaxy pairs in the tangential direction or know the spatial separation in the radial direction. Considering all of these uncertainties the time-scale for two galaxies at roughly 20 kpc separation will merge within 0.5–1 Gyr.

Converting a measured merger fraction derived morphologically has its own advantages and problems. In principle it could be easier to measure the time-scale for merging sensitivity. Analysing a set of N-body simulations of mergers, Conselice (2006) determine the first time-scales on the merger process using the CAS methodology (Conselice 2003) for finding mergers. An example of this is shown in Figure 1 where the morphological evolution of two disk galaxies merging is shown, as well as the resulting asymmetry computation for this simulation. Based on these simulations, viewed at various angles and including galaxies in various orbital configurations, a time-scale in which a merging galaxy would be found within the CAS system can be derived. For galaxies with masses 10^{11} $M_{\odot}$ the merger sensitivity is $\tau_{m} = 0.38 \pm 0.1$ Gyr. Using this merger time-scale we can calculate the merger rate evolution for galaxies up to $z \sim 3$ (Figure 2).

A new, and potentially powerful, method for measuring the evolution of the merger rate is to determine how the correlation function of galaxies changes over time (e.g., Masjedi *et al.* 2006). The inferred merger rate since $z \sim 0.36$ for luminous elliptical galaxies show that mergers since at least this time have been rare. A similar method applied up to $z \sim 1$ demonstrates some evolution, perhaps one merger per massive galaxy since $z \sim 1$ (Bell *et al.* 2006).

3. Implications of the Merger History

We can use the merger rate to determine the total number of mergers an average galaxy undergoes since the beginning of our observational epoch. By integrating the merger rate since $z \sim 3$ we find that a typical massive galaxy with $M_* > 10^{10}$ $M_\odot$ undergoes $4.4^{+1.6}_{-0.9}$ mergers (Figure 2). An additional feature of the N-body models analysed in Conselice (2006) is the ability to determine the merging galaxy mass ratios that can produce high asymmetries. The result of this is that the CAS method is only sensitive to major mergers, that is mergers with a mass ratio of 1:3 or lower (see also Hernandez-Toledo *et al.* 2005). This also allows us to determine how much mass is likely added to galaxies due to the merger process since $z \sim 3$. The result is that a galaxy which undergoes on average 4.4 major mergers can increase its total mass by a factor of ~ 10. Due to the advent of deep X-ray imaging, we can also now test the idea that galaxy interactions and black hole build up are related. The evidence for a connection is ambiguous (Grogin *et al.* 2005; Pierce *et al.* 2006), unless there is a significant delay between the merger and AGN activity.

The uncertainties on merger fraction histories and rates are still uncomfortably large. Future surveys utilising high-resolution wide-field near-infrared imaging will revolutionise this field. Complete redshift surveys at $z > 1.5$ will furthermore allow us to determine the pair and interaction history at higher redshifts, although such a survey will be largely impossible until the existence of 20–30 m telescopes. There are also largely no constraints on the minor merger history, although methods to measure these are in development. These and other technical advances in the coming years will advance our knowledge of the role of mergers and interactions in galaxy formation considerably.

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