The structures of distant galaxies – IV. A new empirical measurement of the time-scale for galaxy mergers – implications for the merger history

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ABSTRACT

Understanding the role of mergers in galaxy formation is one of the most outstanding problems in extragalactic astronomy. While we now have an idea for how the merger fraction evolves at redshifts $z < 3$, converting this merger fraction into merger rates, and therefore how many mergers an average galaxy undergoes during its history, is still uncertain. The main reason for this is that the inferred number of mergers depends highly upon the time-scale observational methods are sensitive for finding ongoing or past mergers. While there are several theoretical and model-based estimates of merger times, there is currently no empirical measure of this time-scale. We present the first observationally based measurement of merger times utilizing the observed decline in the galaxy major merger fraction at $z < 1.2$ based on $> 20000$ galaxies in the Extended Groth Strip Survey and Cosmic Evolution Survey. Using a new methodology described in this Letter, we are able to determine how long a galaxy remains identifiable as a merging system within the CAS system. We find a maximum CAS major merger time-scale of $1.1 \pm 0.3$ Gyr at $z < 1.2$, and a most likely CAS merger time-scale of $0.6 \pm 0.3$ Gyr, in good agreement with results from $N$-body simulations. Utilizing this time-scale, we are able to measure the number of major mergers galaxies with masses $M_\star > 10^{10} M_\odot$ undergo at $z < 1.2$, with a total number $N_m = 0.90^{+0.44}_{-0.23}$. We further show that this time-scale is inconsistent with a star formation origin for ultrahigh asymmetries, thereby providing further evidence that structural methods are able to locate mostly merging galaxies.

Key words: galaxies: evolution – galaxies: formation – galaxies: structure.

1 INTRODUCTION

One of the key observable quantities for understanding the evolution of galaxies is the merger rate. This is defined as the number of galaxies which are merging per unit time, per unit volume, as a function of the history of universe. The merger rate, when known, reveals the ultimate importance of mergers within the galaxy formation process. Previous papers in this series have explored this issue in great depth, and have derived the merger history in terms of the merger fraction evolution up to $z = 6$ (Conselice, Rajgor & Myers 2008, hereafter Paper I; Conselice & Arnold 2009, hereafter Paper II; Conselice, Yang & Bluck 2009, hereafter Paper III). These papers find that the merger fraction increases with higher redshifts, and largely flattens at roughly $z > 1.5$ or so. The merger fraction is also non-neglectable, and in general between 2 and 6 major mergers occur per galaxy with stellar mass $M_\star > 10^{10} M_\odot$ since $z = 3$.

This large uncertainty in the cumulative number of mergers is the result of uncertainties in the time-scale for the merger process. While it is relatively easy to measure the merger fraction, converting this into a merger rate requires knowledge of the time sensitivity of our methods for locating merging galaxies. For example, if a method of finding mergers was sensitive to long-lived features, such as outer tidal tails, then the merger fraction would be high. However, because the time-scale is also large in this case, the merger rate $\sim f_m/\tau_m$ would be the same if the process for measuring the merger fraction had a very short-time sensitivity, as while merger fractions can differ the merger rate must be the same if measuring the same process (e.g. Paper III).

The major merger fractions and rates we measure in Papers I–III all use the CAS system, which is well calibrated on nearby and high-redshift objects in various environments (e.g. Conselice, Bershady & Jangren 2000a,b; Conselice 2003; Conselice et al. 2003; Conselice, Blackburne & Papovich 2005; Conselice 2006a; Paper I; Paper II; Paper III). However, a major unknown factor is the time-scale sensitivity of the CAS system within the major merger process.

There have been several attempts to understand and calculate what this merger time-scale sensitivity is. The first attempt was carried out by Conselice (2006a) who measured $N$-body models of...
the merger process to determine how long a merging galaxy would be asymmetric enough to be considered a major merger. Conselice (2006a) calculated an average value of $\tau_m = 0.4 \pm 0.2$ Gyr. However, these $N$-body models are basic, and do not include star formation, dust, etc., which are all important factors in understanding and interpreting galaxy structure. More recently, Lotz et al. (2008) examined elaborate galaxy mergers that include dust and star formation, and determined a merging time-scale for the CAS method of between 0.4 and 1.2 Gyr, depending on the orbital and initial conditions. While we have a rough range of CAS time-scales, this factor of 2–3 uncertainty does not allow us to accurately measure the total number of mergers, or the merger rate, as a function of time. We also have the issue that these time-scales are all model dependent, and it remains possible that the actual merger time-scales are different, and possibly much longer.

In this Letter, we develop and utilize a new empirical method for measuring merger time-scales based on the evolution of the merger fraction at low redshifts. We have recently found that the merger fraction declines at redshifts $z < 1$, and we use this to obtain a minimum time-scale for detecting mergers. In conclusion, we find that the average CAS merger time-scale at $z < 0.7$ is 0.6 $\pm$ 0.3 Gyr for galaxies with stellar masses $M_* > 10^{10}$ $M_\odot$. We furthermore use this value to argue that the minimum number of major mergers which are detectable with CAS. From empirical observations, it appears that gas-rich major mergers are unlikely the majority of the types detected (e.g. Conselice 2006a; Lotz et al. 2008). We furthermore make the assumption that all gas-rich major mergers are detectable with CAS (see Conselice 2006a, 2009b).

If we assume that within the population of asymmetric galaxies, the typical merger time-scale is $\tau_m$ and that these asymmetric galaxies began their merger sensitivity evenly within the past $\tau_m$ years previous to $z = z_1$, this implies that at $z_1$ there is a uniform probability that a given asymmetric galaxy started its merger process sometime in the past $\tau_m$ Gyr. Therefore, after an amount of time $\delta t$ a fraction of these systems will no longer be asymmetric enough to be counted as a merger. This number is given by

$$N_m \times \frac{\delta t}{\tau_m},$$

(2)

where, as an extreme example, after the entire merger sensitivity time-scale has occurred (i.e. $\delta t = \tau_m$), there would remain no galaxies satisfying the merger criteria. After a time $\delta t$, which we take to be at the observed redshift range $z = z_2$, the number of observable ongoing mergers is then

$$N_{2,m} = N_m - N_m \times \frac{\delta t}{\tau_m}.$$  

(3)

Again, this assumes that there have been no additional mergers within the mass range of interest between $z_1$ and $z_2$. If we divide this equation by $N_{tot}$, we get

$$f_{2,m} = f_{1,m} - f_{1,m} \times \frac{\delta t}{\tau_m},$$

(4)

where we have assumed that the total number of galaxies has not significantly changed between redshifts. This equation can then be solved to find the value of $\tau_m$,

$$\tau_m = \delta t \times \left(1 - \frac{f_{2,m}}{f_{1,m}}\right)^{-1}.$$  

(5)

We note that this measurement of $\tau_m$ is a ‘typical’ CAS merger time-scale sensitivity – it is the sum over all merging systems in their various orbital configurations, dust content, star formation rates, inclination, etc. For a mixture of systems with different time-scales, equation (5) will tend to overestimate the average CAS merger time-scale at a maximum of 20–30 per cent based on Monte Carlo simulations. Equation (5) also does not hold when there are mergers occurring between the two redshifts of interest. Thus, we cannot use equation (5) to measure merger time-scales when merging is ongoing.

The time-scale from equation (5) does, however, apply to any distribution of galaxies, even if during a merger a galaxy is asymmetric at two or more distinct times. We test this by a Monte Carlo simulation of galaxies being asymmetric for two different times, and derive similar time-scales as for continuous mergers, using equation (5). The derived CAS merger time-scale does increase slightly if the gap between when a galaxy remains asymmetric is >50 per cent of the total merger time-scale, but this is a very unlikely scenario (Lotz et al. 2008).

We also carry out a Monte Carlo simulation to determine how much influence a small (10 per cent) fraction of galaxies in our sample with long CAS time-scales (>10 Gyr) would affect our results, finding no significant increase in the measured time-scale. However, simulations suggest that the range of time-scales differs by only a factor of 2–3, and a wide time-scale distribution is an unlikely scenario.

We, however, know that massive galaxies at $z < 1.2$ still undergo some merging (e.g. Paper I; Bluck et al. 2009), even between two close redshifts. If we denote the fraction of galaxies which have begun to undergo a merger between $z_1$ and $z_2$ as $f_{2,new}$ then the time-scale $\tau_m$ can be measured as

$$\tau_m = \delta t \times \left[1 - \left(\frac{f_{2,m} - f_{2,new}}{f_{1,m}}\right)\right]^{-1},$$

(6)

where the value of $f_{2,new}$ needs to be determined independently of the change of merger fraction between $z_1$ and $z_2$. We explore

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Galaxy merger time-scales
possible values for $f_{2,\text{new}}$, although the value is unlikely to be higher than a few per cent at $z < 0.7$. This approach can be generalized by the fact that the value of $f_{2,\text{new}}$ depends on the merger rate, or the inverse merger rate per galaxy, $\Gamma$, which is measured as $\Gamma = \Gamma_{m}/f_{\text{gm}}$, and the evolution of $\Gamma$ can be parametrized as a function of redshift (Paper I; Bluck et al. 2008).

If we measure $\Gamma$ in units of 1 Gyr, such that $\Gamma = \Gamma_{1\text{Gyr}}(\tau_{m}/\Gamma_{1\text{Gyr}})$, then by considering the fraction of new mergers, which is $f_{2,\text{new}} = \delta t/\Gamma$, then the time-scale $\tau_{m}$ is

$$\tau_{m} = \delta t \times \left(\frac{f_{1,m} - f_{2,m}}{f_{1,m}}\right),$$

where the value of $\Gamma_{1\text{Gyr}}$ is measured using a time-scale of 1 Gyr. The values of $\Gamma$ in this Letter are measured, in a slightly different way than previously, as the time between successive mergers. The value of $\Gamma$ we use in equation (7) is based on the merger fractions from Paper III (Section 3).

3 DATA

The data we use for this Letter originate from the study of merger fractions at $z < 1.2$, published by Paper III. Paper III find that the merger fraction drops steadily at $z < 1.2$, although the most rapid drop is seen at $z < 0.7$. This decline is found in both the Extended Groth Strip (EGS) Survey and the Cosmic Evolution Survey (COSMOS).

This evolution is shown in detail in fig. 7 of Paper III, in which paper the values we use are also tabulated. In this Letter, we use the individually measured merger fractions in both the COSMOS and EGS surveys, as well as the combination of the two surveys, to measure the merger fraction. We do not discuss the details of the calculation of the merger fraction, although this is described in great detail in Conselice (2003), Conselice et al. (2008a) and Papers I and II. An important aspect concerning our use of merger fractions within this Letter is that they are measured within the same rest-frame wavelength, and in the same way, at different redshifts.

4 ANALYSIS

Our analysis first consists of examining how equation (5) gives an upper limit on the merger time-scale. We later utilize equation (7) to measure the merger time-scale for our sample while accounting for any additional mergers that have occurred between $z_1$ and $z_2$. We carry out our analyses by applying these two equations to various redshift bins of sizes $\delta z = 0.1$. Our resulting time-scales are the average values we find, while the error is the average error on these measurements, given uncertainties in the measured merger fractions. We also describe the scatter in these values at different redshifts.

When we apply equation (5) to our data the maximum time-scale is $\tau_{m} = 1.1 \pm 0.3$ Gyr. That is, the maximum time for a CAS asymmetry to last is roughly $\sim 1$ Gyr. This is similar to the maximum time-scale found for CAS mergers in N-body models by Lotz et al. (2008). This reveals that any claims that the merger time-scale for CAS assumed to date (e.g., Conselice 2006a; Lotz et al. 2008) are underestimated by more than a factor of 2–3 cannot be correct.

We now utilize the fact that even when the merger fraction is declining there are still ongoing mergers between different redshifts, which will raise the merger fraction, and thus result in an overestimated merger time-scale using equation (5). We use equation (7) to calculate the likely true merger time-scale, through an examination of the merger rate per galaxy, or the time between mergers, given by $\Gamma$.

Using equation (7), the computed merger time-scale ranges between $0.3 \pm 0.3$ and $0.9 \pm 0.3$ Gyr, with an average value of $\tau_{m} = 0.6 \pm 0.3$. In general, we find that the computed merger time-scale is lower at lower redshifts between $z = 0.7$ and 0.2 within the combined EGS and COSMOS samples. The values we calculate are roughly similar to what N-body models of the merger process find is the time-scale for CAS sensitivity (e.g., Conselice 2006a; Lotz et al. 2008). Our measurement of merger times is thus likely correct, given the consistency of independent methods.

Our merger time-scale measurement is smaller by roughly a factor of 2 compared to the results of Kitzbichler & White (2008), who calculate merger time-scales for pairs based on semi-analytical simulations. Our merger time-scale is also shorter than other predictions based on semi-analytical models of merging dark matter haloes (e.g. Boylan-Kolchin, Ma & Quataert 2008), suggesting that the implementations of merging time-scales in these models are off by at least a factor of 2 (see also e.g. Conroy, Ho & White 2007; Bertone & Conselice 2009).

One important caveat about this measurement of the merger time-scale is that we cannot assume that it applies at earlier times, particularly in the early universe at $z > 2$ when galaxies were more gas rich than they are today. In principle, the method used in this Letter can be applied at higher redshifts, but will require more accurate measures of the merger fraction than that provided by the available data (e.g. Paper I). Future large surveys with WFC3 on Hubble will potentially allow this measurement to be made at $z > 1$.

5 IMPLICATIONS

5.1 Number of major mergers at $z < 1$

The implications of this result can be obtained by integrating the merger rate per galaxy over time to obtain the number of major mergers a galaxy undergoes since $z = 1$. We assume in this calculation that the efficiency of detection for major mergers is 100 per cent (see Conselice 2006a, 2009b). The number of major mergers is then given by

$$N_{m} = \int_{z_1}^{z_2} \Gamma_{1\text{Gyr}} \, dz = \frac{H_{1\text{Gyr}}}{(z+1) E(z)},$$

where $H_{1\text{Gyr}}$ is the Hubble time and $E(z) = \left[\Omega_{m}(1 + z)^3 + \Omega_{k}(1 + z)^2 + \Omega_{\Lambda}\right]^{-1/2} = H(z)^{-1}$. Using our average time-scale of 0.6 ± 0.3 Gyr, we find that the total number of mergers occurring since $z = 1.2$ is $N_{m} = 0.90^{+0.44}_{-0.23}$. This number is reduced to $N_{m} \sim 0.5$ mergers if we use the maximum time-scale of $\tau_{m} = 1.1$ Gyr. These numbers are similar to what we calculate in previous papers in this series (Paper III), and even in early work where the merger history at $z < 1$ was uncertain (Conselice et al. 2003; Conselice 2006a). However, this is the first completely empirical method for measuring the merger history at $z < 1.2$, without recourse to models.

This implies that massive galaxies with stellar masses $M_{*} > 10^{10} M_{\odot}$ undergo a relatively high number of average major mergers at $z < 1.2$. Most of this merging (~80 per cent) occurs at $z > 0.5$ (Fig. 1). This shows that the major merger process is indeed still occurring, albeit at a reduced rate, for these massive systems within the last half of the age of the universe.

We, however, still do not know for certain what the mass sensitivity of the CAS system is, although N-body models suggest that it is only sensitive to mergers which are 1:3 or greater. We use this to calculate how much mass these galaxies potentially grow by due to
5.2 Orbital and physical conditions of major mergers at $z < 1.2$

While the results we have discussed and presented thus far concern the derived merger history, we can also use our empirically measured time-scales to determine the likely average physical conditions of the mergers themselves. This is done by comparing the time-scale we calculate to the merger time-scales measured through N-body models of equal-mass galaxy mergers from Lotz et al. (2008). Lotz et al. have calculated the time-scale for merging as a function of orbital parameters, and in terms of initial conditions, such as bulge/disc ratio and gas mass fraction. A large fraction of the differences in Lotz et al. (2008) time-scales are due to the orbital parametrization as one of the prograde-prograde (SbcPP), prograde-retrograde (SbcPR), retrograde-retrograde (RR) or prograde-polar (SbcPol). We determine the average merging conditions for galaxies within our sample up to $z < 1$, assuming that orbital time-scales of the Lotz et al. (2008) major merger models are representative of lower mass ratio mergers.

The time-scale for the CAS method within Lotz et al. (2008) ranges from 0.2 to 1.5 Gyr. The shorter time-scales are for galaxy mergers which are not dominated by gas, and have subparabolic orbits, which tend to produce faster merger time-scales. The longest time-scales occur for galaxies in the SbcPR model, with a merger time-scale of nearly $\tau = 1.5$ Gyr (Lotz et al. 2008). Based on our time-scale measurement, we can rule out that the average merger at $z < 1$ is a retrograde-retrograde merger. Because of their short time-scales, we can also rule out a rapid merger history in subparabolic orbits. In fact, the only simple orbital orientation that matches our average value of the merger time-scale of $\tau \sim 0.6$ Gyr is the prograde-prograde orientation, which has a CAS merger time-scale in Lotz et al. of $\tau_m = 0.74 \pm 0.17$.

The best matching orbital configuration, in comparison to our findings, is the SbcPP, the SbcPPr- and the SbcR models. The SbcPPr- model is a prograde-prograde merger with a small pericentric distance, while the SbcR model is a merger with a highly radial orbit with a prograde-retrograde orientation. This reveals that a typical merging galaxy at $z < 1$ is likely a prograde-prograde merger. However, it remains possible, or even likely, that other merger types are occurring, but these cannot dominate the merger process.

5.3 Could asymmetries be produced through star formation?

In this final section, we address the question of whether the asymmetry criteria for locating mergers could be significant affected by star formation events. While it has been shown through using the clumpiness index (Conselice 2003), and a comparison between asymmetries and distorted kinematics (Conselice et al. 2000b), as well as visual estimates of mergers (Conselice et al. 2005) that ultrahigh asymmetries correlate with merging galaxies, we provide further evidence here based on the asymmetry time-scale.

We argue this based on the fact that the merger time-scale is roughly $\tau_m \sim 0.6$ Gyr, and is no higher than $\sim 1.1$ Gyr at $z < 1.2$. If the asymmetric regions in these galaxies were due to star forming complexes, they would last no longer than a few tens of Myr, as the ages of star formation regions are typically no older than 10–30 Myr (e.g. Palla & Galli 1997). Thus, within roughly half a Gyr, these star-forming regions would no longer be distinct from the rest of the galaxy, and as such would not stand out when measuring asymmetries. We conclude that it is unlikely for star formation to be the cause of the very high asymmetries we attribute to merging galaxies.

It is possible that star formation re-occurs throughout our time-scale, but the drop in the star formation rate is faster than the derived merger fraction, suggesting the two are not coupled. For example, Baldry et al. (2005) find that the star formation rate declines from $0.15 M_{\odot} \text{yr}^{-1} \text{Mpc}^{-3}$ at roughly $z = 1$ to $\sim 0.015 M_{\odot} \text{yr}^{-1} \text{Mpc}^{-3}$ at $z \sim 0$. While Paper III find that the merger fraction declines from $f_m = 0.13$ at $z = 1.2$ to $f_m = 0.04$ at $z = 0.2$. While the star formation rate declines by at least a factor of 10, the merger fraction drops by a factor of 3.

6 SUMMARY

We have made the first empirical measurement of the time-scale for mergers within the CAS system, based on the detailed merger fraction evolution described in Paper III. These merger fractions are taken from the EGS Survey and COSMOS, and constitute $> 20,000$ galaxies with stellar masses $M_*>10^{10} M_{\odot}$.

Our major result is that the time-scale for CAS mergers at $z < 1$ is between 1.1 and 0.3 Gyr. Our best estimated time-scale is $\tau_m = 0.6 \pm 0.3$ Gyr, which gives the total number of mergers occurring
at $z < 1.2$ as $N_m = 0.90^{+0.44}_{-0.23}$, similar to previous work based on $N$-body simulation time-scales, and from changes in the mass density of galaxies at $z < 1$ (Conselice et al. 2007). We calculate that, on average, a galaxy with stellar mass $M_\ast > 10^{10} M_\odot$ will increase its stellar mass by 50 per cent due to these mergers. This timescale also rules out the possibility that star formation is the cause of asymmetries seen in galaxies, as our observed time-scales are over an order of magnitude too long to be produced by single star formation events.

The fact that there is a good agreement between empirically derived merger time-scales and those based on galaxy merger simulations suggests that we are beginning to understand the role of mergers within galaxy evolution. While in the local universe roughly 70 per cent of galaxies with masses $M_\ast > 10^{10} M_\odot$ are discs, the majority of these contain large bulges, and very few are pure discs (e.g. Conselice 2006b). Likely, some of these massive galaxies are undergoing more evolution than others, and it is possible that some of the more clustered systems, such as ellipticals, are more likely to undergo more than one merger at $z < 1.2$, which would also help explain the increase in sizes for these galaxies (e.g. Trujillo et al. 2007; Buitrago et al. 2008).

These results show that mergers are an important part of the galaxy formation process at $z < 1.2$, when most galaxies appear to have morphologies similar to today (e.g. Conselice et al. 2005). Applying this methodology to higher redshifts will prove more challenging, due to the active ongoing evolution of these systems at early times, and the likelihood that some fraction will undergo more than a single merger. This can be probed in the future when large area surveys for galaxy mergers at $z > 1.5$ are carried out.

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