The insignificance of major mergers in driving star formation at $z \simeq 2$

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ABSTRACT

We study the significance of major mergers in driving star formation in the early Universe, by quantifying the contribution of this process to the total star formation budget in 80 massive ($M_*>10^{11} M_\odot$) galaxies at $z \simeq 2$. Employing visually-classified morphologies from rest-frame V-band HST imaging, we find that 55$^{\pm}14\%$ of the star formation budget is hosted by non-interacting late-types, with $27^{\pm}8\%$ in major mergers and $18^{\pm}7\%$ in spheroids. Given that a system undergoing a major merger continues to experience star formation driven by other processes at this epoch (e.g. cold accretion, minor mergers), $\sim 27\%$ is a likely upper limit for the major-merger contribution to star formation activity at this epoch. The ratio of the average specific star formation rate in major mergers to that in the non-interacting late-types is $\sim 2.2:1$, suggesting that the typical enhancement of star formation due to major merging is modest and that just under half the star formation in systems experiencing major mergers is unrelated to the merger itself. Taking this into account, we estimate that the actual major-merger contribution to the star formation budget may be as low as $\sim 15\%$. While our study does not preclude a major-merger-dominated era in the very early Universe, if the major-merger contribution to star formation does not evolve significantly into larger look-back times, then this process has a relatively insignificant role in driving stellar mass assembly over cosmic time.

Key words: galaxies: formation -- galaxies: evolution -- galaxies: high-redshift -- galaxies: star formation -- galaxies: interactions -- galaxies: bulges

1 INTRODUCTION

Understanding the formation of massive galaxies is a central topic in observational cosmology. The observed peak in the cosmic star formation rate (SFR) at $z \simeq 2$ (e.g. Madau et al. 1998; Hopkins & Beacom 2006; Le Borgne et al. 2009) indicates that a significant fraction of the stellar mass in today's massive galaxies is likely to have formed around this epoch. However, the principal mechanisms that created this stellar mass remain unclear. Was the star formation driven by vigorous, major-merger (mass ratios $>1:3$) induced starbursts? Or were processes other than major mergers - e.g. cold accretion, minor mergers, etc. - responsible for creating the bulk of the stars in today's massive galaxies, as suggested by recent theoretical work (e.g. Keres et al. 2009; Dekel et al. 2009)?

Modern surveys that access large UV/optically-selected samples of galaxies at $z > 1.5$ have facilitated the empirical study of star formation around $z \simeq 2$ (e.g. Daddi et al. 2004; Erb et al. 2006; Reddy et al. 2006; Daddi et al. 2007; Santini et al. 2009; Hathi et al. 2010; Wuyts et al. 2011). Star-forming galaxies at this epoch lie on a star-formation 'main sequence' (e.g. Daddi et al. 2007; Reddy et al. 2012), where galaxy SFRs are proportional to their stellar masses with a slope of unity (relatively passive galaxies lie below this sequence). The growing body of observational work on these galaxies increasingly suggests that much of the cosmic star formation at this epoch may be unrelated to the major-
merger process. Integral-field spectroscopy of star-forming galaxies around \( z \approx 2 \) has revealed a high fraction of systems with properties indicative of turbulent disks and only a modest incidence of major mergers (e.g. Förster Schreiber et al. 2006; Genzel et al. 2006). However, starbursts can be driven either via major mergers or by dense nuclear star-forming regions (e.g. Di Matteo et al. 2005; Genzel et al. 2009; Cresci et al. 2011; Mancini et al. 2011; see also Law et al. 2009, van Dokkum et al. 2011). Imaging studies, that have explored the rest-frame UV and optical morphologies of star-forming galaxies at these epochs (e.g. Lotz et al. 2006; Förster Schreiber et al. 2011; Law et al. 2012a), have also indicated a preponderance of non-merging systems amongst high-redshift star formers, suggesting that the role of major mergers may indeed be subordinate to that of other processes (such as cold flows or minor mergers) in driving star formation in massive galaxies at this epoch.

In a recent study, Rodighiero et al. (2011) have shown that 'starbursts' - systems that show enhanced star formation and lie off the main sequence of normal star-forming galaxies - have a relatively minor role at this epoch, accounting for around 10% of the cosmic star formation activity. However, starbursts can be driven either via major mergers or by dense nuclear star-forming regions (e.g. Di Matteo et al. 2007; Dekel et al. 2009; Daddi et al. 2010). More importantly, many major mergers share the same star-formation characteristics as normal star-forming galaxies at this epoch (e.g. Law et al. 2012a, see also Di Matteo et al. 2007, Kaviraj et al. 2012) and thus lie on the main star-formation sequence itself. As a result, a unique one-to-one mapping is unlikely to exist between major mergers and starbursts. To probe the relative significance of major-merger-driven star formation at \( z \approx 2 \), it is desirable to quantify the proportion of the total star formation budget that is attributable to systems that are morphologically selected as major mergers at this epoch. This has not been directly addressed by previous work and represents both a quantitative empirical result and a useful constraint on theoretical models at high redshift.

Deep near-infrared imaging from current WFC3 surveys - which trace rest-frame optical wavelengths at \( z \approx 2 \) - enables us to morphologically classify massive galaxies at this epoch and study how star formation activity is apportioned in terms of galaxy morphology (e.g. major mergers, non-interacting late-types, etc.). It is worth noting, however, that a system undergoing a major merger at \( z \approx 2 \) continues to experience star formation driven by gas inflow via other processes such as cold accretion and minor mergers (major mergers can be thought of as simply the 'clumpiest' part of the material flowing in along the cosmic web). Simulations indicate that star formation due to these other processes is significant at this epoch and possibly comparable to major-merger-driven activity (e.g. Dekel et al. 2009). This appears consistent with recent empirical work (e.g. Kaviraj et al. 2012; Law et al. 2012a) which indicates that SFRs in non-interacting systems can be similar to those in major mergers. Hence, in addition to splitting the star formation budget by morphology, it is necessary to consider the fraction of star formation in major-merging systems that is unrelated to the merger itself (and subtract this from the star formation fraction hosted by systems with major-merger morphology).  

Here, we probe these questions using a complete, rest-frame optically-selected sample of massive (\( M_* > 10^{10} \, \text{M}_\odot \)) galaxies at \( z \approx 2 \), drawn from the WFC3 Early Release Science (ERS) programme, which provides unprecedentedly deep near-infrared HST imaging and ten-filter photometry in the GOODS-South field. Section 2 describes the galaxy sample that underpins this study. In Section 3, we describe the derivation of galaxy properties e.g. SFRs, stellar masses and internal extinctions. We study the proportional contribution of major mergers to the total star formation budget in Section 4 and summarise our findings in Section 5. Throughout, we use the WMAP7 cosmological parameters (Komatsu et al. 2011) and present photometry in the AB magnitude system (Oke & Gunn 1983).

2 GALAXY SAMPLE AND MORPHOLOGICAL CLASSIFICATIONS

The WFC3 ERS programme has imaged \( \sim 45 \, \text{arcmin}^2 \) of the GOODS-South field in the WFC3 UVIS (F225W, F275W, F336W) and IR (F098M [Y], F125W [J], F160W [H]) channels, with exposure times of 1-2 orbits per filter. The observations, data reduction, and instrument performance are described in detail in Windhorst et al. (2011). Together with the existing ACS BViz imaging (Ciavolino et al. 2004), the data provide 10-band panchromatic coverage over 0.2 - 1.7 \( \mu \text{m} \), with 5\( \sigma \) point source depths of \( AB \leq 26.1 - 26.4 \, \text{mag} \) in the UV and \( AB \leq 27.2 - 27.5 \, \text{mag} \) in the IR.

Here, we focus on an \( H \)-band selected sample of 80 ERS

\[ \text{Note that the situation is significantly different at low redshift, where gas-rich major mergers can enhance star formation by orders of magnitude (e.g. Milos & Hernquist 1996), because secular processes drive star formation weakly. Almost all the star formation in low-redshift major mergers is, therefore, attributable to the merger itself.} \]

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galaxies, that have stellar masses $M_* > 10^{10} M_\odot$ and photometric redshifts (calculated using the EAZY code, Brammer et al. 2008) in the range $1.9 < z < 2.1$. The accuracy of the photometric redshifts at this epoch is $\Delta z \sim 0.1$ and the nominal time interval defined by this redshift range is $\sim 0.3$ Gyr. The $H$-band traces rest-frame $V$ at $z \approx 2$ and the galaxy sample is complete within these stellar mass and redshift ranges (Windhorst et al. 2011). Thus, we are not biased against galaxies with low star formation rates. Studying the massive end of the galaxy population restricts us to systems that are both bright ($\langle H(AB) \rangle < 24.2$ mag) and extended which facilitates reliable morphological classification. The narrow redshift interval minimizes morphological K-corrections and overlap between the spheroid and major-merger morphological classes (as we discuss in Section 4).

Here we classify galaxies via visual inspection of their composite J-H images. Since the J and H filters correspond to the rest-frame optical wavelengths at $z \approx 2$, these images trace the underlying stellar populations in each galaxy and not just the UV-emitting star-forming regions. Visual classification of morphologies in the high-redshift Universe has been commonly employed in the literature, using rest-frame optical HST images that have similar or fainter surface-brightness limits compared to the ERS images used here (e.g., Windhorst et al. 2002; Caissie et al. 2010; Kacprzak et al. 2011; Cameron et al. 2011; Kocevskij et al. 2012; Law et al. 2012a). Visual classification offers better precision and consistency than morphological parameters (such as CAS, $M_2$, Gini coefficient, see e.g. Abraham et al. 1996; Conselice et al. 2003; Lotz et al. 2004; Taylor-Mager et al. 2007), which can be more sensitive to image resolution and signal-to-noise (e.g. Lisker 2008; Kartaltepe et al. 2010) but are valuable for classifying large datasets, where visual classification is prohibitively time-consuming.

Galaxies are classified into the following three broad morphological classes: (1) spheroids [2] non-interacting late-types and [3] major mergers, which are disturbed systems that exhibit multiple nuclei and clear, extended tidal features. The number fractions in classes [1], [2] and [3] are 19%, 39% and 42% respectively. Figure 1 presents examples of objects drawn from each morphological class.

3 FOOTER
unlike studies that specifically target star-forming systems, the mass-complete sample employed here is not biased against galaxies with low star formation rates. In the bottom panel of Figure 2, we present the distribution of derived internal $E_B-V$ values for our galaxies. The spread in our value ($0 < E_B-V < 0.5$ mag) agrees well with that found by other studies (e.g. Law et al. 2012b) and the median of our distribution ($E_B-V \sim 0.25$ mag i.e. $A_V \sim 2.2$ assuming Calzetti et al. 2000) is in good agreement with the literature at $z \approx 2$ (see e.g. Trevese et al. 2007, Law et al. 2012b and Cucciati et al. 2012, see their Figure 4).

4 THE MAJOR-MERGER CONTRIBUTION TO THE STAR FORMATION BUDGET

We begin by exploring how star formation activity is apportioned in terms of galaxy morphology, by summing the derived SFRs of galaxies in each morphological class and considering the fractional contribution of these classes to the total star formation budget (Figure 3). We find that $\sim 55\%$ of the star formation activity takes place in non-interacting late-types, with $27\%$ in major mergers and the rest ($18\%$) in systems that have spheroidal morphology. It is worth noting that the proportion of star formation driven by morphology selected major mergers calculated here is higher than the corresponding value derived for starbursts by Rodighiero et al. (2011). As we noted in the introduction, this is due to the fact that many major mergers exhibit similar or only modestly-enhanced SFRs compared to normal star-forming galaxies, lie on or close to the star-forming main sequence (see Figure 2 above) and are, therefore, not part of the more extreme starburst population.

The predominance of non-interacting late-types in the total star formation budget indicates that major mergers are not the dominant mechanism driving star formation in massive galaxies at $z \approx 2$. Furthermore, as we noted in the introduction, systems undergoing major mergers continue to experience star formation via other processes (e.g. cold flows and minor mergers). Hence, $27\%$ represents an upper limit to the major-merger contribution to the star formation budget. To improve our estimate, we consider the enhancement of star formation due to major merging, since this better represents the portion of the star formation activity that is directly attributable to this process. While measuring this enhancement is not possible in individual major mergers, we can estimate a typical value for the population as whole by comparing the mean specific SFR in the major mergers to that in the non-interacting late-types.

The ratio of the mean specific SFRs in these two morphological classes is $\sim 2.2$ (major mergers : non-interacting late-types), implying that, on average, around half the star formation in major-mergers are likely driven by other processes. This relatively modest enhancement in star formation activity due to major merging is consistent with the findings of recent theoretical work (e.g. Cen 2011) and also empirical studies that do not find significant differences between the SFRs of galaxies that are morphologically disturbed and those that are not at this epoch (e.g. Kaviraj et al. 2012; Law et al. 2012a). Thus, if around half the star formation in major mergers is unrelated to the merger itself, then the major-merger contribution to the total star formation budget is likely to be as low as $\sim 15\%$ (i.e. $27\% \times 1.2/2.2$).

Before we conclude this section, we briefly discuss the spheroid population in the context of the major mergers. We note first that the time interval spanned by our study ($\sim 0.3$ Gyr) is shorter than the effective timescales (0.5-2 Gyr) over which major mergers coalesce (see e.g. Lotz et al. 2008; Newman et al. 2012), so that the morphological classes do not overlap with each other. More importantly, however, Kaviraj et al. (2012) have used high-resolution cosmological simulations to demonstrate that spheroids at $1 < z < 3$ that are remnants of recent major mergers (i.e. ones that coalesced within the last $< 0.5$ Gyr) will exhibit clear tidal features at the depth of the ERS images. This study has further demonstrated that many newborn spheroids in this redshift range do not carry such morphological disturbances, indicating that a significant fraction of these systems are not built via major mergers (in agreement with the results of recent theoretical work, e.g. Dekel et al. 2009). Around $15\%$ of the spheroids in our sample show morphological disturbances and these galaxies account for $\sim 3\%$ of the total star formation budget. While the spheroid and major merger classes do not overlap (as discussed above), it is clear that, even if we add the disturbed spheroids to the major merger portion of the star formation budget, our conclusions would remain unchanged. Our analysis therefore indicates that major mergers contribute a relatively insignificant fraction ($\sim 15\%$) of the total star formation budget in massive galaxies at $z \approx 2$ and are not the principal driver of cosmic star formation at this epoch.

5 SUMMARY

We have explored the significance of major mergers in driving star formation at high redshift, by quantifying the contribution of this process to the total star formation budget in a sample of 80 massive ($M_* > 10^{10} M_\odot$) galaxies at $z \approx 2$. We have found that $\sim 55\%$ of the total star formation activity in massive galaxies at this epoch is hosted by late-type
We are grateful to the Director of the Director's Discretionary time for the WFC3 ERE programme. Partial contributions to the overall buildup of the large survey datasets - to comprehensively study the contribution of major mergers to the star formation budget in massive galaxies at this epoch to ~15%. Our analysis therefore indicates that the contribution of major mergers to the total star formation budget in massive galaxies at z ~ 2 is significantly significant and this process is non-negligible and this process is the principal driver of cosmic star formation at this epoch.

Since our study is based on 'instantaneous' star formation rates, it provides only a snapshot of the star formation budget in massive galaxies at z ~ 2. Thus, while our data cannot rule out a merger-dominated era in the very early Universe, if the merger contribution to stellar mass assembly does not evolve significantly into earlier look-back times (z > 2), then major mergers are unlikely to be significant contributors to the overall buildup of stellar mass in the Universe. In forthcoming papers we will use morphological analyses of large datasets such as CANDELS - e.g. via projects such as Galaxy Zoo (Lintott et al. 2008), which uses 460,000+ members of the public to visually classify large survey data sets - to comprehensively study the contribution of major mergers to the star formation budget as a function of stellar mass, environment and redshift.

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