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The insignificance of major mergers in driving star formation at z≃2

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ABSTRACT

We study the significance of major-merger-driven star formation in the early Universe, by quantifying the contribution of this process to the total star formation budget in 80 massive ($M_* > 10^{10}$ $M_\odot$) 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 $18^{\pm 6}$% 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), ∼27% is an *upper limit* to 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 ∼2.2:1, suggesting that the enhancement of star formation due to major merging is typically 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 ∼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 strongly 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 processes that build 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) 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. Kereš 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. 2005; 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 $z \simeq 2$ 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. 2008; Shapiro et al. 2008; Förster Schreiber et al. 2009; Cresci et al. 2009; Genzel et al. 2011; Mancini et al. 2011,

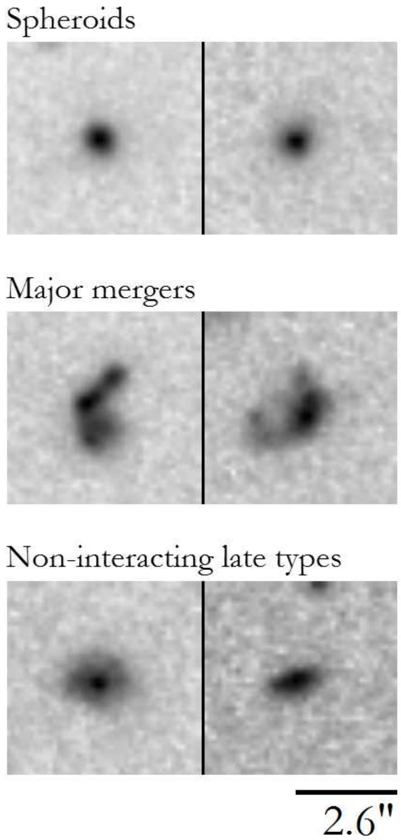

Figure 1. Example J+H composite images for the morphological classes into which we split our galaxy sample. Galaxies are classified into spheroids (top row), major mergers (disturbed systems with multiple nuclei and clear, extended tidal features, middle row) and non-interacting late-types (bottom row). An angular scale which spans half the image is shown. The images are ∼45 kpc on a side. Note that the images usually appear better on screen than in print.

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 in driving star formation 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 $z \simeq 2$, 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 $z \simeq 2$ – 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 $z \simeq 2$ 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). Both theoretical (e.g. Dekel et al. 2009) and observational (e.g. Kaviraj et al. 2012; Law et al. 2012a) work indicates that star formation due to these other processes is significant at this epoch and possibly comparable to the major-merger-driven activity. Hence, in addition to splitting the star formation budget by morphology, it is necessary to consider the proportion of star formation in major-merging systems that is unrelated to the major-merger process, and subtract this from the fraction of the star formation budget hosted by systems with major-merger morphology[1].

Here, we probe these questions using a complete, rest-frame optically-selected sample of massive ($M_* > 10^{10}$ $M_\odot$) galaxies at $z \simeq 2$, 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 ∼45 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 (Giavalisco et al. 2004), the data provide 10-band panchromatic coverage over 0.2 - 1.7 μm, with 5σ point source depths of $AB \lesssim 26.1 - 26.4$ mag in the UV and $AB \lesssim 27.2 - 27.5$ mag in the IR.

Here, we focus on an H-band selected sample of 80 ERS galaxies, that have stellar masses $M_* > 10^{10} M_\odot$ and redshifts in the range $1.9 < z < 2.1$. For 12% if our sample (10 galaxies) we use published spectroscopic redshifts from Santini et al. (2009); Popesso et al. (2009); Ferreras et al.

[1] 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. Mihos & 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.

(2009). For the remaining objects we use photometric redshifts, calculated using the EAZY code (Brammer et al. 2008). The peak of the redshift probability distribution from EAZY is used as the best estimate of the redshift - the accuracy of EAZY redshifts at this epoch is $\Delta z \sim 0.1$ and the nominal time interval our defined by redshift range is ~0.3 Gyr. The H-band traces rest-frame V at $z \simeq 2$ and the galaxy sample is complete within these stellar mass and redshift ranges (Windhorst et al. 2011). Studying the massive end of the galaxy population restricts us to systems that are both bright ($H(AB) < 24.2$ mag) and extended, which facilitates reliable morphological classification.The narrow redshift interval minimises both 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 $z \simeq 2$, 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; Cassata et al. 2010; Kaviraj et al. 2011; Cameron et al. 2011; Kocevski et al. 2012; Law et al. 2012a). Visual classification offers better precision and consistency than morphological parameters (such as CAS, M_{20}, 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%, 43% and 38% respectively. Figure 1 presents examples of objects drawn from each morphological class.

3 PARAMETER ESTIMATION: STELLAR MASSES AND INTRINSIC STAR FORMATION RATES

A variety of methods have been employed in the literature to derive galaxy SFRs. Calibrations (often based on samples of local galaxies) can be used to convert X-ray, UV, infrared or radio luminosities into estimates of SFR (see e.g. Reddy & Steidel 2004; Daddi et al. 2007; Pannella et al. 2009; Elbaz et al. 2011). Alternatively, galaxy spectral energy distributions (SEDs) can be fitted to theoretical star formation histories (SFHs) to derive SFRs (e.g. Shapley et al. 2005; Law et al. 2012a). Since dust is included as a free parameter in these SFHs, intrinsic (i.e. dust-corrected) SFRs can be derived self-consistently using this method. The derivation of reliable SFRs ideally requires rest-frame UV photometry (as is the case here), since the leverage in the SFR and the dust extinction comes largely from these wavelengths.

In this paper, we calculate galaxy SFRs via SED fitting. The WFC3/ACS photometry of each individual galaxy is compared to a large library of synthetic photometry, constructed using constant SFHs, each described by a stellar mass (M), age (T), metallicity (Z) and internal extinction (E_{B-V}). We vary T between 0.05 Gyrs and the look-back time to $z = 20$ in the rest-frame of the galaxy, Z between 0.1 $Z_{\odot}$ and 2.5 $Z_{\odot}$ and E_{B-V} between 0 and 1 mag. Synthetic magnitudes are generated by folding the model SFHs with the stellar models of Bruzual & Charlot (2003), with dust attenuation applied following Calzetti et al. (2000). The likelihood of each model, $\exp(-\chi^2/2)$, is calculated using the value of χ^2, computed in the standard way. Estimates for parameters such as stellar mass, internal extinction and SFR are derived by marginalising each parameter from the joint probability distribution, to extract its one-dimensional probability density function (PDF). We use the median of this PDF as the best estimate of the parameter in question, with the 25 and 75 percentile values (which enclose 50% of the probability) yielding an associated uncertainty. Since dust is explicitly taken into account in this process, we derive *intrinsic* SFRs, free of internal reddening, directly from the SED fitting process. The derived internal extinctions, SFRs and stellar masses are uncertain by ~0.1 mag, ~0.1 dex and ~0.2 dex respectively.

In the top panel of Figure 2, we plot our derived SFRs vs. galaxy stellar mass. The SFR values for our star-forming galaxies are consistent with the star formation main sequence at these epochs defined by the recent literature.

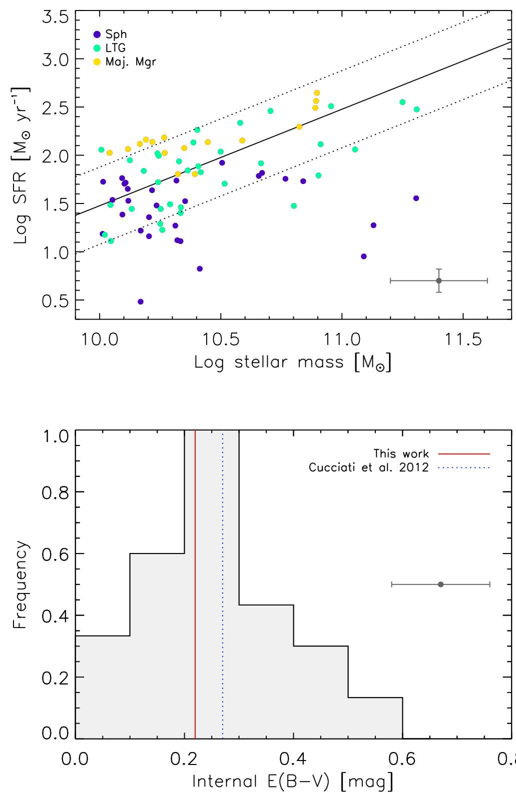

Figure 2. TOP: SFR as a function of galaxy stellar mass in our galaxy sample. The main sequence of star-forming galaxies at $z \simeq 2$ is shown using the solid line (the observed scatter is indicated using the dotted lines). Galaxy morphologies are shown colour-coded (black = spheroids, blue = non-interacting late-types, red = major mergers). BOTTOM: The distribution of derived extinction values for our galaxies. The median value is shown by the vertical red line and the median from the recent literature (see Tresse et al. 2007 and Cucciati et al. 2012) is shown by the blue dotted line.

Galaxies that lie below this sequence are typically spheroids, which are relatively passively-evolving systems. Recall that, 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 values ($0 < E_{B-V} < 0.5$ 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. $A_{FUV} \sim 2.2$ assuming Calzetti et al. 2000) is in good agreement with the literature at $z \simeq 2$ (see e.g. Tresse 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 $55^{\pm 14}$% of the star formation activity takes place in non-interacting late-types, with $27^{\pm 8}$% in major mergers and the rest ($18^{\pm 6}$%) in systems that have spheroidal morphology. It is worth noting that the proportion of star formation driven by *morphologically 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 $z \simeq 2$. 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 ∼2.2:1 (major mergers : non-interacting late-types), implying that, *on average*, around half the star formation in major-mergers is 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 ∼15% (i.e. 27% × 1.2/2.2).

Before we conclude this section, we briefly discuss the

Morphology	Fraction of SF budget
Non-interacting late-types	$0.55^{\pm 0.14}$
Major merger	$0.27^{\pm 0.08}$
Spheroids	$0.18^{\pm 0.06}$

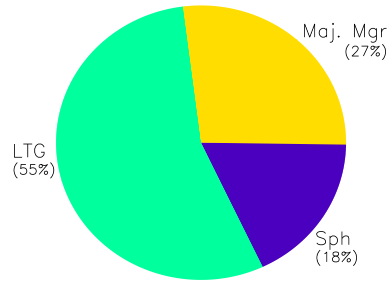

Figure 3. TOP: The fraction of the total star formation budget in massive ($M_* > 10^{10}$ $M_\odot$) systems at $z \simeq 2$ that is hosted by various morphological types. Major mergers account for less than a third (27%) of the total star formation budget, while non-interacting late-type galaxies host more than half of the star formation activity. Given that systems undergoing major mergers continue to experience star formation driven by other processes, 27% is an *upper limit* to the major merger contribution to the star formation budget. The actual contribution is likely to be ∼15% of the total star formation budget (see text in Section 4 for details). BOTTOM: A pie-chart visualisation of the star formation budget apportioned in terms of galaxy morphology (Sph = Spheroids, LTG = Non-interacting late-type galaxies, Maj. Mgr = Major mergers).

spheroid population in the context of the major mergers. We note first that the time interval spanned by our study (∼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 ∼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 added 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 (∼15%) of the total star formation budget in massive galaxies at $z \simeq 2$ 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 $z \simeq 2$. We have found that $55^{\pm 14}$% of the total star formation activity in massive galaxies at this epoch is hosted by late-type galaxies that are not interacting with other systems, with $27^{\pm 8}$% in major mergers, and the rest in spheroids.

Since systems undergoing major mergers continue to experience star formation driven by other processes (e.g. cold flows and minor mergers), ∼27% is an *upper limit* to the contribution of major mergers to the total star formation budget. To improve our estimate, we have considered the typical enhancement of star formation induced by a major merger, since this is the portion of star formation activity which is directly attributable to this process. We have estimated this enhancement using the ratio of the mean specific star formation rate in the major merger population to that in the non-interacting late-type galaxies. In agreement with recent observational and theoretical work, we have found a relatively modest enhancement (×2.2), which implies that, on average, just under half the star formation activity in major mergers is unrelated to the merger itself. This reduces the contribution of major mergers to the total 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 $z \simeq 2$ is relatively insignificant and this process is not 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 $z \simeq 2$. Thus, while our data cannot rule out a merger-dominated era in the very early Universe, if the major-merger contribution to stellar mass assembly does not evolve strongly 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 450,000+ members of the public to visually classify large survey datasets – 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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