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Minor mergers: fundamental but unexplored drivers of galaxy evolution

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Abstract. We use the SDSS Stripe 82 to study the stellar-mass growth that is triggered by minor mergers in local disk galaxies. Since major mergers destroy disks and create spheroids, morphologically disturbed spirals are likely remnants of minor mergers (since the disk remains intact). Disturbed spirals exhibit enhanced specific star formation rates (SSFRs), with the enhancement increasing in galaxies with 'later' morphological type (that have larger gas reservoirs and smaller bulges). By combining the SSFR enhancements with the fraction of time spirals in various morphological classes spend in this 'enhanced' mode, we estimate that ∼40% of the star formation activity in local spirals is directly triggered by minor mergers. Combining our results with the star formation in local early-type galaxies – which is almost completely driven by minor mergers – suggests that around half the star formation activity at the present day is likely to be triggered by the minor-merger process.

Keywords. galaxies: formation – galaxies: evolution – galaxies: interactions – galaxies: spirals

1. Introduction

The standard ΛCDM model of galaxy formation hypothesizes a hierarchical growth of structure over cosmic time (e.g. Hatton *et al.* 2003), in which galaxies and their host dark-matter halos grow, both through mergers with systems of similar mass ('major mergers'), and via the accretion of smaller objects ('minor mergers'). A consequence of the shape of the observed luminosity function – in which smaller galaxies far outnumber their more massive counterparts (e.g. Cole *et al.* 2001) – is that minor mergers are significantly more common than major interactions.

While past studies of merging have largely explored the effects of major mergers (e.g. Darg *et al.* 2010), the recent literature has highlighted the important role of minor mergers (mass ratios $\lesssim$ 1:4) in influencing the evolution of massive galaxies. Minor merging is a frequent process, that is both predicted and observed to be ∼3-4 times more common than major interactions at late epochs (e.g. Kaviraj *et al.* 2009). While each individual minor interaction may have a relatively small effect on the massive galaxy, the *cumulative* impact of minor mergers over cosmic time is significant, both in terms of the stellar content of massive galaxies and their structural properties.

A burgeoning literature has now begun probing the impact of minor mergers on spiral galaxies. Empirical studies of spiral minor-merger *remnants* have largely focussed on individual case studies of very nearby galaxies. These efforts typically demonstrate enhancements in star formation and, in some cases, nuclear activity (e.g. Smith *et al.* 1996), indicating that the minor-merger process is indeed influencing the growth of both the galaxy and its central black hole.

In this contribution we explore the role of minor mergers in triggering stellar mass growth in spirals in the nearby Universe by enhancing star formation during the later stages of such mergers. Our aim is to quantify the enhancement in star formation that is produced by minor merging and then combine that with the fraction of time a typical spiral spends in this enhanced star formation mode to estimate the fraction of the cosmic star formation budget that is triggered by this process.

2. Data

The galaxies used here are drawn from the Sloan Digital Sky Survey (SDSS) Stripe 82, a ~ 300 deg^2 region along the celestial equator in the Southern Galactic Cap ($-50° < \alpha < 59°, -1.25° < \delta < 1.25°$) that offers a co-addition of 122 imaging runs, yielding images that are $\sim$2 mags deeper than the standard-depth, 54 second SDSS scans (which have magnitude limits of 22.2, 22.2 and 21.3 mags in the g, r and i-bands respectively).

Galaxies are classified into standard morphological classes (E/S0, Sa, Sb, Sc, Sd), using visual inspection of both the standard-depth, colour images from the SDSS DR7 and their deeper r-band Stripe 82 counterparts. The sample is restricted to $r < 16.8$ and $z < 0.07$, where morphological classification from SDSS images is likely to be most reliable. The final compilation contains $\sim$6,500 galaxies in this redshift and magnitude range.

We employ published stellar masses from the latest version of the publicly-available MPA-JHU value-added SDSS catalogue†. Briefly, stellar masses are calculated by comparing *ugriz* photometry of individual galaxies to a large grid of synthetic star formation histories, based on the Bruzual and Charlot (2003) stellar models. Model likelihoods are calculated from the values of χ^2, and 1D probability distributions for free parameters, such as stellar masses, are constructed via marginalization. The median of this 1D distribution is taken to be the best estimate for the parameter in question, with the the 16th and 84th percentile values (which enclose 68% of the total probability) yielding a '1σ' uncertainty.

The SFRs are estimated via two different methods, depending on the ionization class of the galaxy, that is derived using an optical emission-line ratio analysis (e.g. Kewley *et al.* 2006), using the values of [NII]/Hα and [OIII]/Hβ measured from the SDSS spectra of individual galaxies. Objects in which all four emission lines are detected with a signal-to-noise ratio greater than 3 are classified as either 'star-forming', 'composite' (i.e. hosting both star formation and AGN activity), 'Seyfert' or 'LINER', depending on their location in the [NII]/Hα vs. [OIII]/Hβ diagram. Galaxies without a detection in all four lines are classified as 'quiescent'.

SFRs for galaxies classified as 'star-forming' (i.e. where the nuclear ionization is driven by star formation) are estimated by comparing galaxy spectra to a library of models, with a dust treatment that follows the empirical model of Charlot *et al.* (2000). For galaxies that are classified as 'quiescent' , or those that are classified as 'AGN/Composite' (in which a significant fraction of the nuclear emission is likely driven by a central AGN), SFRs are calculated using the D4000 break. The correlation between specific SFR and D4000 break for the 'star-forming' subsample is used to estimate the specific SFR of the galaxy in question. Note that the SFRs used here are corrected for both internal extinction and the fixed size of the SDSS fibre.

3. Selection of minor-merger remnants

Theoretical work indicates that the strong gravitational torques induced by major mergers (mass ratios $\gtrsim 1:4$) destroy rotationally-supported disks and produce pressure-

† http://www.mpa-garching.mpg.de/SDSS/DR7/

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Figure 1. Examples of standard-depth, multi-colour images (left) and their deeper r-band Stripe 82 counterparts (right) of spiral minor-merger remnants. We show examples of early-type (row 1, left), Sa (row 1, middle), Sb (row 1, right), Sc (row 2, left) and Sd (row 2, middle) galaxies. The morphological disturbances are typically clearer in the Stripe 82 imaging, making these deeper images necessary for this exercise. While ETGs are not considered in this study, we show an example of a disturbed ETG for comparison to the spirals. Note that the images may look better on screen than in print.

supported spheroidal systems. While major interactions involving very high gas fractions may yield late-type remnants that rebuild disks from the remnant gas (see e.g. Hopkins *et al.* 2009), such conditions are rare at low redshift. Thus, systems in the local Universe that exhibit both disk morphology and tidal disturbances are likely to be remnants of minor mergers, since a major interaction would have destroyed the disk and created a spheroid.

While disturbed spirals are likely minor-merger remnants, visual identification of such systems requires deep, high-resolution colour imaging. Deep images are required for detecting the tidal features that result from recent minor interactions, while high-resolution, colour images enable us to efficiently differentiate disks, which have inhomogeneous structure, from the smooth, homogeneous light distributions of early-type (i.e. spheroidal) galaxies. The combination of standard-depth colour images and co-added scans makes the SDSS Stripe 82 an ideal platform for a large-scale study of spiral minor-merger remnants. To identify our sample, we visually inspect both the standard-depth colour image and the r-band Stripe 82 counterpart of each galaxy and flag those that are morphologically disturbed.

Figure 1 shows examples of disturbed spirals and, for comparison, their counterparts in the ETG population. The morphological disturbances are most easily detected in the Stripe 82 imaging, making these deep images indispensable for this exercise. Note that, while previous work has flagged morphological disturbances via visual inspection (e.g. Nair *et al.* 2010), these have been based on standard-depth SDSS images. Since the faint tidal debris produced by minor mergers is only visible in deeper imaging, such as that available in the Stripe 82, using just the standard-depth images would significantly underestimate the fraction of galaxies that have undergone recent minor interactions.

4. Enhancement of star formation due to minor mergers

We begin by setting up a theoretical framework to quantify the fraction of star formation in spiral galaxies that is triggered by the minor-merger process.

We define the following quantities: ϕ_0 is the normal specific star-formation rate of a spiral galaxy in the absence of a minor merger, m is its stellar mass, D is the duty cycle

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Table 1. Columns from left to right: (1) Morphological class (2) duty cycle (D in Eqn 4.1) of the remnant phase of the minor-merger process i.e. the fraction of time the galaxy appears disturbed due to minor mergers (3) enhancement of specific star formation rate in remnant phase of the minor-merger process (η in Eqn 4.1) (4) the fraction of star formation driven by minor mergers, calculated using Eqn. 4.2 (5) proportion of the star formation budget in spiral galaxies that is hosted by this morphological class (from Kaviraj 2014).

Morphology	D	η	F_{mm} **(via Eqn. 1)**	**Proportion of spiral SF budget**
Sa	0.16	1.98	0.27	0.19
Sb	0.17	3.62	0.43	0.34
Sc	0.13	6.15	0.48	0.32
Sd/Irr	0.11	6.14	0.43	0.15

of the remnant phase of the minor-merger process i.e. the fraction of time the galaxy appears disturbed due to minor mergers and η is the enhancement in the specific star formation rate while the galaxy is in this disturbed phase. The stellar mass (S) produced in a time period (δt) can then be expressed as:

$$S = \underbrace{\phi_0.(1-D).m.\delta t}_{\mathrm{S_{NORM}}} + \underbrace{\eta.\phi_0.D.m.\delta t}_{\mathrm{S_{MM}}} \tag{4.1}$$

$\mathrm{S_{NORM}}$ represents the stellar mass formed while the galaxy is in a normal star-forming mode (i.e. in the absence of a minor merger), while $\mathrm{S_{MM}}$ represents the stellar mass formed while the galaxy experiences enhanced star formation during the remnant phase of a minor merger. The fraction of star formation triggered by minor mergers (F_{MM}) is then:

$$F_{\mathrm{MM}} = \frac{S_{\mathrm{MM}}}{S} = \frac{\eta.D}{1+D.(\eta-1)} \tag{4.2}$$

As might be expected, F_{MM} depends on a combination of the enhancement of star formation during the disturbed phase and the fraction of time that the galaxy spends in this phase. While we cannot measure these quantities for individual galaxies, we can calculate *mean* statistical estimates for η and D, if large populations of minor-merger remnants are available, as is the case in this study. As has been suggested in the previous literature, the star formation enhancement is likely to be higher in 'later' morphological types, which host larger gas reservoirs and smaller bulges that are less able to stabilize the disk against gas inflows (e.g. Martig *et al.* 2009). It is, therefore, desirable to perform this analysis as a function of morphological type.

Assuming that the detectability of morphological disturbances does not evolve in the short redshift range studied here, the duty cycle (D) is given by the fraction of galaxies that are disturbed. In column 2 of Table 1, we present the fraction of disturbed spirals as a function of morphology. We find similar duty cycles (∼11-17%) across different morphological types. The decreasing duty cycles towards 'later' morphological types is likely driven by the average galaxy mass being lower in these classes, which affects the ability of the galaxy to attract satellites.

We calculate mean SSFR enhancements (η) using the published MPA-Garching SSFRs of the relaxed and disturbed spirals in each morphological class. To perform this comparison statistically, we extract, in each morphological class (Sa/Sb/Sc etc.), 1000 samples of relaxed galaxies, each with the same redshift and r-band distribution as that of the disturbed systems. Matching in redshift and magnitude implies that we are comparing galaxies at similar distances and with similar luminosities, making the comparison more meaningful. We then calculate the median SSFR of each 'matched' relaxed sample and construct the ratio (disturbed:relaxed) of median SSFRs for each comparison, which we

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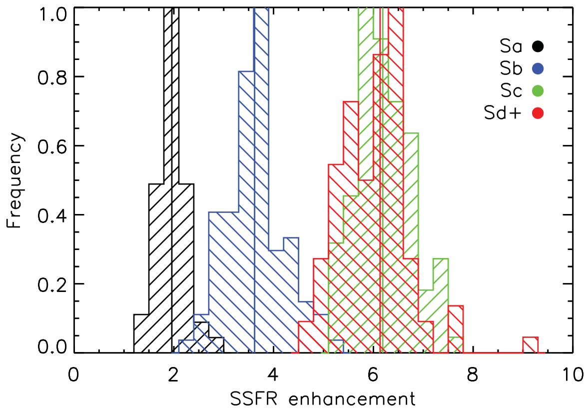

Figure 2. The SSFR enhancement in disturbed spirals in different morphological classes (see legend). The enhancement is defined as the ratio of the median SSFR of the disturbed objects to that in a control (undisturbed) sample that has the same redshift and r-band distribution. See text for details.

define as the SSFR enhancement. This yields, for each morphological class, a distribution of SSFR enhancements (Figure 2). We take the median of this distribution as a typical value for η for the morphological class in question.

Figure 2 indicates that the SSFR is enhanced in minor-merger remnants regardless of galaxy morphology, the enhancement increasing in galaxies that have 'later' morphological type. While disturbed Sa galaxies exhibit median enhancements of around a factor of $\sim$2, this climbs to a factor of $\sim$6 for Sc galaxies and later morphological classes. The values of η are presented in column 3 of Table 1.

5. The fraction of disk and cosmic star formation that is triggered by minor mergers

Given the values of η and D calculated above, we use Eqn. 4.2 to estimate the fraction of star formation that is triggered by minor mergers (F_{MM}) in each morphological class (column 4 in Table 1). The values of F_{MM} are $\sim$0.27 for Sa galaxies and climb to $\sim$0.43-0.48 in Sb and later morphological types. Multiplying the values of F_{MM} with the proportion of the star-formation budget in spirals that is hosted by each morphological class (column 5 in Table 1, taken from Kaviraj 2014), then yields an estimate for the *total* fraction of star formation in spiral galaxies that is attributable to minor mergers. We estimate this fraction to be $\sim$40% (this is consistent with the results of Kaviraj 2014, who estimated an empirical lower limit for this value of $\sim$25%.)Thus, a significant fraction of stellar mass in local spirals is likely to be created in enhanced star-formation episodes during the latter stages of minor mergers.

Note that our analysis has only considered systems that are visibly morphologically disturbed, and not those that may have experienced a recent minor merger, but where the mass ratio is not sufficiently high to induce morphological disturbances at the depth of the SDSS images. While we assume that the star formation enhancement in such mergers is negligible, the robustness of this assumption is difficult to test without dedicated theoretical simulations, which are beyond the scope of this paper. As a result, the value of 40% derived above may also be a lower limit.

Finally, it is worth combining our results with the star formation in ETGs, which is driven by minor mergers (at least in low-density environments) and accounts for $\sim$14%

of the cosmic star formation budget (Kaviraj 2014). This indicates that *around half (0.4×0.86% [LTGs] + 14% [ETGs]) of the cosmic star formation activity at the present day is triggered by the minor-merger process.*

6. Summary

We have used a sample of bright ($r < 16.8$), local ($z < 0.07$) galaxies from the SDSS Stripe 82 to probe the role of minor mergers in driving stellar mass and black hole growth in nearby massive spiral (disk) galaxies. Our study has been based on a sample of galaxies that have been visually classified into standard morphological classes (E/S0, Sa, Sb, Sc, Sd, etc.) using both colour images from the SDSS DR7 and their deeper r-band counterparts from the Stripe 82.

Since 'major' (i.e. equal or nearly equal-mass) mergers produce spheroids, an effective route to studying spiral galaxies that are minor-merger remnants is to use spirals that are morphologically disturbed. The disturbed morphology indicates a recent interaction, and the continued presence of a disk indicates that the interaction was not a major merger (since this would have destroyed the disk and created a spheroid). Using the DR7 and Stripe 82 images, we have flagged spiral galaxies that are morphologically disturbed, thus selecting the nearby spiral minor-merger remnant population in the Stripe 82 field.

We have used this sample to quantify the stellar mass growth in spiral galaxies that is plausibly triggered by minor mergers. The proportion of minor-merger-driven star formation depends both on the enhancement of star formation during the remnant phase of a minor merger (η) and the fraction of time galaxies spend in this enhanced star-formation mode (the 'duty cycle', D). While we cannot measure these quantities for individual galaxies, we can calculate mean statistical estimates for η and D, if large populations of minor-merger remnants are available, as is the case in this study.

Assuming that the detectability of morphological disturbances does not evolve in the short redshift range studied here, D can be estimated by the fraction of galaxies that are morphologically disturbed. η can be calculated using the ratio of the measured SSFRs in the relaxed spirals to that in the disturbed spirals.

The duty cycle is relatively insensitive to morphological class and ranges between 11 and 17%. The SSFRs are enhanced in the disturbed spirals, regardless of morphology, with the enhancement increasing in galaxies that have 'later' morphological type. While disturbed Sa galaxies exhibit SSFR enhancements of a factor of $\sim$2, this increases to a factor of $\sim$6 for Sc and later morphological types. Our results indicate that the star-formation enhancements are higher in galaxies that host larger internal gas reservoirs and smaller bulges (that are less able to stabilize the disk against radial gas inflows), as might be expected from the recent literature.

The duty cycles and SSFR enhancements imply that the fraction of star formation driven by minor mergers range from $\sim$27% in Sa galaxies to $\sim$43-48% in Sb and later morphological types. Combining this with the proportion of the star formation budget hosted by each morphological class then yields *a total minor-merger-driven fraction of star formation in spirals of ~40%*. This is consistent with the results of Kaviraj (2014), who estimated an empirical lower limit for this value of $\sim$25%. Thus, while most of the star formation in today's spiral galaxies is unrelated to mergers, a significant fraction is attributable to the minor-merger process. It is worth noting that our analysis has been restricted to galaxies that show morphological disturbances. Thus, we have disregarded systems that might have undergone a recent minor merger, but where the mass ratio is not high to induce morphological disturbances at the depth of the Stripe 82 imaging. While the robustness of this assumption is difficult to test without dedicated theoretical simulations, this implies that the estimated value of 40% above may also be a lower limit. Combining our results with the star formation in early-type galaxies, which is dominated by minor mergers (at least in low-density environments) and accounts for 14% of cosmic star formation budget, indicates that around half the star formation activity at the present day is likely triggered by the minor-merger process.

Given the significance of this process in driving star formation, studying the role of minor mergers across a large range in redshift is essential. The most detailed insights are likely to come from high-resolution spatially-resolved studies of local minor-merger remnants using the HST, that employ sensitive tracers of star formation like the UV. As noted in the introduction above, local star-forming ETGs are excellent initial laboratories for such spatially-resolved analyses that probe the star-formation laws associated with satellite accretion. At intermediate redshift ($z < 2$), the population of minor-merger remnants can be studied using the deep, high-resolution imaging offered by the HST, in legacy fields such as CANDELS. At earlier epochs this exercise will likely require deep, high-resolution imaging from future instruments like LSST and the Extremely Large Telescopes. In any case, without a robust determination of minor-merger-driven stellar mass and black hole growth over cosmic time, our understanding of galaxy evolution is likely to remain incomplete.

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