

Enhancing and inhibiting star formation: high-resolution simulation studies of the impact of cold accretion, mergers and feedback on individual massive galaxies

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Abstract. The quest for a better understanding of the evolution of massive galaxies can be broadly summarised with 2 questions: how did they build up their large (stellar) masses and what eventually quenched their star formation (SF)? To tackle these questions, we use high-resolution RAMSES simulations (Teyssier 2002) to study several aspects of the detailed interplay between accretion (mergers and cold flows), SF and feedback in individual galaxies. We examine SF in major mergers; a process crucial to stellar mass assembly. We explore whether the merger-induced, clustered SF is as important a mechanism in average mergers, as it is in extreme systems like the Antennae. We find that interaction-induced turbulence drives up the velocity dispersion, and that there is a correlated rise in SFR in all our simulated mergers as the density pdf evolves to have an excess of very dense gas. Next, we introduce a new study into whether mechanical jet feedback can impact upon the ability of hot gas haloes to provide a supply of fuel for SF during mergers and in their remnants. Finally, we briefly review our recent study, in which we examine the effect of supernova (SN) feedback on galaxies accreting via the previously overlooked cold-mode, by resimulating a stream-fed galaxy at $z \sim 9$. A far-reaching galactic wind results yet it cannot suppress the cold, filamentary accretion or eject significant mass in order to reduce the SFR, suggesting that SN feedback may not be as effective as is often assumed.

Keywords. methods: numerical, galaxies: evolution, galaxies: star clusters, galaxies: interactions, galaxies: high-redshift, galaxies: starburst, galaxies: jets, stars: supernovae: general

1. Clumpy star formation induced by mergers

It has been widely demonstrated with previous generations of merger simulations, that merging galaxies undergo a nuclear starburst. In this picture, gas is driven to the centre by tidal torques, where it is compressed and turns into stars at a very high rate (Barnes & Hernquist 1991). This was compatible with observations of ULIRGs which exhibit centrally concentrated star formation. However, there is now significant observational evidence of the existence of merging galaxies whose star formation is extended and clustered (e.g. the Antennae), as well as attempts by simulators to model these specific systems (Teyssier *et al.* 2010). We undertake a more general study of clustered star formation by performing 5 idealised simulations of equal-mass mergers (with $\sim 5\text{pc}$

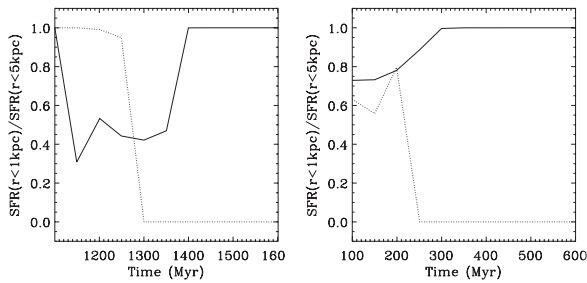


Figure 1. The ratio of the SFR within a 1kpc radius to that within 5kpc radius for galaxy 1 (solid line) and galaxy 2 (dotted line - when this goes to zero, galaxy 2 has merged with galaxy 1). **Left:** Merger m5. **Right:** Merger m3.

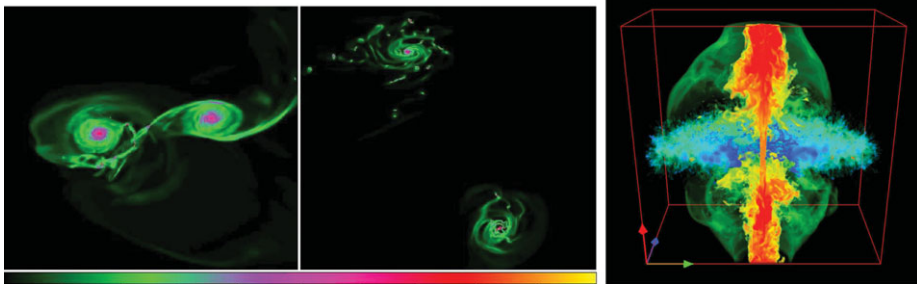


Figure 2. Left(2 panels): Gas density map to illustrate the increased clumpiness of the gas as merger m5 progresses. There is a 100Myr time difference between the left and right panels - initially both discs are relatively smooth, but one becomes noticeably more clumpy. **Right:** Image of jet interacting with cold gas disc and a hot ambient medium. See Gaibler *et al.* (2012) for details of the jet modeling.

resolution) with orbital parameters that can be considered ‘average’ for a LCDM cosmology. The full results of this study will be presented in Powell *et al.* (2012, in prep).

1.1. *Extended, clustered star formation*

In Fig. 1 we show the ratio of the SFR within 1 kpc to that within 5 kpc for galaxy 1 (solid line) and galaxy 2 (dotted line) in mergers m5 (left-hand panel) and m3 (right-hand panel). When this quantity is 1, all SF is within the central 1 kpc and so it could be considered to be a ‘nuclear’ starburst. When the quantity is lower it indicates some of the SF is occurring beyond 1 kpc and so could be considered ‘extended’. Here we see two extreme examples. Merger m3 has very concentrated SF, whereas merger m5 has a period of more extended star formation where the ratio reaches values of ~ 0.5 , in between two phases where the SF is centrally concentrated. The appearance of new/larger clumps in merger m5 is illustrated in the density maps in Fig. 2. The SF of all the mergers tends towards being centrally concentrated as the galaxies approach coalescence. Although it seems that stars formed in the nucleus dominate the SFR at the very peak of the starburst, extended/clumpy star formation still occurs to a greater or lesser extent in most of the mergers in our sample. This process could lead to significant phases of enhanced SF before the main starburst, alter the stellar distribution in massive ellipticals and even have implications for the origin of globular clusters.

1.2. *How does the merger affect the gas properties?*

In order to try to understand the mechanisms responsible for the merger-induced clumpy SF we measure the evolution of some of the gas properties. Fig. 3 (left-hand panel) shows the time evolution of the 1D velocity dispersion (solid line) measured in 100pc cells and averaged over a cube of side-length 30kpc, centred on one of the galaxies in merger m4. The dotted line shows the global SFR at the same times. It is interesting that the increase

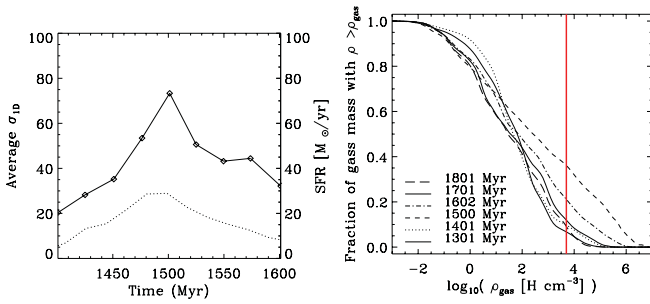


Figure 3. **Left:** The average 1D velocity dispersion within a 15kpc radius (solid line) and the global SFR (dotted line) for one of the mergers (m4). **Right** The cumulative gas density pdf within a radius of 15kpc, also for merger m4. The vertical line shows the threshold for star formation.

in velocity dispersion is correlated with the increase in SFR and we note that this result is seen for all the mergers in our sample. There are two main possible sources of turbulence that could drive up the velocity dispersion: supernova feedback (which is included in the simulations) or the interaction itself. We rerun merger m4 for the duration of the starburst with supernova feedback switched off and find that the velocity dispersion curve remains the same, suggesting the interaction is driving increased turbulence.

Fig. 3 (right-hand panel) shows the time evolution of the gas density pdf for merger m4. It is clear that there is significant evolution of the pdf as the merger progresses (and as the velocity dispersion goes up, as just demonstrated). A large excess of very dense gas is created and this increases the amount of gas eligible for SF (the vertical line marks the SF threshold in the simulations). This trend is observed for all mergers.

1.3. Revisiting the Kennicutt-Schmidt Relation

There is ongoing debate about whether quiescent and starbursting galaxies form one or more sequences on the Kennicutt-Schmidt (KS) plot. Daddi *et al.* (2010) recently showed it was possible to fit two separate sequences and Teyssier *et al.* (2010) suggested that resolving clumpy star formation could be the key to reproducing/explaining this with simulations. Fig. 4 shows examples of the evolution of a merging galaxy on the KS plot. We do not see strong evidence for a clear bimodality, but rather some scatter in between the two relations. We note that merger m5 (left-hand panel) occurs after a long time has elapsed, which is why it starts below the disc sequence (the pre-merger disc has evolved away from the disc sequence).

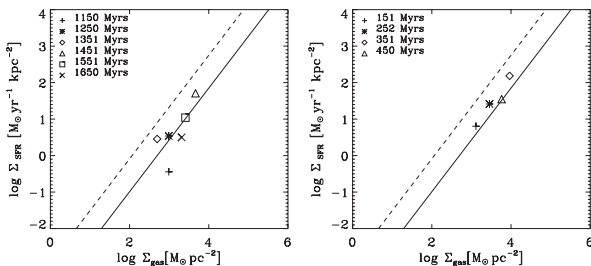


Figure 4. The time evolution of one galaxy from a merger on the Kennicutt-Schmidt plot. Fits from Daddi *et al.* (2010) for quiescent (solid line) and starbursting (dotted line) galaxies are overplotted. **Left:** Merger m5 a ‘slow’ merger. **Right** Merger m3, a ‘rapid’ merger.

2. Star formation fueled by hot gas haloes in mergers

Idealised merger simulations have been typically performed without hot gas haloes (including those discussed above). Recently, Moster *et al.* (2011) included this component and found it affects the remnant properties as it acted as a reservoir of fuel for later SF. However, the impact of strong feedback, such as that from an active galactic nuclei has not yet been taken into account. Jets could potentially keep the hot halo hot, preventing

it from being a fuel supply. We are currently testing simulations which combine idealised merger simulations including hot gas haloes with the jet module presented in Gaibler *et al.* (2012) (see Fig. 2, right-hand panel), in order to address this issue.

3. Star formation fueled by cold flows

In addition to mergers, cold flows are another important source of fuel for SF. This is particularly true for low mass galaxies (which can't support stable virial shocks, Birnboim & Dekel 2003) and at high redshift (where the filaments are narrower and denser). In the hierarchical picture, however, this also has a knock-on effect for galaxies at lower redshifts and higher masses (Keres *et al.* 2005). We also observe supernova-driven winds at high-redshift and we expect feedback from these winds to be particularly effective at reducing, or shutting down star formation in low-mass galaxies (Dekel & Silk 1986). Essentially then, we expect both cold flows and galactic winds to be effective simultaneously.

We perform ultra-high resolution ($\sim 0.5\text{pc}$) cosmological resimulations of the $z \sim 9$ progenitor of a Milky Way-like galaxy to follow how its evolution is influenced by the combined effects of cold gas accretion via filaments and a supernova-driven galactic wind. This resolution allows us to directly model the Sedov blastwave phase of supernovae. Due to the expansion and overlapping of 'bubbles' formed by the blastwaves, a high-speed wind is driven to several times the galaxy's virial radius. By comparison with a simulation without supernovae, we establish that the wind has had no effect on the accretion rate via the filaments and does not eject significant mass, so it is not able to reduce the SFR. This suggests SN feedback is not as effective (in this regime) as previously thought. We refer the reader to Powell *et al.* (2011) for the full details and results.

4. Conclusions

We have highlighted aspects of galaxy evolution in which refinements to the classical pictures are now required because of more detailed information gleaned from observations and/or simulations: the addition of clumpy star formation to the nuclear starburst model; the inclusion in merger studies of not just hot gas haloes, but the feedback that may affect them; and the impact that filaments (often neglected) can have on the predicted efficiency of supernova feedback. We have demonstrated that hydrodynamical simulations are an invaluable tool to investigate all these refinements, but note that having high resolution is absolutely crucial, or these effects are simply not captured.

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