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# The Theory of Forming Submillimetre Galaxies

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**Abstract.** Submillimetre-selected galaxies are the most luminous, heavily star-forming galaxies in the Universe. While this field has exploded observationally over the past decade and a half, theorists have struggled to develop a concordance model for their origin. Here, I review the major theoretical efforts in this field. I then present a newly developed model for the origin of this enigmatic population of galaxies.

**Keywords.** galaxies: star formation, starburst, evolution, formation

## 1. Introduction

Since the report of their discovery in back to back *Nature* papers in 1998 (Barger *et al.* 1998; Hughes *et al.* 1998), understanding the origin and cosmological role of 850$\mu$m-selected Submillimetre Galaxies (SMGs) has been a source of great interest to both observational and theoretical astrophysicists. The most luminous of these systems are the brighest galaxies in the Universe, and they form as many as a few thousand solar masses per year (compared to the paltry $\sim 1 - 2$ M$_\odot$ yr$^{-1}$ of our own galaxy; see the recent review by Casey, Narayanan & Cooray 2014). These galaxies are heavily dust-enshrouded, and the less luminous subset of these galaxies (that form at just tens to hundreds of solar masses per year) contribute significantly to the cosmic infrared background. SMGs generally reside at redshifts $z \sim 2 - 3$, though have been discovered at redshifts as high as $z \sim 5 - 6$ Riechers *et al.* (2013); Vieira *et al.* (2013). While the exact stellar masses of these systems are argued about in the literature (e.g. Hainline *et al.* 2011; Michałowski *et al.* 2012), it is known that they are generally quite massive, residing in many$\times 10^{12} - 10^{13}$ M$_\odot$ halos at $z \sim 2$,

## 2. The Theoretical Challenge

Understanding the physical origin of these systems has proven to be a source of great consternation and frustration for galaxy formation theorists. The fundamental difficulty is as follows. The easiest mechanism for forming galaxies with SFRs $\geqslant 1000$ M$_\odot$ yr$^{-1}$ at redshifts $z \sim 2 - 3$ that are as massive as SMGs are via gas-rich galaxy mergers (Narayanan *et al.* 2009, 2010a,b). However, as noted by Davé *et al.* (2010), when examining large cosmological dark-matter only simulations, it becomes rapidly apparent that there are nowhere near enough galaxy mergers at $z = 2 - 3$ to account for the SMG population given the typical duty cycle of SMGs formed in merger simulations (Fakhouri & Ma 2008; Hopkins *et al.* 2010; Hayward *et al.* 2013). At the same time, mergers are an extremely *inefficient* producer of submillimetre-wave photons. For example, when Hayward *et al.* (2011) examined the submllimetre evolution (utilising the dust radiative transfer package SUNRISE; Jonsson, Groves & Cox 2010) of idealised galaxy merger simulations, they found a very weak dependence between the synthetic 850$\mu$m flux density and the star formation rate. This weak powerlaw relation owes to the fact that mergers typically produce rather compact starbursts, and thus heat the dust. As the dust heats, the SED shifts toward the blue, thus giving relatively negligible increase to the submillimetre-band SED. On the other hand, the typical star formation history of galaxies of comparable mass to observed SMGs in cosmological simulations typically peak at redshifts $z = 4 - 6$, and therefore are unable to provide enough ultraviolet photons to be reprocessed into the copious submillimetre luminosity typically seen in SMGs (e.g. Davé, Finlator & Oppenheimer 2011).

This fundamental challenge has resulted in numerous physical models in the literature with a wide range of predicted physical properties of SMGs. While I don't have the luxury of unlimited space to fully delve into the various models, I highly recommend, in my very unbiased opinion, Chapter 10 in the super-awesome review by Casey, Narayanan & Cooray (2014) for more details, and the history of this field as of early 2014. Here, we provide a few anecdotal examples from some of the more well-cited models in the field.

Baugh *et al.* (2005) was one of the first to highlight the central issues surrounding the theoretical challenge in forming SMGs. Utilising a fork of the Durham Semi-Analytic Model (SAM), these authours found that in order to account for SMGs in their cosmological model (while, importantly, simultaneously matching both the high-redshift Lyman Break Galaxy population, as well as the present epoch $K$-band luminosity function), that SMGs needed to owe their origin to roughly 22% major mergers, and 77% minor (mass ratio $< 1/3$) mergers (González *et al.* 2011). A notable distinction in this model was that the stellar initial mass function was flat for starbursting systems. This model has since been updated, and while a top-heavy stellar IMF is still necessary, the magnitude of the slope is much less extreme (Cowley *et al.* 2014).

Cosmological hydrodynamic simulations have similarly had a difficult time in fully matching the observed properties of SMGs. Owing to a lack of spatial resolution of most hydrodynamic simulations in the early 2000s (typically 3-5 kpc), to date no cosmological hydrodynamic simulation has performed bona fide radiative transfer to identify galaxies as SMGs. The most extensive study utlising this modeling technique was performed by Davé *et al.* (2010). These authours examined a 100 Mpc $h^{-1}$ volume, and took the ansatz that the most heaviliy star forming galaxies in the simulation were the SMGs. In order to then match the observed abundances of SMGs, this required SMGs to have a typical SFR of $\sim 180 - 600$ $M_{\odot}$ $yr^{-1}$. This model was able to match the inferred stellar masses, metallicities, gas fractions and clustering measurements of SMGs. The typical star formation rates were a factor 2-3 lower in these models than typically inferred from observations, though these could potentially be reconciled by uncertainties in the assumed stellar IMF of high-$z$ starbursts (Narayanan & Davé 2012a,b). Importantly, in these models, almost none of the galaxies were undergoing a major merger.

Finally, taking a hybrid approach to understand the origin of SMGs, in a series of papers, Hayward *et al.* and Narayanan *et al.* combined a large number of hydrodynamic simulations of idealised galaxy discs and galaxy mergers (with a large range of both galaxy merger mass ratios and galaxy masses) with dust radiative transfer calculations (Hayward *et al.* 2011, 2012, 2013; Narayanan *et al.* 2009, 2010b,a). These authours then convolved the calculated 850$\mu$m duty cycles of these galaxies with observed stellar mass functions and galaxy-galaxy merger rates derived from cosmological dark matter only simulations to infer the theoretical number counts. While these models found success in matching the observed abundances of SMGs, they were unable to capture the realistic environment of SMGs in formation, owing to the idealised nature of the galaxy evolution simulations.

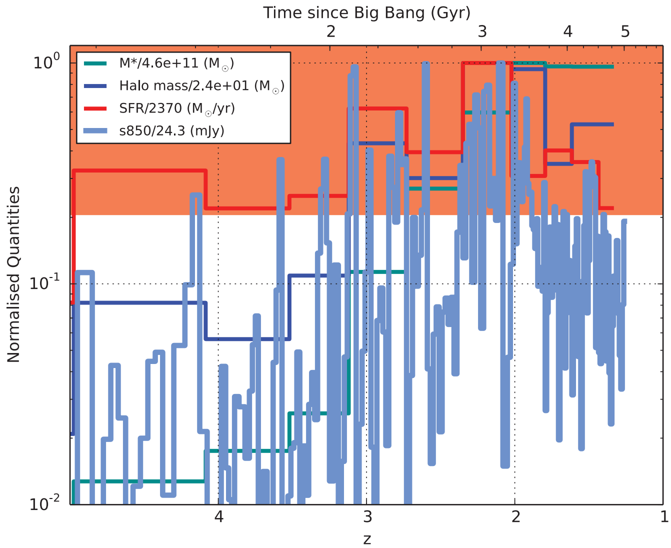


**Figure 1.** Evolution of physical quantities and our synthetic 850$\mu$ m flux density with time. The orange shaded region shows the typical selection criteria for SMGs.

## 3. A New Picture for SMG Formation

Motivated by these numerical experiements, we have conducted a series of cosmological hydrodynamic zoom simulations of galaxy formation (Hopkins *et al.* 2014). The goal with these simulations is to simulate the cosmic environment surrounding galaxies that could potentially represent SMGs, while still maintaining relatively high spatial resolution. We first conducted a large box/low resolution dark-matter only simulation; we then identified a halo of interest, and re-simulated this at high resolution, and with gas included. Motivated by clustering measurements of SMGs (Hickox *et al.* 2012), we selected a massive halo with a ($z = 0$) mass of $M_{\rm halo} = 6 \times 10^{13}$ M$_\odot$. The hydrodynamics were simulated utilising the code GIZMO (Hopkins 2014). Important to this study are the inclusion of various forms of stellar feedback (including radiative momentum deposition, energy deposition from supernova and stellar winds, and HII region feedback; see Hopkins *et al.* (2014) for details).

In order to calculate the inferred photometric properties of these hydrodynamic simulations, we have developed a new dust radiative transfer package, POWDERDAY. This code projects the particle data from the hydrodynamic simulation onto an octree adaptive grid, and then calculates the stellar SEDs utilising FSPS (Conroy, Gunn & White 2009). The stellar radiation fields are then propagated through the dusty interstellar medium utilising HYPERION (Robitaille 2011), and subsequently analysed. Threaded throughout the code is YT (Turk *et al.* 2011), facilitating the individual codes playing nice with one another.

Figure 1 shows our main results. The galaxy has a rising star formation history (SFH), which peaks at redshifts $z \approx 2 - 3$. The SFH peaks late compared to most models of galaxies of this mass owing to the stellar feedback in the simulations: feedback from early star formation drives gaseous bubbles which provides a reservoir to be banked for later star formation. By this time, the ISM is sufficiently enriched with metals that the galaxy may be viewed as a submillimetre-luminous system.

The morphology of this system is extremely clumpy. As the central galaxy evolves, numerous subhaloes bombard the centre, providing more fuel for star formation. This is

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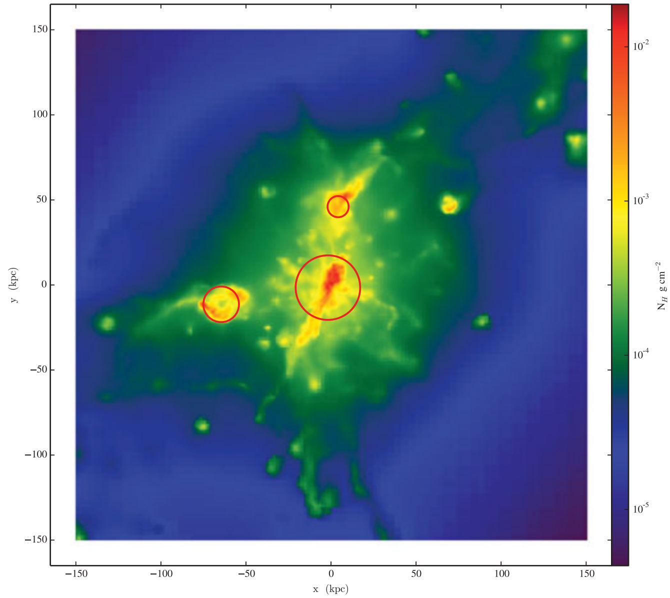


**Figure 2.** Gas surface density projection plot of an SMG at $z \sim 2$. The red circles correspond to individual dark matter halos with the sizes corresponding to their virial radii. The panel is 300 kpc on a side. SMGs will typically break up into multiple emission peaks in our model.

evident in Figure 2, where we show an example snapshot of one of our model galaxies, with individual subhalos denoted (with size corresponding to their virial radius). Our model therefore predicts that high-resolution observations of SMGs will reveal multiple emission sources, rather than one (or even two merging) galaxies. The galaxy has stellar masses and star formation rates comparable to those observed. This picture is notably different from a classical merger-driven scenario. At the same time, the long duty cycle and general abundance of halos of this mass suggest that this sort of model can account for the observed abundance of high-$z$ SMGs.

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## References

Barger A. J., Cowie L. L., Sanders D. B., Fulton E., Taniguchi Y., Sato Y., Kawara K., & Okuda H., 1998, *Nature*, 394, 248

Baugh C. M., *et al.*, 2005, *MNRAS*, 356, 1191

Casey C. M., Narayanan D., & Cooray A., 2014, *Physics Reports*, 541, 45

Conroy C., Gunn J. E., & White M., 2009, *ApJ*, 699, 486

Cowley W. I., Lacey C. G., Baugh C. M., & Cole S., 2014, arXiv/1406.0855

Davé R., Finlator K., & Oppenheimer B. D., 2011, arXiv/1108.0426

Davé R., Finlator K., Oppenheimer B. D., Fardal M., Katz N., Kereš D., & Weinberg D. H., 2010, *MNRAS*, 404, 1355

Fakhouri O. & Ma C.-P., 2008, *MNRAS*, 386, 577
González J. E., Lacey C. G., Baugh C. M., & Frenk C. S., 2011, *MNRAS*, 413, 749
Hainline L. J., Blain A. W., Smail I., Alexander D. M., Armus L., Chapman S. C., & Ivison R. J., 2011, *ApJ*, 740, 96
Hayward C. C., Jonsson P., Kereš D., Magnelli B., Hernquist L., & Cox T. J., 2012, *MNRAS*, 424, 951
Hayward C. C., Kereš D., Jonsson P., Narayanan D., Cox T. J., & Hernquist L., 2011, *ApJ*, 743, 159
Hayward C. C., Narayanan D., Kereš D., Jonsson P., Hopkins P. F., Cox T. J., & Hernquist L., 2013, *MNRAS*, 428, 2529
Hickox R. C., *et al.*, 2012, *MNRAS*, 421, 284
Hopkins P. F., 2014, arXiv/1409.7395
Hopkins P. F., Kereš D., Oñorbe J., Faucher-Giguère C.-A., Quataert E., Murray N., & Bullock J. S., 2014, *MNRAS*, 445, 581
Hopkins P. F., Younger J. D., Hayward C. C., Narayanan D., & Hernquist L., 2010, *MNRAS*, 402, 1693
Hughes D. H., *et al.*, 1998, *Nature*, 394, 241
Jonsson P., Groves B. A., & Cox T. J., 2010, *MNRAS*, 186
Michałowski M. J., Dunlop J. S., Cirasuolo M., Hjorth J., Hayward C. C., & Watson D., 2012, *A&A*, 541, A85
Narayanan D., Cox T. J., Hayward C. C., Younger J. D., & Hernquist L., 2009, *MNRAS*, 400, 1919
Narayanan D. & Davé R., 2012a, *MNRAS*, 423, 3601
Narayanan D. & Davé R., 2012b, arXiv/1210.6037
Narayanan D. *et al.*, 2010a, *MNRAS*, 407, 1701
Narayanan D., Hayward C. C., Cox T. J., Hernquist L., Jonsson P., Younger J. D., & Groves B., 2010b, *MNRAS*, 401, 1613
Riechers D. A., *et al.*, 2013, *Nature*, 496, 329
Robitaille T. P., 2011, *A&A*, 536, A79
Turk M. J., Smith B. D., Oishi J. S., Skory S., Skillman S. W., Abel T., & Norman M. L., 2011, *ApJS*, 192, 9
Vieira J. D. *et al.*, 2013, *Nature*, 495, 344