Galaxy formation & evolution: the far-ir/sub-mm view

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Abstract. We review our current knowledge of the population of high-redshift sub-mm/mm galaxies, with particular emphasis on recent results from the SCUBA HAlf Degree Extragalactic Survey (SHADES). All available evidence indicates that these objects form the high-redshift, high-luminosity, high-mass tail of the dusty starforming galaxy population revealed at lower redshifts and luminosities by Spitzer. Current theoretical models of galaxy formation struggle to reproduce these extreme objects in the numbers indicated by current surveys.

1. Introduction

It is now 10 years since the advent of array cameras on sub-mm/mm telescopes provided the first discoveries of sub-mm/mm galaxies (SMGs; Smail et al. 1997). Over the intervening decade a series of surveys at 850µm with SCUBA (Smail et al. 1997; Barger et al. 1998; Hughes et al. 1999, 2000; Cowie et al. 2002; Scott et al. 2002; Webb et al. 2003; Serjeant et al. 2003; Wang et al. 2004; Coppin et al. 2006) and at millimeter wavelengths with MAMBO and AzTEC (Greve et al. 2004; Dannerbauer et al. 2004; Carilli et al. 2005; Laurent et al. 2005; Bertoldi et al. 2007) have been undertaken in order to clarify the prevalence and properties of SMGs, and their role in the process of galaxy formation.

Multi-frequency follow-up has shown that SMGs are heavily dust-obscured galaxies at high redshift (z > 1) undergoing intense star-formation with inferred star-formation rates of several hundred to a few thousand solar masses per year. These dusty star-forming galaxies have a comoving number density of $n > 10^{-5} \text{Mpc}^{-3}$, approximately comparable to the number density of $2-3L^*$ massive elliptical galaxies observed in the local Universe (Scott et al. 2002). This, combined with preliminary measurements of their dynamical masses (Greve et al. 2005; Tacconi et al. 2006) and clustering properties (Scott et al. 2006), suggests that SMGs represent an important phase in the formation of present-day massive galaxies. However, SMGs have not proved to be a natural prediction of semi-analytic models of galaxy formation (Baugh et al. 2005). Current work in this field is thus focussed on providing improved data on the SMG population of sufficient quality to allow detailed statistical comparison with theory.
2. SHADES

Taken together, all the early sub-mm surveys (Clusters - Smail et al. 1997; Hubble Deep Field - Hughes et al. 1998; Canada-UK Deep Sub-mm Survey - Eales et al. 1999; Hawaii Flanking Fields survey - Barger et al. 1999; 8-mJy survey - Scott et al. 2002; 8-mJy IRAM MAMBO follow-up - Greve et al. 2004; HDF "supermap" - Borys et al. 2003) cover $\approx 500$ arcmin$^2$, but with widely varying depth and data quality. While interesting results have been extracted from a combined re-analysis of these surveys (e.g. Scott et al. 2006), this early work demonstrated the need for a much larger, homogenous, fluximited sub-mm/mm survey. In an attempt to fulfil this requirement, the SCUBA Half Degree Extragalactic Survey (SHADES) was commenced at the JCMT in 2003.

SHADES was designed to provide the first homogeneous sub-mm survey of sufficient size to provide a complete flux-limited sample of several hundred SMGs. The aim was to achieve a clean measurement of the number counts and redshift distribution of bright ($S_{850\mu m} \approx 8$ mJy) SMGs, along with a first measurement of the strength of their angular clustering (van Kampen et al. 2005; Mortier et al. 2005). The relatively shallow depth of the survey ($\sigma_{850} \approx 2$ mJy) was chosen both to minimise the problems of source confusion (given the 14-arcsec JCMT beam at 850$\mu$m), and to maximise the effectiveness of multi-frequency follow-up. In addition, it is the brightest star-burst galaxies which appear to offer the most challenging test of theoretical models of galaxy formation (e.g. Baugh et al. 2005).

The SHADES 850$\mu$m maps were made over a period of 3 years with an increasingly ailing SCUBA camera, eventually retired due to cryogenic problems. The final sub-mm data cover an area $\sim 1/4$ of square degree down to an rms depth of $\sigma_{850} \approx 2$mJy in two fields with deep multi-wavelength ancillary data: the Lockman Hole and the Subaru/XMM deep field (SXDF). While short of the original goal, the final maps still form the largest extragalactic sub-mm imaging survey of meaningful depth undertaken to date, and provide a uniquely powerful resource for the study of the bright sub-mm population (Figure 1).

The 850$\mu$m data have been subjected to an extremely thorough analysis, with 4 independent sub-groups undertaking independent data reduction and source extraction. The final merged results of this process are reported in Coppin et al. (2006), and include a new sample of 120 SMGs with statistically deboosted fluxes, and a definitive measurement of the 850$\mu$m source counts in the range $1 - 10$ mJy (Figure 2).

3. Identifications

As a result of the rather poor positional accuracy (typically 2–3′′ r.m.s.) provided by single-dish sub-mm/mm detections, further long-wavelength follow-up observations have proved essential for the robust identification of SMG galaxy counterparts. An attractive and unambiguous way to refine sub-mm source positions is to obtain deep interferometric follow-up observations at mm/sub-mm wavelengths, as demonstrated by IRAM PdBI and SMA observations of some of the brightest SMGs discovered to date (Downes et al. 1999; Dannerbauer et al. 2002, 2004, 2008; Younger et al. 2007; Wang et al. 2007). However, current
mm/sub-mm interferometry is still too demanding and expensive to be applied to large statistical samples of SMGs, and wide-field radio imaging continues to offer the best route for refining the positions of the majority of bright SMGs (Ivison et al. 2002).

Within the SHADES fields, deep VLA imaging at 1.4 GHz has allowed \(\approx 70\%\) of the SHADES sources to be identified with radio counterparts, yielding positions accurate to \(\approx 1\) arcsec (Ivison et al. 2007). The vast majority of the resulting identifications are unique and unambiguous, allowing the use of SMA follow-up to be focused on those sources for which it is required to differentiate between alternative radio counterparts (Younger et al. 2008). The importance of this careful two-stage approach is nicely demonstrated by the case of a SHADES source which has three alternative statistically acceptable radio counterparts (Ivison et al. 2007). Deep SMA observations (Iono et al. 2008, in prep) have now shown that the sub-mm emission is confined to one of the radio counterparts, and is located at the position of a galaxy which is invisible in the deep Subaru optical images (to \(R > 27\)), but is clearly detected in the near-infrared (Figure 3). The case of this sub-mm source demonstrates the power of sub-mm interferometry, but also the importance of deep near-infrared data for an unambiguous identification and study of the host galaxy.

Finally, mid-infrared observations with Spitzer have also been used to further raise the identification fraction in SMG samples, including SHADES (Egami et al. 2004; Ivison et al. 2004; 2007). However, some of the latest SMA results demonstrate that apparent Spitzer identifications of radio-unidentified SMGs need to be treated with caution (Younger et al. 2007; 2008).

4. Redshifts

The ability to locate the position of the SMGs to arcsec accuracy has allowed deep spectroscopic observations of SMG counterparts at both optical (Chapman
Figure 2. The 850$\mu$m number counts as derived from the SHADES SCUBA maps shown in Figure 1. The result is the best estimate to date of the number counts in the 1-10 mJy range, and resolution of 20-30% of the background.

2003, 2005; Swinbank et al. 2004) and more recently mid-infrared wavelengths (Menendez-Castro et al. 2006; Valiante et al. 2007; Pope et al. 2008). However, because the optical counterparts of SMGs are generally very faint and red, the number of SMGs with robust spectroscopic redshifts remains rather low (only 10% of the SHADES sources currently have unambiguous spectroscopic redshifts).

Given the difficulty (and in some cases impossibility) of determining optical spectroscopic redshifts for SMGs, a significant amount of effort has been invested in the development of redshift estimation techniques based on both radio/sub-mm and infrared/optical photometry. The radio:sub-mm flux-density ratio was first proposed as a crude (but potentially unbiased and complete) method for estimating the redshifts of SMGs by Carilli & Yun (1999). The use of long-wavelength photometry has been developed further by Aretxaga et al. (2003), and applied to the SHADES sample in Aretxaga et al. (2007). The results broadly confirm the findings of previous studies - the vast majority of the bright SMGs have redshifts in the range $2 < z < 3$, with very few SMGs found at $z < 1$, and little evidence for a significant high-redshift tail beyond $z \simeq 4$. Interestingly, it is generally the brightest SMGs which appear to lie at the highest redshifts (e.g. Younger et al. 2008), providing further evidence of the existence of downsizing in cosmic star-formation history.

More accurate redshift estimates can be obtained from the more extensive optical+near-infrared+Spitzer-IRAC photometry, albeit this is necessarily confined to SMGs with clearly detected infrared counterparts. Within SHADES this technique has been applied by Dye et al. (2008) in the Lockman Hole field, and by Clements et al. (2008) in the SXDF. These studies have also enabled an
Figure 3. Optical and near-infrared images of the field around a sub-mm galaxy (Iono et al. in prep). In both images the exact position of the sub-mm galaxy as obtained by SMA interferometry is indicated by the green circle. The true galaxy counterpart is clearly seen in the $K$-band, but completely invisible in the $R$-band.

exploration of the stellar masses and star-formation histories of the SHADES galaxies. The results indicate that bright sub-mm sources are housed in galaxies which are already massive (typically a few $\times 10^{11} M_\odot$) with the “current” starburst having been preceded by previous star-formation events which formed at least half of the final stellar mass.

5. The nature of sub-mm galaxies

Armed with reliable identifications and redshift estimates for SMGs it is possible to begin to study the physical properties of these sources. In particular, to place SMGs in the broader context of galaxy evolution, it is important to investigate the masses, sizes and morphologies of the galaxies which host these most luminous dust-enshrouded starbursts.

Studies of the rest-frame optical/UV light of sub-mm sources have revealed a complex and often disturbed morphology (Smail et al. 2004; Conselice et al. 2003; Chapman et al. 2004; Swinbank et al. 2006) suggesting major interactions and/or non uniform dust obscuration. However, very little is known about the morphology at longer wavelengths, which better traces the stellar mass of the system. In particular, it is still unclear whether sub-mm galaxies are disc galaxies (as might be expected for gas-rich star-forming systems) or massive ellipticals (as perhaps suggested by their number density, which matches that of present-day $> 2 - 3 L^*_{\text{elliptical galaxies}}$).

A limited number of sub-mm galaxies have been studied in the infrared (e.g. Smail et al. 2004; Swinbank et al. 2006), but to date no systematic study of the morphologies of sub-mm galaxies has been undertaken. To judge the relevance of any size and morphological information which might be gleaned
from the imaging of the sub-mm galaxies, it is also important to assemble data of comparable quality for a well-defined control sample. Recently, Targett et al. (2008, in prep.) have obtained deep, high resolution (0.5 arcsec) K-band imaging of 15 bright (S$_{850\mu m}$ > 8mJy) sub-mm galaxies at $z \simeq 2$ together with a sample of 13 radio galaxies at the same redshift. This latter sample was chosen as a control because radio galaxies are the most massive galaxies in existence at this epoch and will certainly evolve into massive ellipticals. As shown in Figure 4, SMGs are very compact with an effective radius of $\simeq 3$ kpc, significantly smaller than the radio galaxies at the same redshift. The analysis of the light profile also reveals a substantial difference between radio and sub-mm galaxies. The distribution of the Sérsic indexes shown in figure 4 suggests that the SMGs are mostly discs while the radio galaxies, as perhaps expected, are generally found to be de Vaucouleurs spheroids (Targett et al. 2008, in prep).

These results are also in agreement with recent high-resolution molecular CO measurements of a sample of bright sub-mm galaxies at $z > 2$ obtained by Tacconi et al. (2006). These CO observations reveal that the millimeter line and continuum is compact with sizes < 4 kpc. A large fraction ($\simeq 60\%$) of the sources with CO detections show a double-peaked line profile (Tacconi et al. 2006; Neri et al. 2003; Greve et al. 2005), indicative of orbital motion. However, with the current resolution it is not possible to distinguish between a single rotating disc and two galaxies in a final stage of merging. It is also worth noting that recent deep, high-resolution radio observations of a sample of 12 sub-mm galaxies found rather extended radio emission with linear sizes in the range 1 – 8 kpc (Biggs & Ivison 2008)

Another parameter of fundamental importance for understanding the nature of SMGs is galaxy mass. Measurements of molecular gas mass via CO observations (Neri et al. 2003; Greve et al. 2005) and dynamical masses (Tacconi et al. 2006; see also Swinbank et al. 2006 for masses derived via integral field spectroscopy) all suggest that sub-mm galaxies are gas rich ($M_{\text{gas}} \simeq 10^{10} - 10^{11}M_{\odot}$) and massive ($M_{\text{dyn}} \simeq 5 \times 10^{10}M_{\odot}$). These estimates are also in agreement (within the errors) with stellar mass estimates ($M_{\text{stars}} \geq 10^{11}M_{\odot}$) obtained by
fitting the optical and near-infrared spectral energy distribution (Borys et al. 2006; Clements et al. 2008; Dye et al. 2008).

6. Discussion and future prospects

It is sometimes asserted that sub-mm galaxies are bizarre objects caught in a very unusual or extreme phase/mode of star formation. However, their observed properties in fact seem largely as expected on the basis of extrapolation from less extreme starburst galaxies at lower redshift. For example, as shown by Bouché et al. (2007), because of their small sizes and large gas densities, SMGs lie at the high surface-density end of the apparently universal “Schmidt-Kennicutt” relation. In other words, an object with a mass of $10^{11} M_\odot$ in gas within a radius of few kpc is *expected* to produce $\sim 1000 M_\odot$ of stars per year. Similarly, it is also “expected” that such extreme starbursts should be hosted by some of the most massive galaxies in existence at $z > 2$, given the relationship between stellar mass and star-formation rate at $z \approx 2$ found by Daddi et al. (2007).

In conclusion, sub-mm galaxies appear to be massive gas rich discs engaged in a major star-formation event triggered, in at least some cases, by a “recent” galaxy-galaxy interaction. Given the starburst is relatively compact, one can speculate that we are witnessing these galaxies completing the formation of their cores. Although the sub-mm galaxies are best described as discs, in terms of density (and space density) they are much more like ellipticals/bulges than present day star-forming spiral galaxies. The SMGs we observe at high redshift thus seem destined to evolve into massive, passive spheroids, awaiting relaxation and further extended mass growth (e.g. by dry mergers) by a factor $\approx 2$.

Over the next 3-5 years we can expect our understanding of SMGs to be placed on a much firmer footing be a series of genuinely revolutionary new projects. First, at the time of writing the SHADES consortium is completing a new, expanded study of the SHADES fields using 1.1mm maps of the full 0.5 square degree area made with AzTEC on the JCMT (Austermann et al. 2008, in prep). Second, SCUBA2 is currently being installed at the JCMT in Hawaii, and is expected to commence the SCUBA2 Cosmology Legacy Survey in early 2009. Third, Herschel is due to launch later this year, and will provide complete SEDs and bolometric luminosities for large numbers of the SMGs uncovered with SCUBA2. Finally, these photometric surveys will set the stage for the detailed astrophysical study of SMGs with the Atacama Large Millimetre Array.

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