Chapter 6

Summary

At the time of their discovery in the late 1990's, SMGs founded a new observational field: they afforded the opportunity to study galaxies that made up the bulk of (obscured) stellar growth at cosmologically-significant redshifts ($z \gtrsim 2$) that had until then remained inconspicuous in optical/UV surveys. With ultra-luminous energetic outputs ($L_{IR} \gtrsim 10^{12}$ $L_\odot$; C05), large stellar masses ($M_{stellar} \sim 10^{11}$ $M_\odot$) and inferred high SFRs $\gtrsim$ 1000 $M_\odot$ yr^{-1} (Borys et al. 2005), SMGs are prime candidates for the progenitors of the most massive galaxies at $z \sim 0$ and the likely major stellar build-up sites at $z \sim 2$ (Lilly et al. 1999; Smail et al. 2004).

At low redshifts, a plethora of studies have shown that dust-enshrouded galaxies with comparable luminosities have complex, disturbed morphologies (e.g., Soifer et al. 2000; Scoville et al. 2000), with intense starburst and AGN activity concentrated in a compact region ($\lesssim$ 1 kpc; Charmandaris et al. 2002), suggestive of a merger-driven origin. The extreme luminosities of distant SMGs match, but are they high-redshift analogs of local ultra-luminous infrared galaxies and do they host similar astrophysics?

In this thesis I have concentrated on the mid- and near-IR spectroscopic study of the sub-sample of SMGs with identified radio-counterparts and spectroscopic UV redshifts compiled by Chapman et al. (2005). Our main results are:

1. **SMGs are dominated by star formation.** From the mid-IR spectra of the largest sample observed to date with *Spitzer*-IRS we find that the majority of SMGs (80%) display strong PAH spectral features, while only a minority (12% of our sample) display continuum-dominated spectra. This indicates that SMGs are

undergoing intense star formation, and that some diversity in AGN contribution to the mid-IR is present within the population. However, from the composite SMG spectrum – as revealed by an enhanced hot-dust continuum at $\lambda_{rest} \sim 10\ \mu$m – we determine that this AGN contribution is $\lesssim 35\%$ to the total luminous output. The SMG population is dominated by intense starburst activity and displays among the most luminous PAH features observed locally and at high redshift: it likely includes some of the most intense star-formation events ever witnessed in the Universe.

2. **SMGs have spatially extended mid-IR emission.** The observed ratio of PAH features – sensitive to the hardness of the ionization field and reddening – and the strength of the silicate absorption feature at $\lambda \sim 9.7\ \mu$m – which provides insight into the distribution of dust along the line of sight – suggest lower extinction towards the mid-IR line and continuum emitting regions within SMGs, as compared with either local nuclear starbursts or ULIRGs. Given the compact mid-IR emission from local ULIRGs, the difference in extinction argues that the mid-IR emission in SMGs, both continuum and PAH-emission, arises in a more extended component ($\gg$ 1–2 kpc).

3. **SMGs display velocity offsets suggestive of powerful outflows.** We study the rest-frame optical line emission in a sample of SMGs to provide a more accurate redshift for the bulk of the gas in the ISM of the potential well of these galaxies. We find redshift differences between rest-frame UV and Hα lines amounting to $\sim$ *few* $\times$1000 km s^{-1}, which indicate that large velocity outflows are present. Considering the enriched chemical abundances hosted by SMGs, with near- to super-solar metallicities, such outflows are potentially powerful at transforming the intergalactic environments.

4. **SMGs have Hα extended emission, exceeding sizes of local ULIRGs.** With spatially-resolved integral field spectroscopy with Keck OSIRIS we distinguish multiple galactic-scale sub-components within a sample of SMGs, as traced by Hα emission. In particular, we distinguish spatially between regions bright in Hα emission that are dominated by AGN activity from those where star formation is taking place. We show that SMGs host SFR surface densities a factor of $\sim 2-6$ higher than the

median value for optically-selected high-redshift galaxies, but similar to local ULIRGs and circumnuclear starbursts, though the spatial extent of Hα emission is significantly larger in SMGs, $\sim 8 - 16$ kpc.

5. **SMGs comprise multiple galactic-scale sub-units.** We see no evidence for ordered orbital motion – such as would be present in a gaseous disk – but find relative velocities of $\sim few \times 100$ km s^{-1} between sub-components in individual SMGs. This may suggest that these sub-units are remnants of originally independent systems undergoing a merger. Considering the similarities between the individual clumps in SMGs with those of individual LBGs in terms of size and velocity dispersions – taken as a proxy of dynamical mass–, these results suggest that the mergers in SMGs may comprise multiple 'LBG-like' sub-units.

The dominant role of star formation in SMGs, their large dynamical and (estimated) gas masses and their wide spatial extension all suggest that the SMG phase denotes a flaring-up that rapidly depletes the available gas through intense star formation of large spatial extension across these systems. With extended emission ($\gtrsim 8 - 17$ kpc) beyond that found in local ULIRGs ($\lesssim 1$ kpc; Charmandaris et al. 2002), it is possible that the evolutionary stages prior to the SMG phase are distinct from the major mergers that produce local ULIRGs. Minor mergers may also play an important role in the assembly of galaxy mass (Guo & White 2007) and could potentially provide an additional origin to the SMG phase.

It has been a notorious challenge for galaxy formation models to reproduce the 850 μm counts – which require replicating the extreme luminosities of SMGs – without overshooting the number density of bright and massive galaxies at $z \sim 0$ (Granato et al. 2000; Baugh et al. 2005). Furthermore, under the assumption that SMGs are high-redshift analogs of local ULIRGs, the abundance of this galaxy population is contingent on the frequency of (major) galaxy mergers igniting powerful starbursts at these high redshifts. Therefore, the possibility of invoking less dramatic events to trigger an SMG phase in galaxies could hold promise in the context of galaxy formation theory.

6.1 Future Directions

Through this past decade, a collective multi-wavelength effort has enabled a steadily growing picture of the astrophysical details of SMGs (e.g., Ivison et al. 1998; Frayer et al. 1998, 1999; Blain et al. 1999, 2002; Chapman et al. 2004; Frayer et al. 2004; Sheth et al. 2004; Smail et al. 2004; Swinbank et al. 2004; C05; Greve et al. 2005; Kneib et al. 2005; Lutz et al. 2005; Takata et al. 2006; Hainline et al. 2006, 2009; Tacconi et al. 2006, 2008; Menéndez-Delmestre et al. 2007, 2008; Valiante et al. 2007; Younger et al. 2007; Pope et al. 2008). The research presented in this thesis comprises a significant step towards understanding the astrophysical properties of the ensemble of SMGs, and also suggests a number of (clear) paths for furthering their investigation. In particular, the OSIRIS results that we have presented comprise merely a few objects of a nascent observing program. We are in the process of increasing our sample with the aim of furthering our understanding of the inner dynamics in SMGs as traced by the ionized near-IR emitting gas. Furthermore, we have initiated an effort to combine the power of spatially-resolved Hα OSIRIS spectroscopy with deep imaging with the Keck near-IR camera NIRC-2 in conjuction with LGS-AO to probe the detailed near-IR continuum morphology and stellar colors of the lower surface-brightness extended stellar component of SMGs. The combination of existing *HST*-ACS data (Smail et al. 2004) and high-resolution near-IR imaging will allow us to estimate SEDs of kpc-scale components within SMGs and to provide an insight into color gradients and thus the distribution of obscuration in these systems.

In the near future, the upcoming launch of the *Herschel* Space Observatory will extend our exploration of the extragalactic Universe to encompass the longer IR wavelengths beyond the *Spitzer* view. *Herschel* GTO programs have already been approved for $\lambda \sim 110 - 500$ μm imaging of the HDF, Lockman Hole, and Groth Strip fields, as part of two large collaborations: the PACS Evolutionary Probe (PEP) and the Herschel Multi-tiered Extragalactic Survey (HerMES). These observations will map rest-frame $\lambda \gtrsim 24$ μm for $z \gtrsim 2$ galaxies, which can give us additional insight to the ongoing star-formation activity. They will also provide for better constraints of the far-IR SED of SMGs, which will give us a better understanding of their typical dust temperatures and luminosities.

We make special note that the target of most SMG studies has been the radio-identified sample of SMGs with precise positions on the sky (within $\sim 1''$) and spectroscopically-confirmed UV redshifts compiled by C05. However, $\sim 30\%$ of the sources uncovered at $\lambda = 850-1100\,\mu$m do not display a sufficiently bright radio counterpart for unambiguous identification and their follow-up study at other wavelengths has been slower as a consequence. As discussed in Chapter 3, it is still unclear whether inherent differences in dust temperatures and/or differences in redshift distributions exist between SMGs with identified radio-counterparts and those without (Chapman et al. 2004; Younger et al. 2007). The first step towards characterization of this radio-undetected SMG population is to obtain accurate positions ($\lesssim 1''$), to undertake spectroscopic follow-up and obtain reliable redshifts. The Submillimeter Array (SMA) and the Combined Array for Research in mm-wave Astronomy (CARMA) are currently available instruments that has been shown to be suitable for this task (Younger et al. 2007; Sheth, K. et. al. in prep).

In only a few years the Atacama Large Millimeter/submm Array (ALMA) will come online with a resolution $\sim 0.005''$ at the highest frequencies that will surpass that of Hubble and the VLA by a factor of ~ 10. These high-resolution observing capabilities will not only allow for accurate positions of SMGs, but will also allow the detailed mapping of molecular gas morphology and mass as traced by CO rotation lines ($J > 2$) without incurring in the extremely demanding typical observing times ($\gtrsim 30$ hrs per source) that are currently necessary (Neri et al. 2003; Greve et al. 2005; Tacconi et al. 2006, 2008). ALMA will also enable high-resolution imaging in the mm/submm bands down to the sub-mJy flux level, avoiding the problem of confusion that has limited current submm cameras to $\gtrsim 2$ mJy and pushing the detection limit down to the realm of more *normal* galaxies at the SMG redshifts.