THE FUTURE OF SUBMILLIMETER GALAXY STUDIES IN THE NEXT DECADE

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ABSTRACT

Over the last two decades, the Submillimetre Common-User Bolometer Array (SCUBA) and SCUBA-2 on the James Clerk Maxwell Telescope (JCMT) achieved gread success in discovering the population of dusty starburst galaxies in the early universe. The SCUBA-2 surveys at 450μm and 850 μm set important constraints on the obscured star formation over cosmic time, and in combination of deep optical and near-IR data, allows the study of protoclusters and structure formation. However, the current submm surveys by JCMT are still limited by area of sky coverage (confusion limit mapping of only a few deg^2), which prevent a systematic study of large samples of the obscured galaxy population. In this white paper, we review the studies of the submillimeter galaxies with current submillimeter/millimeter observations, and discuss the important science with the new 850μm camera in the next decade.

1 Introduction

The thermal dust continuum emission at far-infrared wavelengths is an important trace of the dust and gas contents and star forming activities in galaxies (e.g.,). At high redshift, the UV and optical emission from the stellar component is dimming dramatically. However, the hump of the thermal dust emission is shifted to the submillimeter bands, and due to the negative k-correction, the observing flux densities at submillieter and millimeter wavelengths do not drop with redshift. Thus, the submm/mm windows open a unique opportunity to probe active star formation and galaxy evolution toward the earliest epoch. Over the last two decades, the submillimeter facilities, such as the Submillimetre Common-User Bolometer Array (SCUBA) and SCUBA-2 on the James Clerk Maxwell Telescope (JCMT) and SPIRE on the Herschel Space telescope etc., achieved gread success in discovering the population of dusty starburst galaxies in the early universe ().

Dusty starbursts have been found into the epoch of reionization (EoR; $z > 6.3$). Some of them are found as quasar hosts and/or companions (e.g., Bertoldi et al. 2003; Decarli et al. 2017), and yet some are found in "blind" sub-mm/mm surveys (e.g., Riechers et al. 2013; Strandet et al. 2017). In terms of IR luminosities, they are all ULIRGs ($L_{IR} > 10^{12} L_{\odot}$) and HyLIRGs ($L_{IR} > 10^{13} L_{\odot}$), which translate to dust-embedded star formation rates (SFRs) of

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$> 100 - 1000 M_{\odot}/yr$. The very existence of such high-z U/HyLIRGs has important implications. The burst of star formation traces the most active stage of galaxy evolution. The submm sources detected in the core of overdensity regions also probe the early evolution of galaxy clusters. In addition, The prevalence of dust at $z \approx$ 6-7 means that there must be very active star formations at even earlier epochs ($z \sim 10$ and beyond).

Bright submm/mm emission was also detected in the host galaxies of optically luminous quasars at z$\sim$2 to 7. The single dish surveys at sub-mJy sensitivity reveal that about 30% of them are hosted in dusty starburst systems with FIR luminosities comparable to that of the ULIRGs and HyLIRGs, suggesting massive star formation co-eval with rapid supermassive black hole (SMBH) accretion. These quasar-starburst systems became important targets for further interferometer observations to search and resolve the gas and dust content. The follow-up molecular CO and [C II] observations probe the distribution of dust, gas, and star forming activity, as well as the host dynamics (), and thus, set key constraints on the early growth of the SMBH-galaxy systems ().

The obscured star formation discovered in submm surveys provides essential complement to probe the cosmic star formation history (SFH). Traditionally, tracing the evolution with cosmic time of the galaxy luminosity density from the far-UV (FUV) to the far-infrared (FIR) offers the prospect of an empirical determination of the global star formation history (SFH) and heavy element production of the Universe (Madau & Dickinson 2014 and references therein; Rowan-Robinson et al. 2016; Livermore et al. 2017). However, lacking precise astrometry at FIR wavelengths at high redshifts often prevents us from connecting FUV to FIR data and providing the required complete understanding of cosmic SFH. To study the formation and evolution of galaxies, it is crucial to determine the redshift distribution of sources. Large samples of high redshift galaxies have been imaged with space facilities like Hubble, Spitzer, Herschel and ground-based telescopes at multiple wavelengths and their redshifts can be determined by photometric observations at multiple bands. Alternatively, a small fraction of sources have been confirmed with spectroscopic measurements and narrow-band imaging. Due to large extinction, observations at optical and/or near-infrared are difficult and only bright sources can be detected at high redshifts. For some sources with large amount of dust, they are very likely to be invisible with current optical facilities in a limit observing time.

The mapping capability of the single dish telescopes at submm wavelengths are also becaming important in tracing overdensity and structure formation in the early universe. Clusters of galaxies are the most massive bound structures in the local universe. They are largely dominated by ‘red and dead’ elliptical galaxies, and the oldest and most massive elliptical galaxies lie at their cores (eg. [13]). Studies of the stellar populations of these massive galaxies reveal them to be old, with inferred formation redshifts $z > 3$ and with the bulk of their stellar populations forming over a short time scale. This would imply that the progenitors of the massive elliptical galaxies in the cores of clusters must have formed in major starbursts.

Finding galaxy clusters in formation at these high redshifts is a difficult task. The standard methods of cluster detection include X-ray and SZ observations of the hot intracluster medium, and the search for red sequence galaxies in the optical and near-IR. All of these methods fail for forming galaxy clusters; the first two since young systems are yet to Virialize and thus lack a significant intracluster medium that can be detected by X-rays or SZ, and the last because the galaxies making up the cluster are still star forming and thus do not lie on the red sequence. The high star formation rates (SFRs) of forming giant elliptical galaxies, however, in principle allow us to search for these objects in the far-IR, since, like starbursts in the local universe, they should be luminous at these wavelengths. Recent results using *Herschel* and *Planck* data in the far-IR and submm have begun to find candidate protoclusters in this way.

2 Current Status

Submm surveys were carried out with JCMT in the last two decade, including the SCUBA program which discovers the first submillimeter galaxy sample at high redshift, the SCUBA-2 Cosmology Legacy Survey (S2CLS, Geach et al. 2017), the SCUBA-2 Large eXtragalactic Survey (S2LXS, Geach et al. 2017), S2COSMOS/eS2COSMOS (Simpson et al. 2017), and SCUBA-2 Ultra Deep Imaging EAO Survey (STUDIES, Wang et al. 2017). The SCUBA-2 surveys image the submm sky to a 1σ noise level of $0.9 \sim 2$ mJy, discovering the extreme starburst systems with FIR luminosities on orders of 10^{12} to 10^{13} $L_{\odot}$. These observations, together with the data from Spitzer and Herschel at shorter wavelengths, measure the submm source number densities and update the star formation rate density (e.g., Hughes et al. 1998; Daddi et al. 2005; Gruppioni et al. 2013; Rowan-Robinson et al. 2016; Geach et al. 2017, 2018; Wang et al. 2017), revealing that the submillimeter galaxies contribute significantly to the cosmic star formation history over a wide range of redshift (Madau & Dickinson 2014; Rowan-Robinson et al. 2016).

To study the SFH in the early Universe, observations by space telescopes at far-infrared and ground facilities at submm become an important tool to detect highly dust-obscured galaxies. However, due to the poor resolution and confusion level of the space telescopes, the observations will only select bright sources and therefore largely underestimate the SFR at high redshifts. Ground-based facilities like JCMT/SCUBA2 can provide better sensitivity and resolution in comparison with space facilities like Herschel. However, due to a relatively low mapping speed the statistic results still suffer large uncertainties by the cosmic variance from small surveyed fields. Large area of deep surveys are highly required in future.

In addition, to fully understand the early cosmological star formation history, we will need large samples of high-z dusty starbursts selected in a systematic manner. The most promising method to construct such samples is through the use of FIR/sub-mm colors in blind, un-biased surveys. The typical cold-dust emission (as being heated by star formation) in galaxies has its peak at around rest-frame 100 μm, and the color selection is to utilize this characteristics. The so-called "500 μm riser" technique is an implementation tailored for the BLAST and the Herschel/SPIRE bands (e.g. Pope & Chary 2010; Roseboom et al. 2012): a dusty galaxy at $z > 4$ should have red colors in 250, 350 and 500 μm bands because its SED is "rising" through these three bands as the peak is redshifted to ~ 500 μm and redder wavelengths. An extension of this technique to higher redshifts is the "850/870 μm riser" method, where a redder band at 850 or 870 μm is added to the selection (e.g., Riechers et al. 2017).

A growing number of protoclusters and protocluster candidates are being found using far-IR and submm techniques. Casey [4] summarises results on five specific protoclusters at $2 < z < 3.1$ with spectroscopic confirmation, as well as a further three candidates at higher redshifts. Meanwhile, there is an increasing number of candidate protoclusters with estimated redshifts around 2 to 3 emerging from work on the *Herschel* and *Planck* surveys, including at least 27 candidates emerging from investigating *Planck* sources lying within the large area *Herschel* surveys [7], [**?**], and 228 resulting from colour selection from the *Planck* [12] all sky survey. The nature of these sources is currently unclear since nearly all the sources lack the spectroscopic followup necessary to confirm, or otherwise, their protocluster nature. One of the *Planck* candidates has been found to be a superposition of two galaxy overdensities at different redshifts (1.7 and 2.0, [6]) while photometric redshifts suggest that several others are genuine protoclusters ([**?**], [4]). Over the next ten years the spectroscopic study of these candidates should allow considerable progress in confirming their nature and studying the detailed physics of the processes driving the star formation in their member galaxies.

Theoretically, protoclusters at z ~2 are expected to be very large structures. Theoretical models show that the eventual members of a Coma-sized cluster at zero redshift will be spread over scales of 10s of Mpc [10]. Observations of several confirmed protoclusters ([1]; [14]; [5]) seem to confirm this result, with structures seen on scales of 3 to 15 Mpc. However, there is a mismatch between the detailed predictions of SFRs and other properties for protocluster galaxies from theoretical models and what we appear to be seeing in the population revealed by *Herschel* and *Planck* (see eg. [7]). At higher redshifts, theoretical predictions suggest a different picture, with the cores of eventual protoclusters showing high rates of star formation on scales of a few 100kpc at $z \sim 6$ [**?**]. The observational situation at higher redshift is somewhat confused, however. Starbursting cluster cores may have been seen at $z \sim 4$, rather lower than the predicted redshift, in followup observations of very red sources from *Herschel* [**?**] and the South Pole Telescope [9], but protocluster candidates at $z \sim 6$ selection through Lyα emission by HyperSuprime Cam (Harikane et al., 2019) show structures, including far-IR luminous sources, extended on scales of 10 Mpc instead. It is thus clear that much remains to be learnt about the early stages of galaxy cluster formation.

In summary, the submm/mm bands are unique in tracing obscured star formation and galaxy evolution over the cosmic time. The great success of the existing JCMT/SCUBA and SCUBA-2 survey proved that the 850μm band at Mouna Kea is the most efficient window for deep imaging to detect the submm population at high redshift. However, the current submm surveys by JCMT and other ground-based telescopes are limited by the small area of sky coverage. e.g., The deep SCUBA-2 surveys (S2CLS, S2COSMOS) cover only ≤ 5 deg^2 of sky area. For comparison, much large sky area are aleardy covered with deep optical, near-infrared, and radio observations (e.g., Stripe 82 of 300 deg^2). The lack of deep submm data in these region prevent a systematic study of large samples of the obscured galaxy population. The poor mapping capability also limit the submm observations of sample of protoclusters. The population of obscured star formation in the extended structures of protoclusters are still poorly constrained. Thus, the new JCMT 850μm camera with a 10 times faster mapping speed becomes an urgent request for developing large submm surveys.

3 The Next Decade

3.1 Selection of Dusty Starbursts at Very High Redshifts

High-z dusty starbursts are rare. Depending on the exact color criteria adopted, the surface density of 500 μm risers in the HerMES and the H-ATLAS areas is ~ 10 deg^{-2} or less. While there is not yet sufficient statistics of 850/870 μm risers, there is evidence that they are even rarer (e.g. Duivenvoorden et al. 2018). By providing an increase of $10 \sim 20\times$ in the mapping speed than SCUBA2, the planned JCMT new wide-field camera will be the most powerful tool in our search for dusty starbursts at $z > 7$ and beyond.

3.2 Cosmic star formation history based on the large, deep surveys

Large samples of SMGs have been detected with the JCMT/SCUBA2 (e.g., Geach et al. 2017), and follow-up observations with ALMA have mapped some SCUBA2 sources. Machine-learning algorithm can efficiently identify the likely counterparts at optical/NIR for the SCUBA2 sources by using ALMA observations as a training sample (An et al. 2018). A new bolometer camera at JCMT with a mapping speed of 10 times faster than the current SCUBA2 can be used to finish a much wider field with multiple optical/NIR archival data in an efficient way. Together with the machine-learning method, this can well constrain the cosmic SFH and significantly reduce the cosmic variance for the measurements.

However, it is difficult to efficiently search for high redshift sources even with ALMA. Currently, lacking of identified high redshift sources will largely underestimate their corresponding SFRs at z >5. ALMA observations show some SCUBA2 sources without any optical/NIR counterparts. The latter could be good high-redshift candidates. The deep continuum observations with single dishes can reveal a large sample of SMGs and the follow-up high resolution observations with the interferometers like ALMA can locate their accurate positions. Together with archival multiwavelength data and possible follow-up deep observations at optical/NIR with large optical/NIR telescopes or on-going facility like TMT, one can constrain the cosmic SFH at high redshift. The machine-learning method is also helpful to identify the likely high-redshift candidates without any optical/NIR counterparts. It may provide informative clues or constraints on the cosmic SFHs at high redshift when ultra-deep optical/NIR observations are currently not available yet.

To compare with the cosmology simulation, we always require a large survey area to reduce the cosmic variance and to find some extreme sources or extreme environments, which are important astrophysical laboratories. The number density of massive galaxies at high redshifts can be use to test different galaxy evolution models, which predict massive galaxies decline very rapidly at z>4.

Other under-going large area surveys with IRAM30m/NIKA2 and LMT/TolTEC will provide deep observations at the mm wavelength and reach a superior sensitivity. Together with the data from the next-generation of SCUBA2 at JCMT, one can efficiently select high redshift candidates based on the color criterion. Ultra-deep radio surveys at LOFAR and SKA precursors can be important for getting cross identifications and accurate positions due to their superior sensitivities and large field of views in comparison to the submm surveys.

3.3 Protoclusters and the galaxy cluster formation

The far-IR/submm based protocluster surveys discussed above were not designed for this work. They have found protocluster candidates with total SFRs $> 10000 M_{\odot}$/yr, with individual member galaxies forming stars at rates of 100s to 1000s of $M_{\odot}$/yr, but it is likely that they are seeing only the peak of the luminosity function both of protoclusters and of galaxies within protoclusters because of the relatively limited sensitivity of these surveys to sources at such high redshifts. Meanwhile, dependence on selection at short submm wavelengths, typically 350, 500 or 550 μm for the *Herschel* and *Planck* surveys, hampers studies of the highest redshift protoclusters at $z \geq 6$. At the same time, the existing samples have been selected using a range of ratehr heterogenous methods, making statistical assessments of luminosity functions and evolution rather difficult.

The next decade will see a range of developments that will move these studies forward. Firstly, spectroscopic followup of the existing samples will significantly increase the number of confirmed protoclusters known at $z \geq 2$. This will be achieved using both mm/submm spectroscopy using ALMA and NOEMA, and optical/near-IR observations with instruments like KMOS and MUSE. Secondly, theoretical models for these objects, which require detailed n-body-hydro codes with high spatial resolution, will improve our insight into this population. Thirdly, large area surveys at mm wavelengths using instruments such as NIKA2 and TOLTEC will provide new candidate protoclusters for detailed examination. It is here where JCMT will be able to contribute, since the addition of large area surveys at higher frequency submm wavelengths will greatly enhance our ability to select candidate protoclusters from $z \sim 2$ to the highest redshifts. The protocluster candidates we currently know have an area density of about 1 per 40 sq. degrees, so the necessary surveys will have to be large area and ideally reaching a sensitivity of $\sim$ 1mJy. Such surveys will be sensitive to not only the population we already know but also fainter protoclusters and protocluster galaxies, allowing us to examine the luminosity function of these objects. The proposed 10x enhanced mapping speed over SCUBA2 will make a few hundred sq. deg. 850μm survey to these sensitivities possible as part of a large area Legacy Survey, which will also be useful for many other studies. At the same time a larger field submm instrument will be needed to survey the $\sim$15 Mpc region around known protoclusters to search for starbursting galaxies in their infall region that, if the predictions of Muldrew et al. [10] are current, will subsequently fall into the clusters. Other instrumentation developments, such as KIDS-based submm imaging spectrometers, able to measure redshifts for all submm sources in a field simultaneously, would be ideal to followup the protocluster candidates detected in these surveys, and to characterise the molecular and atomic gas properties of their member galaxies, allowing this population to be confirmed and analysed much more rapidly than is possible with current instruments.

The JCMT thus has a huge potential for studying rare submm emitters, such as protoclusters, using the proposed new instrumentation.

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