Chapter 1

Introduction

In the past years, the star formation history (SFH) of our Universe is a challenging issue in cosmology (Blain et al., 1999d) due to difficulties in observing galaxies at high redshift. Many observations have been carried out to determine the star formation rate (SFR) at different epochs. In the local Universe, the ultraluminous infrared galaxies (ULIRGs) are thought to be dusty galaxies and powered by star formation. Blain et al. (1999b) showed that the dusty galaxies could be the dominate population of submillimeter galaxies, which are discovered by SCUBA surveys since 1993. In the local Universe ,the peak of ULIRGs' spectral energy distribution (SED) is at the IR band (Genzel et al., 1998), one can expect to observe them at $z = 2\sim 3$ at submillimeter wavelength. By modeling the SFR and luminosity function, one can predict the submillimeter source counts (Blain and Longair, 1993, 1996; Blain et al., 1999a; Busswell & Shank, 2001; Rowan-Robinson, 2001) and compare them with observed source counts.

SCUBA on JCMT has been the major instruments in searching for submillimeter galaxies. Up to 2002, the surveys carried out by SCUBA have discovered about 150 extragalactic submillimeter sources (Smail et al., 1997; Hughes et al., 1998; Blain et al., 1999c; Barger et al., 1999; Eales et al., 2002; Scott et al., 2002; Smail et al., 2002). However, the disadvantage of SCUBA is its confusion problem, so that it can not observe sources fainter than confusion limit (Blain et al., 1998), this issue will be discussed in Section 1.5.

Nowadays, researchers are able to study extragalactic submillimeter sources using interferometers. The first submillimeter array, SMA, cooperated by Smithsonian Astrophysical Observatory and Academia Sinica in Mauna Kea, Hawaii will be fully operated in late 2003. It will provide high angular resolution up to 0.1 arcsecond, the benefits of high resolution observation study will be discussed in Chapter 4. Another submillimeter array is the Atacama Large Millimeter Array (ALMA), which will contain 64 antennas, 12 meters in diameter for each antenna, and is located at Llano de Chajnantor, Chile. These instruments will help us understand which population(s) dominates submillimeter galaxies. One of the main goals of this thesis is to carry out a series of SMA/ALMA mock observations and estimate the detection ratio for these two interferometers using different settings.

The structure of this thesis is described as follows. In the rest of this chapter, methods of determining star formation history of the Universe are briefly reviewed, followed by the background of the source count observations, including the observations done by SCUBA and some theoretical models. In Chapter 2, we describe the procedures we used to carry out mock observations. The methods for data analysis are also mentioned in Chapter 3. The mock observation results are shown in Chapter 3. We also provide the definition and estimate of detection ratio in that chapter. Discussions of techniques for mock observations and the impact of new submillimeter to the current theories are shown in Chapter 4. The possible contributions from interferometer observations via different strategies to study extragalactic submillimeter sources, including the constraints on source counts and SFR, are presented in Discussions. Our conclusion and summary is presented in Chapter 5.

1.1 Cosmic star formation history

Though many observations have been carried out to determine the star formation rate (SFR) at different epochs, an unresolved issue of star formation history of our Universe is the underestimate of the star formation rate at $z > 2.8$ (Dunlop, 1998). Fig. 1.1 shows the star formation density as a function of redshift $\tau_{SFR}(z)$. The curve of SFRs at different redshifts are estimated from radio luminosities of 6C/B2 and LBDS sources (the thick curve in Fig. 1.1). The masses are converted from the central massive black hole mass consumption rate per Mpc^3 by assuming an efficiency of 0.1 %. Compare optical and radio galaxies, the radio sources are well studied up to $z \simeq 4$ and the radio waveband is immune from the effect of dusts. Therefore, if the evolution of radio source is a good tracer of the star formation rate and indeed true at all epochs, the peak of SFR shall be located at z $\simeq 2 \sim 2.5$. Their result is consistent with the cosmic SFR based on luminosity density of AGN Boyle & Terlevich (1998) (the thin dotted curve in Fig 1.1).

The determinations of the SFR in local universe are given in different works. The Universidad Complutense de Marid (UCM) survey (Gallego et al., 1996) and KPNO International Spectroscopic Survey (KISS) (Gronwall , 1998) give the similar SFR density as 0.013 $M_\odot$ yr^{-1} Mpc^{-3} at z ≤ 0.045 using H_α emission in emission-line galaxies. In other wavebands, the SFR $\sim$ 0.0103 $M_\odot$ yr^{-1} is provided using 0.2 μm observation of the rest frame ultraviolet emissions of galaxies. Treyer et al. (1998) used H$\alpha + [NII]$ to drive Hα luminosity function at z < 0.3. For the SFR at higher redshift, there are spectroscopic redshift surveys carried out by Lilly et al. (1996). Their samples are out z $\sim$ 1. Observations made in the near infrared wavelength by Connolly et al. (1997) have provided further support for the suggestion of the SFR peaks at z $\sim$ 1 - 2. The discovery of Lyman break galaxies (LBGs) using Lyman-dropout selection techniques gives the SFR up to z $\sim$ 3 (Steidel et al. , 1996a). Apply this technique on a photometric redshift survey, such as Hubble Deep field (Steidel et al., 1996b), the following studying gives the SFR beyond z = 3 (Madau et al., 1996). Those observations in optical, UV and IR give a different SFH from radio point of view (Dunlop, 1998). By applying the correction for dust extinction on Lyman breaking galaxies, the revised SFR is presented by (Pettini et al., 1998). One can expect that the extinction due to the interstellar dust in optical wavelength reduce the estimate of the SFR at high redshift, by a factor $\sim$ 10 (Blain et al., 1999b). To understand the SFH of our Universe in dusty galaxies, direct observations of those star forming galaxies are needed.

To study the SFH in the dusty galaxies, the SED of dusty galaxies gives us the information about their SFR. We can determine its SFR when the redshifts and luminosities of dust galaxies are known. If we do think the dusty galaxies represent the star-forming galaxies, we may use them to track the star-formation history of the Universe. In the next section, we review the history of the discovery and study of those star-forming galaxies.

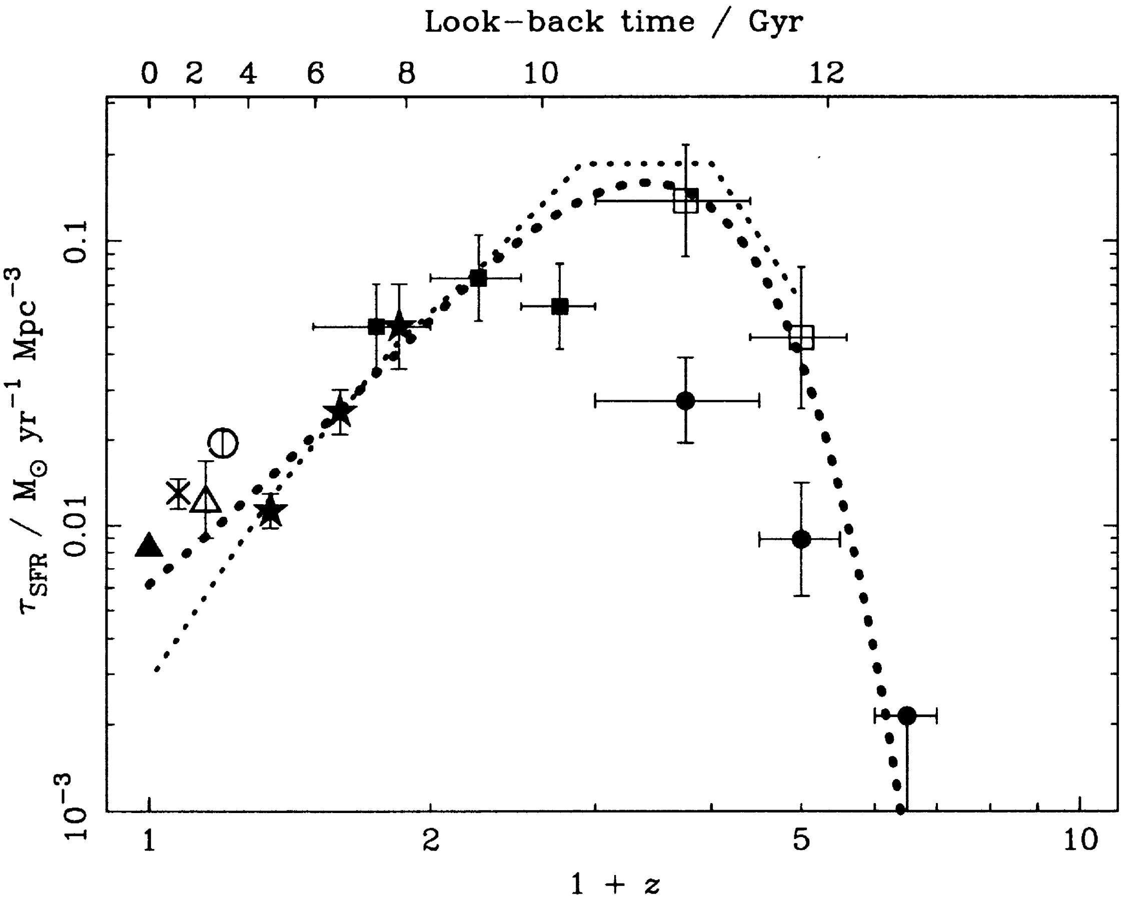

Fig. 1.1 : Star formation density as a function of redshift. (Blain et al., 1999b). The thick dotted curve is the SFR inferred from the radio data , eg. 6C/B2 catalog and Leiden-Berkeley Deep survey (LBDS) (Dunlop, 1998). Filled triangle, diagonal cross, open triangle, empty circle, stars, filled squares, filled circles and empty squares represents data from Gallego et al. (1996), Gronwall (1998) ,Treyer et al. (1998), Tresse & Maddox (1998), Lilly et al. (1996), Connolly et al. (1997), Madau et al. (1996) and Pettini et al. (1998), respectively. (See text in Section 1.1 for detail.)

1.2 ULIRGs as the local counterparts of submillimeter sources

The Infrared Astronomical Satellite (IRAS) is an Anglo-American-Dutch space program. The satellite was launched in 1983, and its major science goal is to survey more than 95% of the sky at wavelengths from 10 to 100 μm with sensitivity as close as the thermal zodiacal background. The IRAS detector of 10σ sensitivities are 0.7, 0.65, 0.85, 3.0 mJy at 12, 25, 60, 100 μm with different fields of view, 0.75×4.5, 0.75×4.6, 1.5×4.7 and 3.0×3.0 square arcmin (Neugebauer et al., 1984). The importance of IRAS survey in extragalactic astronomy is that it provides the first homogeneous all-sky galaxy catalogs. In its 10 months lifetime, it produced a catalog containing over 25000 galaxies. That is more than 100 times the number known previously.

The highly successful far-infrared all-sky survey carried out by IRAS discovered a new population of galaxies. The early IRAS mini-survey (Rowan-Robinson et al, 1984) provides first 900 deg^2 area and 8709 sources. 86 galaxies in mini-survey are found and their IR (8-1000 μm) luminosities are greater than 10^{11} solar luminosity (Soifer et al. , 1984). Follow up observations in optical wavelength show that the counterparts of those luminous IR galaxies are not optically luminous. Those galaxies were called luminous IR galaxies (LIRGs) because they emit large amount of energy at IR instead of optical wavelength (Sanders & Mirabel , 1996). Among them, the most luminous objects are ultraluminous infrared galaxies (ULIRGs), which emit energies larger than 10^{12} solar luminosity. In IRAS 1 Jy survey, there are 118 ULIRGs found in IRAS faint source catalog (Kim & Sanders, 1998).

To understand the energy sources of those LIRGs and ULIRGs, the spectroscopic survey has been carried out by Infrared Space Satellite (ISO) (Genzel et al., 1998). The energy sources of LIRGs and ULIRGs are coming from star formation process and central AGN. In their IRAS galaxies sample, 70% $\sim$ 80% are predominately powered by the recent formed massive stars, and 20% $\sim$ 30% are powered by central AGN. Their result confirms that the ULIRGs represent the star forming galaxies in the local Universe.

Research shows that the total energy emitted from dusty galaxies at high redshift is four times greater than that inferred from rest frame ultraviolet observations because a large population of luminous strongly-obscured galaxies at $z \leq 5$ is missing from optical surveys (Blain et al., 1999b). Therefore, one can expect to observe more star forming galaxies at high redshifts. This fact encourages us to search for the distant star forming galaxies at other wavebands.

1.3 Predicted submillimeter source counts

A feasible way to study the star forming galaxies at high redshifts is to observe their source counts. Generally, the source counts, total number of sources brighter than given S_ν, can be expressed as the following equation,

$$N(>S_\nu) = \int_0^{z_0} \int_{L(S_\nu)}^{\infty} \Phi(L,z) dL D^2(z) \frac{dr}{dz} dz, \tag{1.1}$$

where $\Phi(L,z)$ is the comoving luminosity function describing the evolution of source at different redshifts and luminosities. The variable $D^2(z)dr$ gives the comoving volume of a spherical shell, whose thickness is dr, of our Universe. The luminosity of a source can be expressed by

$$L(S_\nu, z) = 4\pi(1+z)D^2(z)S_\nu \tag{1.2}$$

Therefore, in order to construct a source count model, we need to know (1) the comoving luminosity function, (2) the world model for calculating comoving distance, (3) the spectrum energy distribution f_ν and (4) source evolutions. Nowadays, the different source count models are mainly based on the different assumption of evolution functions.

The first source count model of submillimeter sources is provided by Blain and Longair (1993). In their work, the 60 μm IRAS galaxies luminosity function is used (Saunders et al., 1990) to carry out calculations of their model. The luminosity function can be expressed as the follows,

$$\varphi(L) = C\left(\frac{L}{L_*}\right)^{1-\alpha} \exp\left[-\frac{1}{2\sigma^2}\log_{10}^2\left(1+\frac{L}{L_*}\right)\right], \tag{1.3}$$

where $C = (2.6 \pm 0.8) \times 10^{-2} h^3$ Mpc^{-3}, $\alpha = 1.09 \pm 0.120$, $\sigma = 0.724 \pm 0.031$ and $L_* = 10^{8.47\pm0.23} h^{-2} L_\odot$. In Eq. 1.3, no source evolution is assumed. The density evolution function should be $\varphi(L,z) = (1+z)^{6.7}\varphi(L,0)$, according to Saunders et al. (1990).

Additionally, from the study of the populations of radio sources and quasars, the density is evolved with the redshift.

$$\varphi(L,z) = (1+z)^3\varphi(L,0) \tag{1.4}$$

In this work, the luminosity evolution is assumed increasing as $(1+z)^3$ out to $z = 2$, beyond $z = 2$ the luminosity evolution remains constant, $(1+z_{max})^3$, where $z_{max} = 2$ (Blain and Longair, 1993). So,

$$L(z) = L(0)(1+z)^3. \tag{1.5}$$

For the galaxies spectrum, the modified black body emission is a good approximation of a dust spectrum and can be expressed as Eq. 1.6.

$$L = \int f_\nu(\nu)\epsilon_\nu(\nu)d_\nu, \tag{1.6}$$

where $f_\nu(\nu)$ is black body radiation function, and $\epsilon_\nu(\nu)$ is emissivity function. The emissivity of dust grains can be expressed as the function of frequency ν, $\epsilon_\nu \propto \nu^x$, where x is equal to 2 at frequency $\nu < 3 \times 10^2$ GHz and equal to 1 at $\nu < 3 \times 10^3$ GHz.

Combining all information described earlier in this section, Blain and Longair presented the first source count models both in 450 and 1100 μm . In their work, the redshift distributions of submillimeter galaxies under different assumptions are also showed in Fig. 1.2. In the figure, panel (a) shows source count models, that are assumed the luminosity evolution of sources remain constant for all epoches. panel (b) shows source count models involving the luminosity evolution. The luminosity of all galaxies change as $(1+z)^3$ in the redshift interval $0 < z < 2$ and remain constant as 27 times local luminosity at all redshift greater than $z = 2$ (Blain and Longair, 1993).

The modifications, including luminosity evolution and density evolution, are suggested by the same group (Blain and Longair, 1996). The modified models predicted the submillimeter source counts at all SCUBA wavelength, 350, 450, 750 and 850 μm. In the paper, the observational strategies are also discussed, including choice of frequency, survey duration and survey area. For the SCUBA, the best strategy would be observing an area of 0.1 deg^2 for an observing time of 3×10^4 seconds ($\sim$ 10 hours). The 750/850-μm array are the best instruments due to their higher sensitivities. In summary,

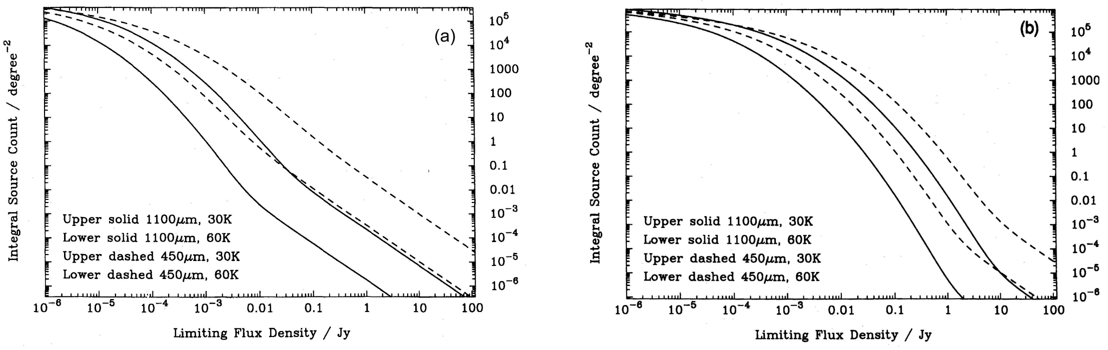

Fig. 1.2 : Cumulative source count models in 450 and 1100 μm (Blain and Longair, 1993).

the works done in 1993 gives the models of submillimeter source counts and the observational strategies is given in their paper in 1996. Fig. 1.3 shows source count models at different wavelength. The upper panel shows source counts at 350 and 450 μm, and source counts at 750 and 850 μm are shown in the lower panel.

1.4 Submillimeter source counts based on observations

The original idea of searching for the distant star-forming galaxies is provided by Blain and Longair (1993, 1996). They suggested a source count model based on the IRAS galaxy luminosity function(Saunders et al., 1990). The first observation of the submillimeter source counts is started in 1997 by Smail et al. (1997) using SCUBA. They use lensing clusters to search for the distant submillimeter sources. The observation is toward two cluster region, A370 and Cl 2244-02, at 450 and 850 μm . Their result gives source counts of $2.4 \pm 1.0 \times 10^3$ deg^{-2} down to 4 mJy at 850 μm . The following observation carried by SCUBA is the submillimeter survey of the Hubble Deep Field (HDF) (Hughes et al., 1998). It is the first submillimeter wavelength observation toward HDF. In the 50 hours integration time, there are 5 submillimeter sources found in a HDF at 850 μm . Re-analysis of the completed SCUBA submillimeter survey seen through cluster by Blain et al. (1999c) provides deeper counts down to 0.5 mJy. Their result is based on the mass

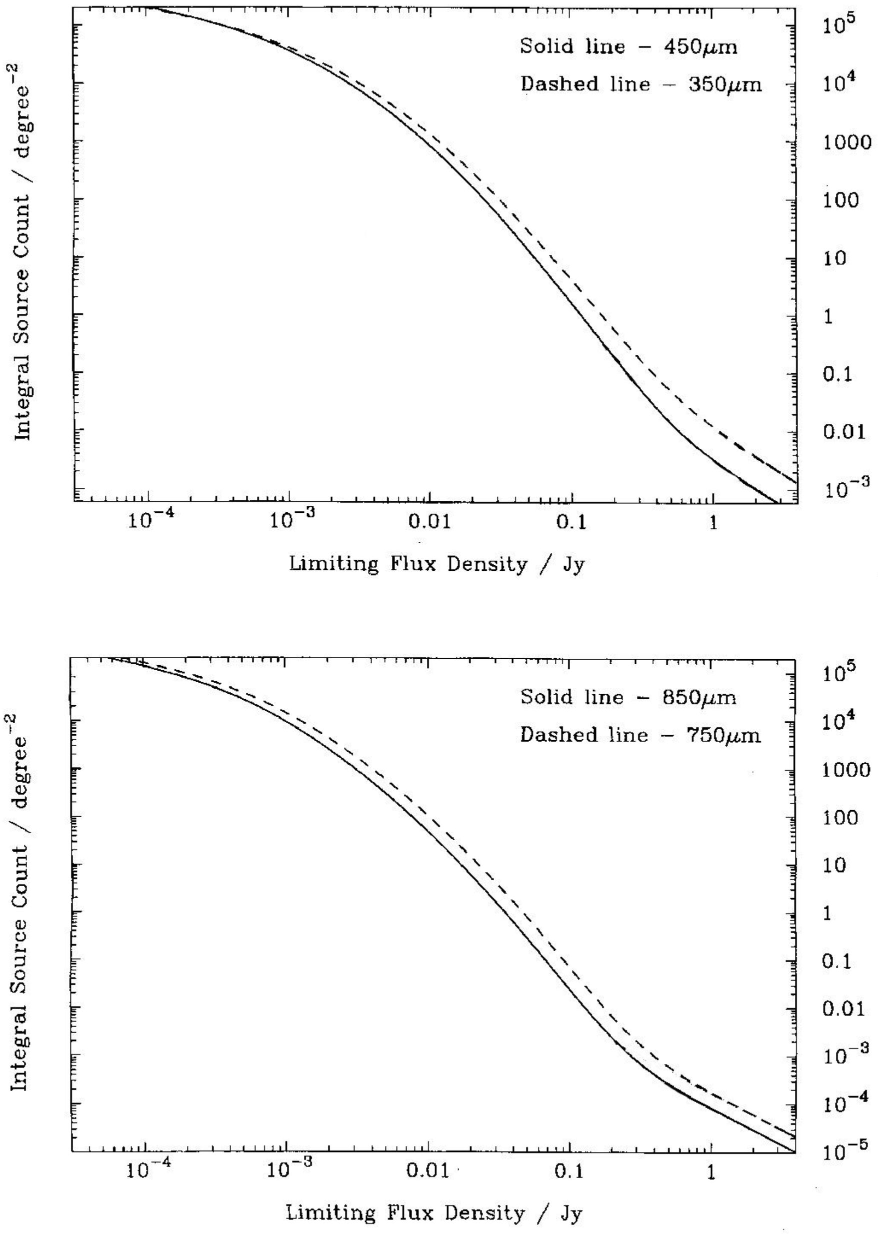

Fig. 1.3 : Cumulative source count models at 350, 450, 750 and 850 μm (Blain and Longair, 1996).

model of the cluster to enhance the sensitivity. The source counts at 850 μm in 0.5 , 1.0, 2.0, 4.0 and 8.0 mJy are 22±9× 10^3 deg^{-2} , 7.9±3.0×10^3 deg^{-2}, 2.6±1.0×10^3 deg^{-2}, 1.5±0.7×10^3 deg^{-2} and 0.8±0.6×10^3 deg^{-2} respectively. In the same year, Barger et al. (1999a) presented the 850 μm source counts with a model using SCUBA on JCMT. The observation fields are the Lockman Hole and 3 Hawaii Survey Fields, SSA13, SSA17 and SSA22. Their result provides a phenomenological source counts model, $n(S) = 3.0 \times 10^3 deg^{-2}/(a + S^{3.2})$, where a varies from 0.4 to 1.0 depending on the 850 μm extragalactic background light. The Canada-UK deep submillimeter survey (Eales et al., 2002) also provides the source counts. The survey area is about 50 arcmin^2 with 14 hours integration, detecting 19 sources down to a 3 σ sensitivity limit between 3 and 4 mJy. SCUBA observation of HDF was carried out to measure the bright end of the submillimeter source counts (Borys et al., 2002). They use the technique called scan-mapping. This new HDF observation using SCUBA provides source counts ,164^{+77}_{-58} deg^{-2},for flux brighter than 12 mJy. In this year (2002), the catalog of SCUBA Lens Survey is released(Smail et al., 2002). In the observations of 7 cluster regions, there are 17 submillimeter galaxies found in these regions. Their result provides the source counts at 850 μm in 0.25, 0,5, 1.0, 2.0, 4.0, 8.0 mJy and 16.0 are 51±21, 27±10, 9.5±3.4, 1.9±1.1, 1.7±0.8, 0.9±0.58 and <0.42, respectively. The most recent SCUBA observation for distant submillimeter sources is SCUBA 8-mJy survey (Scott et al., 2002). This is the largest, covering 260 arcmin^2, survey so far undertaken with SCUBA. The observation area are Lockman-Hole E and ELAIS N2. The 850 μm source counts with flux greater than 8 mJy is 320^{+80}_{-100} per square degree.

Fig. 1.4 shows all previous observation results for searching distant submillimeter sources (Scott et al., 2002) excluding results from SCUBA lensing survey.

1.5 Submillimeter interferometry

Most of extragalactic submillimeter sources are found by SCUBA, yet there are limits on deep SCUBA surveys. The first is its confusion limit. When the sources, fainter than a given flux limit, crowd into a area, which is smaller than the beam size, and their total flux is above the given flux limit, we call this flux limit as confusion limit. The effect of crowded faint sources must be considered in doing deep surveys. This effect is

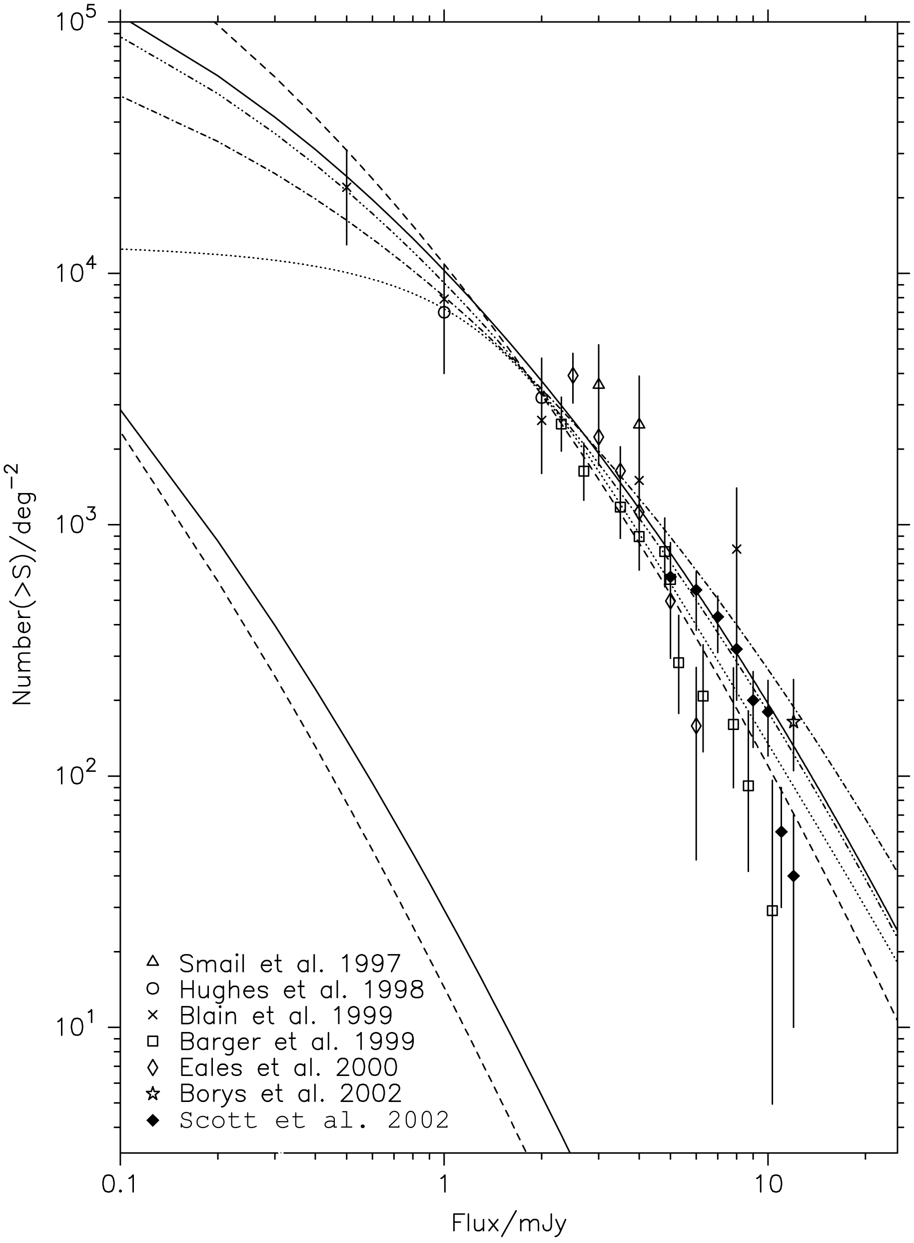

Fig. 1.4 : The cumulative 850 μm source counts (Scott et al., 2002). The upper solid and dashed curves are predicted source counts, based on the IRAS 60 μm luminosity function (Saunders et al., 1990), dust temperature $T_{dust} = 40$K and dust emissivity $x = 1.2$ with the pure luminosity evolution ($L(z) = L(0)(1+z)^3$) and different world models (solid curve: $\Omega_m = 1.0, \Omega_\Lambda = 0.0$; dashed curve: $\Omega_M = 0.3, \Omega_\Lambda = 0.7$). The lower solid and dashed curve are predicted source count with no evolution involved . The dot-dashed curve shows the count model based on different luminosity evolution ($L(z) = L(0)(1+z)^{1.5}\text{sech}^2[\ln(1+2)b - c]\cosh^2 c$, $b = 2.2 \pm 0.1$ and $c = 1.84 \pm 0.1$), the dust emissivity $x = 1.2$ and dust temperature $T_{dust} = 37$ K with different world models (dot-dashed: $\Omega_m = 1.0, \Omega_\Lambda = 0.0$; dot-dot dashed curve: $\Omega_M = 0.3, \Omega_\Lambda = 0.7$). The dotted curve is the best fitting.

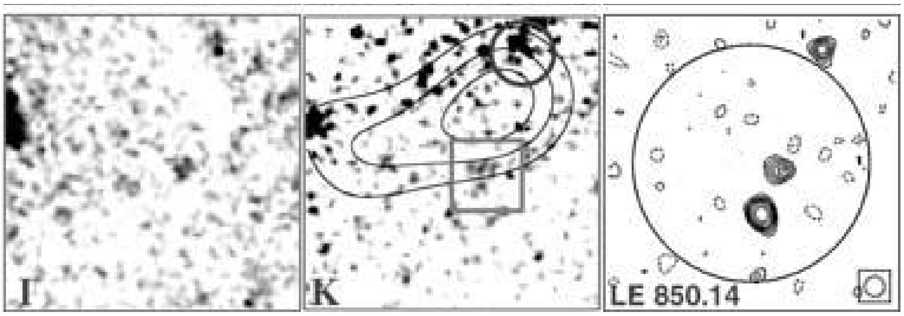

Fig. 1.5 : Multi-wavelength observations of LE 850.14. The left, middle and right panels are observations at I, K and 1.4 GHz wavebands, respectively. Contours overlaid on the middle panel comes from 850 μm SCUBA 8-mJy survey (Ivison et al., 2002).

known as confusion problem. For a specified source count model suggested by Blain and Longair (1996), the 1 σ confusion limit of SCUBA is 0.44 mJy (Blain et al., 1998). This means SCUBA can not carry out a survey to detect sources fainter than 0.44 mJy. The other disadvantage of SCUBA is its resolution. The main beam resolution of JCMT is about 15 arcsecond at 850 μm, which makes it hard to provide accurate positions for doing multi-wavelength study on optical telescopes, whose resolution can be higher the 1 arcsec, (see Fig. 1.5). In the follow up multi-wavelength observations of SCUBA 8-mJy survey, one SCUBA source may composed by several fainter sources. Fig. 1.5 shows the multi-wavelengths observations of submillimeter source LE 850.14 at different wavebands . We can use interferometers to locate the exact positions of submillimeter sources so that we can study the nature of its counterparts at different wavelengths.

SMA and ALMA will be available to study these submillimeter sources in recent years. According to the current knowledge of the submillimeter sources, there is no confusion problem for interferometers because the synthesized beam is small enough, so that there will be no source crowd in the region. Additionally, the high resolution observations provided by interferometers give us accurate positions, which enable us to observe them at other wavelengths, of submillimeter sources.

1.6 This thesis

As described above, one of the goals in this study is to understand the ability of those submillimeter interferometers for detecting extragalactic submillimeter sources. We use models to generate submillimeter skies. Reducing those mock observation data with frequently used astronomical software, *Miriad*. We also show the estimate of the detection ratio for different instruments, configurations and observation time budgets. Based on our simulation results, we also estimate the constraints for source count models and compare SMA/ALMA with competitive telescopes.