SCUBA Deep Fields and Source Confusion

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Abstract. Deep submillimetre(submm)-wave surveys made over the last three years using the SCUBA camera at the 15-m James Clerk Maxwell Telescope (JCMT) have revealed a new population of very luminous high-redshift galaxies. The properties of this population, and their contribution to the intensity of the extragalactic background radiation field are described briefly, especially in the context of the SCUBA lens survey. The potential problems caused by source confusion in the large 15-arcsec SCUBA observing beam for the identification and follow up of the results are discussed. The effects of confusion are not important for the study of 850-μm SCUBA sources brighter than about 2 mJy.

High-redshift surveys for dusty galaxies In 1997 the SCUBA camera at the JCMT [31] became available, providing deep images of 5-arcmin² fields at 450 and 850μm, and allowing the first deep blank-field searches for redshifted thermal dust emission from distant galaxies. By exploiting the positive magnification bias and rich archival data in the fields of seven massive clusters of galaxies, 15 non-cluster sources and 2 cD galaxies [24] were soon detected in the SCUBA Lens Survey [40,44] and several sources were identified [3,14], three having certain identifications and redshifts based on mm-wave CO spectroscopy [26,27,34]. Several other deep surveys in clusters [19,35] and non-cluster fields [5,32,23,21] have confirmed the existence of this population of distant galaxies. Three SCUBA-selected galaxies from all these surveys, without CO detections, have accurate positions from mm-wave continuum interferometry [20,28,29]. Targeted SCUBA observations to image or obtain submm-wave photometry in the fields of both faint radio sources with very faint K-band counterparts [4,18] and known high-redshift objects [33,17,38,1] have increased the number of submm-selected galaxies known. In the first approach, the wide fields and accurate astrometry available from deep radio surveys is exploited to reveal relatively bright submm-selected galaxies [4]. In the second, valuable redshifts are available for the detected submm sources.

A summary of the published submm-wave counts at both 850 and 450μm is presented in Fig. 1, alongside the contribution of the SCUBA Lens Survey galaxies to the integrated background radiation intensity derived from observations using COBE [25]. At 850μm, a significant fraction of the background

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The SCUBA Lens Survey has been carried out since 1997 by Ian Smail, Rob Ivison, Jean-Paul Kneib and the author: a full description of the survey and references to supporting work can be found in the recent catalogue paper [44].
Fig. 1. A compilation of published counts from SCUBA surveys at 850 and 450 µm (lower panels), and the fraction of the background radiation intensity $\nu I_\nu$ contributed by sources exceeding a certain flux density $S$ in the SCUBA Lens Survey (upper panels) [1,11], as shown by the dotted lines in the lower panels. Atmospheric noise is more dominant in the SCUBA results at 450 µm. The key to the references is: BKIS [11], BIKS [13], E00 [23], C00 [19], BCR [4], C01 [18], Borys [15], Dunlop [21], Hu98 [12], S97 [12], Ba98 [2], Ba99 [5], E99 [22].

Radiation has been associated with SCUBA sources brighter than 1 mJy after correcting for the effects of lens magnification [11].

SCUBA surveys provide information about the form of evolution of high-redshift galaxies. The results indicate that a very luminous population of dust-enshrouded high-redshift galaxies exist, and that they emit a greater luminosity than optically selected high-redshift galaxies [12,10,8]. The detected galaxies are almost certainly still observed on the Rayleigh–Jeans side of their thermal dust SEDs, and so uncertainties in the dust temperature of the sources feed through into significant uncertainties in their total luminosity. However, by combining information from radio and 15-µm ISO mid-infrared (IR) flux densities of submm-selected sources, where available, from the extragalactic background spectrum at submm wavelengths, and from multiple-band mm/submm detections of objects with known redshifts, it is likely that a dust temperature of about 40 K is typical [12,46,11,7].
This is thus a reasonable temperature to assume for the bulk of the population; if a greater value is assumed, then the luminosity density is likely to be overestimated.

There has been a suggestion [37] that a fraction of faint SCUBA sources could be very local, cold dust clouds in the Milky Way. In the light of the surface density of detectable SCUBA sources being increased in the fields of $z \approx 0.2$ galaxy clusters – presumably due to magnification bias – this seems unlikely. In addition, the 850-µm counts (Fig. 1) are known to be steep between flux densities of 2 and 10 mJy, and yet a very local population of sources would have counts with a Euclidean slope or flatter. There are also no obvious signs of the brighter cousins of such objects in a 1800-deg$^2$ 400-GHz survey field [36]. Currently it seems unlikely that this suggestion is correct.

A significant difficulty in studying SCUBA-selected galaxies is the relatively coarse 15-arcsec resolution of 850-µm SCUBA images. The effect of red-shifting the thermal dust emission spectrum of distant galaxies, which peaks at restframe far-IR wavelengths of order 60 to 100 µm, into the submm waveband is to overcome the inverse square law, and leads to the standard approximately flat submm-wave flux density–redshift relation for $0.5 < z < 10$. The detection of a submm-wave source at a single wavelength thus provides almost no redshift information. The combination of these two effects – coarse resolution and potential high redshift – makes the certain association of submm sources with counterparts in other wavebands very difficult, as recently discussed elsewhere [43]. So far, extremely deep radio images have provided the best route for reliable follow-up of submm-selected galaxies [42], because of the apparently fairly universal radio-to-far-IR template SED for both nearby and distant galaxies combined with the large field and excellent sensitivity of the VLA [16].

**Source Confusion Noise** There is a further difficulty for interpreting the results of these surveys – the surface density of sources in the faintest images is as great as 0.06 beam$^{-1}$ [32], at which source confusion provides a significant contribution to the noise in the images. Confusion arises because of the uncertain and varying contribution of flux density from the numerous unresolved, undetected faint sources that fall within each observing beam. First recognized as a problem by early radio astronomers, confusion leads to a non-Gaussian distribution of random intensity fluctuations on the sky, whose properties depend on the details of both the shape of the counts and the clustering strength of the galaxies in the survey. Confusion becomes the dominant source of noise for any observations deeper than a certain limit, which generally corresponds to a density of sources on the sky that is greater than about 0.03 beam$^{-1}$. A recent summary of references to confusion and a series of simulations of its effects have been presented by Hogg [30]. Although a variety of analytic schemes have been suggested to study the effects of source confusion [15], numerical simulations are essential in order to make
Fig. 2. The results of confusion simulations for the 15-arcsec SCUBA beam at 850 µm, based on a source population represented by the revised luminosity evolution model [8,12]. The histogram in the left panel represents the results of 3000 simulated observations of the direct distribution of sources on the sky. The underlying source count model is represented by the superimposed solid line. A log-normal distribution – \( \exp\left\{-\frac{\ln(S - \bar{S} + 1)^2}{2\ln(1 + \sigma)^2}\right\} \) with \( \bar{S} = 0.6 \text{ mJy} \) and \( \sigma = 0.47 \text{ mJy} \) – which represents the results accurately is shown by the dashed line. The histogram in the right panel represents the results of 1000 simulations of the sky observed using the SCUBA 3-beam chopping pattern. Three solid Gaussians are superimposed to represent sky and instrument noise levels of 0.25, 0.44 and 1.5 mJy beam\(^{-1}\), which correspond to the simple 1 beam\(^{-1}\) confusion noise estimate, to the noise level in the HDF SCUBA image [32] and to the typical noise level in the SCUBA lens survey fields [40,44] respectively. The dashed line represents a log-normal distribution with \( \bar{S} = -0.1 \text{ mJy} \) and \( \sigma = 0.52 \text{ mJy} \), which provides a reasonable description of the distribution at interesting positive flux densities.

reliable statements, as long as they are based on accurate count models. The results of such simulations, specifically for the SCUBA observing parameters are shown in Fig. 2. The flux density at which the surface density of sources exceeds 1 beam\(^{-1}\) generally provides a reasonable estimate of the width of the distribution of confusion fluctuations; in Fig. 2 it is lower by a factor of about two. The practical survey limit is an order of magnitude greater than the 1 beam\(^{-1}\) value, which corresponds to the traditional rule-of-thumb source density of 0.03 beam\(^{-1}\). The fluctuation distribution can be approximated reasonably by a log-normal distribution.

The deepest SCUBA surveys are as close to the confusion limit as any observations that have been interpreted to derive information about cosmic evolution, and so it is important to understand the effects of confusion. Since the first determination of the submm-wave counts [16], several studies of the
effects of confusion noise in these surveys have been made \cite{Hogg91,30,23}, sometimes with different results. Hogg \cite{30} emphasizes the importance of limiting the depth of a survey to avoid exceeding 0.03 sources per beam, and that the practical confusion limit is about an order of magnitude brighter than the approximate 1-\(\sigma\) value quoted in the SCUBA paper \cite{9}. The effect is illustrated clearly in Fig. 2: the 1-\(\sigma\) estimate is only about 0.25 mJy, but it is not safe to detect sources fainter than about 2 mJy. This conclusion is supported by a study of the properties of correlated noise in the SCUBA image of the HDF \cite{39}. Hogg also shows that the positions of submm-detected sources become impossible to determine accurately at a flux density brighter than the limit for accurate photometry. In contrast, Eales et al. \cite{23} report a systematic increase in the flux density determined for a submm-selected galaxy due to the effects of confusion, which takes the form of a flux-density-independent scaling that is still significant for 10-mJy 850-\(\mu\)m sources. This disagrees with both the results of Hogg and those presented in Fig. 2 here. Only SCUBA surveys with 850-\(\mu\)m detection sensitivities less than 2 mJy are likely to suffer from the effects of confusion.

Most of the well-studied SCUBA-selected galaxies have been drawn from the fields of lensing clusters of galaxies \cite{44,35}. The magnification bias introduced by the clusters has the effect of reducing the contribution of undetected galaxies at a given flux density, and thus reducing the effect of confusion \cite{6}. However, so far no observations have been made in cluster fields to a depth less than 1 mJy, and so this effect has not been observed directly. A joint Netherlands–UK SCUBA project – lead by John Peacock and Paul van der Werf – is underway to obtain a very deep submm-wave image of the cluster A 2218, and so probe the ultimate sensitivity of an 850-\(\mu\)m camera on the 15-m JCMT.

The results of the simulations shown in Fig. 2 can readily be extended to address the importance of source confusion for other mm/submm and far-IR surveys. When we first derived estimates of confusion noise from early SCUBA surveys \cite{8}, much less information was available about how to extrapolate to other beamsizes and observing frequencies. However, the availability of both additional data and the resulting revised models \cite{8} now provides the opportunity to make accurate predictions of the effects for other far-IR and mm/submm-wave telescopes.

**Conclusion** The results of a wide range of deep survey observations carried out using the SCUBA camera at the JCMT have been reviewed. The consequences of source confusion for the results has been discussed. SCUBA surveys in which the detection limit is shallower than about 2 mJy are not likely to be affected significantly by confusion.

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