A New View of Galaxy Evolution from Submillimeter Surveys with SCUBA

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Abstract. Our view of galaxy evolution has been dramatically enhanced by the recent deep field submm surveys carried out with the SCUBA camera on the JCMT. SCUBA has discovered a population of luminous infrared galaxies at redshifts $\sim 1$–4 that emit most of their energy at far-IR/submm wavelengths. The cumulative surface density of submm sources ($\sim 10^4$ deg$^{-2}$ with $S_{850} > 1$ mJy) appears to be sufficient to account for nearly all of the 850 $\mu$m extragalactic background. The SCUBA sources are plausibly the high-$z$ counterparts of more local ($z \lesssim 1$) luminous infrared galaxies that have been identified in IRAS and ISO deep field surveys, the majority of which appear to be major mergers of gas-rich disks accompanied by dust-shrouded nuclear starbursts and powerful AGN. The SCUBA sources are plausibly the progenitors of the present-day spheroidal population. This major event in galaxy evolution, equal in bolometric luminosity to that observed at optical wavelengths, is largely missed by current UV/optical surveys.

Keywords: submillimeter sources, luminous infrared galaxies

1. Introduction

The Submillimeter Common User Bolometer Array (SCUBA) camera on the James Clerk Maxwell Telescope (JCMT) (Holland et al. 1999) has provided a new window for ground-based studies of the high-$z$ Universe. This brief review summarizes results from a large campaign of deep surveys carried out during SCUBA’s first two years of operation on Mauna Kea. Evidence is presented that the submm sources detected in the SCUBA deep fields must be predominantly luminous infrared galaxies (LIGs: $L_{\text{ir}} > 10^{11} L_\odot$) at high redshift ($z \sim 1$–5), and by analogy with local LIGs, that they plausibly represent the building of spheroids through major mergers of gas-rich disks.

2. SCUBA Deep Surveys

Smail et al. (1997) were the first to infer a substantial population of luminous submm galaxies from their SCUBA detections at 850 $\mu$m/450 $\mu$m of background sources amplified by weak lensing from foreground clusters. Subsequent blank-field surveys at 850$\mu$m/450$\mu$m (Hughes et al.

\[^1\] L_{\text{ir}} \equiv L(8\text{–}1000\mu m)$. Unless otherwise stated, $H_o = 50$ km s$^{-1}$ Mpc$^{-1}$, $q_o = 0$.\n
1998; Barger et al. 1998; Eales et al. 1999), confirmed the surprisingly large space density of faint submm sources, and in addition, showed that their optical and near-infrared counterparts were often quite faint, as illustrated below in our own data for the Lockman Hole.

2.1. THE LOCKMAN HOLE

The 850 $\mu$m data for the Lockman Hole deep field are shown in Figure 1. The two SCUBA sources, LH NW1 and LH NW2, detected at 850 $\mu$m ($> 3 \sigma$), have 850 $\mu$m fluxes of 5.1 mJy, and 2.7 mJy, respectively, with upper limits at 450 $\mu$m of $\lesssim 50$ mJy ($5 \sigma$). Neither SCUBA source has an ISOCAM 7 $\mu$m counterpart ($< 35$ $\mu$Jy; $5 \sigma$). LH NW1 appears to be centered on a faint K$'$ source ($K'_{AB} = 21.8$) with disturbed morphology, which is barely detected in the current B-band image ($B_{AB} = 23.5$). LH NW2 is “blank” implying that any counterpart has $K'_{AB} > 22.5$ and $B_{AB} > 24.5$.

![Figure 1. SCUBA 850 $\mu$m detections (2 small thick circles: Barger et al. 1998; Barger, Cowie & Sanders 1999), and ISOCAM 7$\mu$m detections (22 small thin circles: Taniguchi et al. 1997) in the Lockman Hole northwest (LH NW) Deep Field (J2000: RA = $10^h33^m55.5^s$, Dec = $+57^\circ46'18''$) superimposed on a K$'$ image obtained with the QUick InfraRed Camera (QUIRC) on the University of Hawaii 2.2-m telescope. The field-of-view of the ISOCAM detector array and the SCUBA array are indicated by a long dashed line and large solid circle respectively. On the right are two zoomed images of the region outlined by the 45$''$ x 45$''$ box which is centered on the strongest SCUBA source. The zoomed K$'$ image was obtained with the Near InfraRed Camera (NIRC) on the Keck 10-m telescope, and the zoomed B-band image was obtained with the University of Hawaii 2.2-m telescope.](image-url)
3. ULIGs at High Redshift

Figure 2. Observed radio-to-UV spectral energy distribution of the nearest ULIG, Arp 220 (z = 0.018). Labeled tickmarks represent object rest-frame emission that will be shifted into the 850 µm and 2.2 µm observed frame for redshifts, z = 0–5. The insert shows the corresponding observed-frame 850 µm flux and νSν(850)/νSν(2.2) ratio for Arp 220 at redshifts, z = 0–5.

From the strength of the 850 µm detections and the faintness of the K′ counterparts alone, it is relatively straightforward to show that the SCUBA sources detected in the LHNW deep field are most likely to be ultraluminous infrared galaxies (ULIGs: $L_{\text{IR}} > 10^{12} L_\odot$) at high redshift (i.e. $z > 1$). The “submm excess”, ($\equiv \nu S_{\nu}(850\mu m)/\nu S_{\nu}(2.2\mu m)$), for both LHNW1 and LHnw2 is larger than 1 (2.4 and > 3 respectively), which is impossible to produce with normal optically selected galaxies at any redshift, or even by the most extreme infrared selected galaxies at low redshift, but is almost exactly what would be expected for an ULIG at high redshift. Figure 2 shows that the expected flux for the nearest ULIG Arp 220 when placed at $z > 1$ is on the order of a few mJy at 850 µm. Also, the combination of a large negative K-correction in the submm plus a relatively flat or positive K-correction in the near-IR naturally leads to values $\nu S_{\nu}(850\mu m)/\nu S_{\nu}(2.2\mu m) > 1$ for all ULIGs at $z \gtrsim 1.5$. The observed faintness of the high-z submm sources in current B-band images and the non-detections at 7 µm in the deep ISOCAM images are consistent with the large U–B colors and the pronounced minimum at $\sim 3-6 \mu m$ respectively, in the rest-frame SEDs of ULIGs like Arp 220.
4. Source Counts, the Extragalactic Background, and Luminosity Function Evolution

Figure 3. (a) Comparison of the 850 µm source counts (solid squares: from Barger, Cowie & Sanders 1999) with semi-analytic model counts (see text). (b) Comparison of the contribution of the 850 µm sources brighter than 3 mJy (solid circle) and extrapolated contribution of sources brighter than 1 mJy (open circle) to the EBL compared with the Fixsen et al. (1998) analytic approximation (solid curve) to the EBL. The two dashed curves are for observed source temperatures of 50 K and 25 K where each is based on a λ-weighted Planck function.

Figure 3a shows that the cumulative 850 µm counts in the range 2–10 mJy can be approximated by a single power law of the form \( N(S > S_0) = 1 \times 10^4 S^{−2} \) deg\(^{-2}\). Figure 3b compares the contribution of these 850 µm sources with the recent model of the EBL determined from COBE data (Fixsen et al. 1998; Puget et al. 1996, 1999; Hauser et al. 1998). Approximately 25% of the 850 µm EBL resides in sources brighter than 2 mJy, and nearly all of the EBL at 850 µm can be accounted for by sources brighter than 1 mJy, assuming the extrapolation down to 1 mJy given by the fit to the SCUBA data in Figure 3a.

The observed cumulative SCUBA counts imply strong evolution in the co-moving space density of LIGs and ULIGs. Figure 3a compares the observed SCUBA counts with predictions from semi-analytic models using three rather extreme distributions of ULIGs. Model 1 is based on the local IRAS 60 µm luminosity function of galaxies (i.e. \( \sim 0.001 \) ULIGs deg\(^{−2}\) at \( z < 0.08 \): Kim & Sanders 1998; see also Soifer et al. 1987; Saunders et al. 1990) assuming no evolution, which underestimates the observed space density SCUBA sources by nearly 3 orders of magnitude. Model 2 includes no ULIGs, instead attempting to account for the fraction of the optical/UV emission absorbed and reradiated by dust in sources observed in optical/UV deep fields. Model 2 still underpredicts the 850 µm source counts by a factor of \( \sim 30 \). A better fit to the data is provided by Model 3 (similar to Model E of Guiderdoni
et al. 1998), which includes a strongly evolving population of ULIGs, constrained only by recent measurements of the submm extragalactic background light (EBL). and

Figure 4 graphically illustrates how the high luminosity tail of the LF for infrared galaxies must change to match the observed SCUBA counts and inferred redshift distribution (Barger et al. 1999). It is interesting to note that the strong evolution already detected in the 1-Jy sample of ULIGs over the relative small range $z \lesssim 0.3$ [i.e. $\propto (1 + z)^{6-7}$: Kim & Sanders 1998], if continued out to $z \sim 2$, would also provide a good match to the observed cumulative surface density of SCUBA sources.

![Figure 4. The local LFs for infrared selected galaxies from the IRAS Bright Galaxy Sample (Soifer & Neugebauer 1991; Sanders & Mirabel 1996) and for optically selected “normal” galaxies (Schechter 1976), compared to the LFs for slightly more distant ULIGs from the IRAS 1-Jy sample (Kim & Sanders 1998) and for the high-z submm sources detected in the SCUBA 850 $\mu$m deep fields.]

5. Identification of IR/Submm Sources

5.1. Low-z LIGs ($z \lesssim 0.3$)

Substantial progress has been made in understanding the nature of infrared selected galaxies in the local Universe. Ground-based follow-up studies of complete samples of LIGs discovered by the IRAS satellite show that nearly all objects with $L_{\text{IR}} > 10^{11.5} L_\odot$ appear to be strongly interacting/merging, gas-rich, $\sim L^*$ spirals (Figure 5). At the highest luminosities most objects appear to be advanced mergers powered by a mixture of starburst and AGN both of which are fueled by an enormous
concentration of gas that has been funneled into the merger nucleus. These LIGs appear to represent a primary stage in the formation of elliptical galaxy cores, and the ULIG phase also appears to represent an important phase in the formation of quasars and powerful radio galaxies (see SM96 for a complete review).

| ΔRA (arc sec) | ΔDec (arc sec) |
|---------------|---------------|
| 11.65         | 11.51         |
| 12.19         | 11.65         |
| 12.19         | 12.19         |

Figure 5. A representative subsample of R-band images of LIGs (Mazzarella et al. 1999) from the IRAS RBGS (Sanders et al. 1999), illustrating the strong interactions/mergers that are characteristic of nearly all objects with $L_{\text{IR}} > 10^{11.5} L_{\odot}$. The scale bar represents 10 kpc, tick marks are at 20′′ intervals, and $\log (L_{\text{IR}}/L_{\odot})$ is indicated in the lower left of each panel.

5.2. HIGH-z SCUBA SOURCES ($z \sim 1–5$)

Progress in identifying optical/near-IR counterparts of the SCUBA deep-field sources has been frustratingly slow, due in large part to the intrinsic faintness of optical/near-IR counterparts. However, this is now understood – from far-UV studies of local ULIGs (e.g. Trentham, Kormendy & Sanders 1999) – as what would be expected for ULIGs at $z > 1$. Local ULIGs, if placed at $z =1–4$, would have apparent magnitudes in the range $m_B \sim 27–32$, $m_I \sim 25–29$, and $m_K \sim 21–24$!

Currently only $\sim 25\%$ of the sources with $S_{850} > 3$ mJy appear to have “secure” identifications and redshifts (e.g. Barger et al. 1999). However, the best studied of these have properties (e.g. magnitudes, morphology, spectra, gas-content) similar both to local ULIGs as well as to the small sample of high-z ULIGs discovered in the IRAS faint source database (see Scoville, these proceedings).

6. Summary: “Star Formation History” of the Universe

What the SCUBA deep surveys now make abundantly clear is that a substantial fraction of the “activity” in galaxies at high redshifts ($z > 1$) is obscured by dust, and, therefore has been missed in deep optical/UV surveys. This is graphically illustrated in Figure 6 using the latest SCUBA redshift distribution estimates of Barger et al. (1999), assuming that all of the far-IR/submm luminosity is powered by star
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Figure 6. The “star formation rate” vs. $z$ for optical/UV and far-IR/submm selected galaxies. ($H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $q_0 = 0.5$ is used for consistency with previously published optical versions of this plot.). In the optical/near-UV, the mean co-moving SFR is determined from the total observed rest-frame UV luminosity density of galaxies (solid diamond: Trayer et al. 1998; solid circles: Cowie, Songalia & Barger 1999; solid squares: Conolly et al. 1997; solid stars: Steidel et al. 1999). The shaded region and thick solid line represent the maximum contribution to the SFR from far-IR/submm sources (i.e. assuming all of the far-IR/submm emission is powered by young stars) using models with a range of $z$-distributions which are consistent with both the current observations of 850 $\mu$m SCUBA sources (Blain et al. 1999; Barger et al. 1999), and the local volume density of LIGs (Sanders et al. 1999).

formation, and then comparing with similar plots derived for deep optical/UV surveys. Figure 6 suggests that the SCUBA sources dominate the observed optical/UV SFR by at least a factor of 10 at $z > 1$.

What is the relationship of the SCUBA sources to the optically selected high-$z$ population of starburst galaxies? One view is that the SCUBA sources are indeed just the most heavily reddened objects already contained in the optical samples. Favoring this view is the evidence (summarized by Steidel et al. 1999) that on average the more luminous objects in optical samples are also redder, such that after correction for extinction (typically by a mean factor of $\sim 3–5$) using models developed for nearby starburst galaxies (e.g. Meurer et al. 1997; Calzetti 1997) they would have intrinsic luminosities equivalent to that of the SCUBA sources (i.e. $\gtrsim 10^{12} L_\odot$). However, there is little current evidence to show that the SCUBA detections are related to the most heavily reddened optical sources, or that applying a mean dust correction to all optical/UV sources is advised.

An alternative view is that the SCUBA sources represent an inherently distinct population, for example the formation of spheroids and massive black holes, both of which are triggered by the merger of
two large gas-rich disks (e.g. Kormendy & Sanders 1992; Kormendy &
Richstone 1995; SM96). Favoring this view is the fact that the strong
evolution for IRAS ULIGs and SCUBA sources at $z < 1$, and a possible
peak in the range $z \sim 1–3$, is similar to what is observed for QSOs
(e.g. Schmidt et al. 1995) and radio galaxies (Dunlop 1997). For the
UV/starburst population, the more gradual decrease at $z < 1$ and the
flat redshift distribution at $z > 1$ (Steidel et al. 1999) might better
represent the building of disks over a wider range of cosmic time.

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