DEEP SUBMILLIMETER SURVEYS: LUMINOUS INFRARED GALAXIES AT HIGH REDSHIFT

D. B. Sanders

Institute for Astronomy, University of Hawaii, 2680 Woodlawn Drive, Honolulu, HI 96822
Email: sanders@ifa.hawaii.edu

ABSTRACT

Deep surveys at 850µm from Mauna Kea using the SCUBA camera on the JCMT appear to have discovered a substantial population of ultraluminous infrared galaxies (ULIGs: $L_{\text{IR}} > 10^{12} L_\odot$) at high redshift ($z \sim 1 - 4$). The cumulative space density of these sources ($\sim 10^4$ deg$^{-2}$ with $S_{850} > 1$ mJy) is sufficient to account for nearly all of the extragalactic background light at submillimeter wavelengths. Current estimates of the redshift distribution suggest a peak in the comoving space density of SCUBA sources at $z = 1 - 3$, similar to what is observed for QSOs and radio galaxies. The luminosity density in the far-infrared/submillimeter exceeds that in the UV by factors of 3–10 over this redshift range, implying that as much as 80–90% of the “activity” in galaxies at $z \lesssim 4$ is hidden by dust. The SCUBA sources plausibly represent the primary epoch in the formation of spheroids and massive black holes triggered by major mergers of gas-rich disks.

INTRODUCTION

The Submillimeter Common User Bolometer Array (SCUBA) camera (Holland et al. 1999) recently installed on the James Clerk Maxwell Telescope (JCMT) has provided a new window for ground-based studies of the high-z Universe. This brief review summarizes results from the large campaign of deep submillimeter surveys carried out during SCUBA’s first year of operation on Mauna Kea (~Fall ’97–Summer ’98). Evidence is presented that the SCUBA detections must be predominantly ULIGs at high redshift, and that the cumulative space density of these sources is sufficient to account for nearly 100% of the extragalactic background light (EBL) at far-infrared/submillimeter wavelengths. Progress as well as current problems in identifying optical counterparts to the SCUBA sources are then discussed, followed by a review of model calculations comparing the luminosity density in the submm/far-IR with that in the UV over the redshift range, $z = 0 - 5$. Finally, we discuss evidence which suggests that the SCUBA sources, like local ULIGs, are powered by intense circumnuclear starbursts and powerful AGN both of which are fueled by major mergers of gas-rich disks.

SCUBA DEEP SURVEYS

As this Workshop was being held, several observing teams were announcing results from the first deep blank-field submillimeter surveys at 450µm/850µm using SCUBA. Papers by Hughes et al. (1998) for the UK-consortium and by Barger et al. (1998) for the Hawaii-Japan group were announced in press releases during the week of the workshop, and results from the Canada-France consortium were about to be submitted (Eales et al. 1998). These “ultradeep” and “deep” blank-field surveys follow the pioneering surveys of Smail et al. (1997) who were the first to infer a substantial population of luminous submillimeter galaxies from their SCUBA detections at 850µm of background sources amplified by weak lensing from foreground clusters. With the exception of one source detected at 450µm in the cluster fields, all of the SCUBA deep field

---

1Invited review for the workshop “Space Infrared Telescopes and Related Science”, at the 32nd COSPAR Meeting, Nagoya, Japan, 1998, eds. T. Matsumoto and T. de Graauw. To be published in Advances in Space Research (Oxford: Elsevier), 1999.

2This paper draws on new material from the publication by Barger et al. 1999, and the website http://www.ifa.hawaii.edu/~cowie. Due to previous commitments, Len Cowie and Amy Barger were unable to present this review.

3$L_{\text{IR}} \equiv L(8 - 1000) \mu$m in the object rest-frame. Unless stated otherwise, $H_0 = 75 \text{ km s}^{-1} \text{Mpc}^{-1}$, $q_0 = 0$. 
detections have been at 850µm. The HDF (Hughes et al. 1998), and Lockman Hole + SSA13 fields (Barger et al. 1998a,b) are currently the three fields with the deepest SCUBA observations, each with ∼50 Hrs total integration time reaching a noise level, σ_{850} ∼ 0.6–0.8 mJy. Our results for the Lockman Hole are discussed below.

The Lockman Hole

The 850 µm data on the Lockman Hole field (LH_NW; Barger et al. 1998, 1999) are shown in Figure 1. The two SCUBA sources, LH_NW1 and LH_NW2, detected at 850 µm (> 3σ), have 850 µm fluxes of 5.1 mJy, and 2.7 mJy, respectively, with upper limits at 450 µm of < 50 mJy (5σ).

Figure 1. SCUBA 850 µm detections (small thick circles: Barger et al. 1998, 1999), and ISOCAM 7µm detections (small thin circles: Taniguchi et al. 1997) in the Lockman Hole northwest (LH_NW) Deep Field (J2000: RA = 10h33m55.5s, Dec = +57°46′18′′) superimposed on a K′ image obtained with the QUick Infrared Camera (QUIRC) on the University of Hawaii 88-inch 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″ × 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.

Deep observations of the LH_NW field have also been obtained in the mid- and far-infrared with ISO, at B and K′ from Mauna Kea, and at 20 cm with the VLA. As shown in Figure 1, neither SCUBA source has an ISOCAM 7µm counterpart (< 35 µJy; 5σ). 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” in our K′ and B images implying that any counterpart has K′_{AB} > 22.5 and B_{AB} > 24.5. The ISO-PHOT sources detected in a wider area (44′ × 44′) survey centered on LH_NW have relatively large position uncertainties (typically 20″–30″), however there are no 95 µm or 175 µm detections within ∼2′ of
either SCUBA source (the 5 σ upper limits are \( S_{95} < 40 \text{ mJy} \) and \( S_{175} < 75 \text{ mJy} \); Kawara et al. 1998). The VLA results are still preliminary, but any radio continuum counterparts must have \( S_{20cm} \lesssim 500 \text{ \( \mu \)Jy} \) (5 σ) (M. Yun, private communication).

ULIGs at High Redshift

From the strength of the 850 \( \mu \text{m} \) detections and the faintness of the K’ counterparts alone, it is relatively straightforward to show that the SCUBA sources are most likely to be ULIGs at high redshift (i.e. \( z > 1 \)). The “submillimeter excess”, \( (\equiv \nu S_\nu(850)/\nu S_\nu(2.2)) \), for both LH_NW1 and LH_NW2 is larger than 1 (2.4 and >3 respectively), which is impossible to produce from 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 prototypical ULIG Arp 220 at \( z > 1 \) is on the order of a few mJy at 850 \( \mu \text{m} \). Also, the combination of a large negative K-correction in the submillimeter plus a relatively flat or positive K-correction in the near-IR naturally leads to values \( \nu S_\nu(850)/\nu S_\nu(2.2) > 1 \) for all ULIGs at \( z \gtrsim 1.5 \). The observed faintness of the high-z submillimeter sources in current B-band images and the non-detections at 7 \( \mu \text{m} \) in the deep ISOCAM images are consistent with the large U–B colors and the pronounced minimum at \( \sim 3\text{-}6 \mu \text{m} \) respectively, in the rest-frame SEDs of ULIGs like Arp 220. The non-detections at 95 \( \mu \text{m} \) and 175 \( \mu \text{m} \) are consistent with the relatively high noise levels in the ISOPHOT images coupled with the steep positive K-correction encountered over the rest-frame wavelength range \( \sim 20\text{-}80 \mu \text{m} \) for all ULIGs.

![Arp 220 SED](image)

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 \( \mu \text{m} \) and 2.2 \( \mu \text{m} \) observed frame for redshifts, \( z = 0 \sim 5 \). The insert shows the corresponding observed-frame 850 \( \mu \text{m} \) flux and \( \nu S_\nu(850)/\nu S_\nu(2.2) \) ratio for Arp 220 at redshifts, \( z = 0 \sim 5 \).
Table 1 summarizes the 850 µm cumulative source counts from all of the SCUBA deep field surveys published to date. Taking into account the different sensitivity limits and the reported formal uncertainties, there appears to be good agreement on both the shape of the logN-logS plot over the observed range of 2–10 mJy, as well as on the extrapolated cumulative counts down to 1 mJy obtained from P(D) analyses of the low-level fluctuations in the ultradeep images. In retrospect, it is remarkable how little time it has taken to reach consensus on the surface density of faint submillimeter sources per SCUBA field. This success is first and foremost due to the excellent performance of SCUBA, but was also helped by a phenomenally well timed six consecutive months of near record low mean submillimeter opacity on Mauna Kea, and the commitment of relatively large blocks of observing time to several teams of observers.

Table 1. SCUBA Source Counts at 850 microns

| λ (µm) | Counts (deg⁻²) | Flux Limit (mJy) | Reference | Fields |
|--------|----------------|------------------|-----------|--------|
| 850    | 2500±1400      | 4                | Smail et al. (1997) | 2 clusters (A370, CL2244-02) |
| "      | 1100±600       | 8                | Holland et al. (1998) | background sources in 3 star fields |
| "      | 800±100        | 3                | Barger et al. (1998) | LH_NW; SSA13 |
| "      | 7000±3000      | 1                | Hughes et al. (1998) | HDF |
| "      | 1800±600       | 2.8              | Eales et al. (1998) | CFRS |
| "      | 1500±700       | 4                | Blain et al. (1999) | 7 clusters |
| "      | 7900±3000      | 1                | "                | " |
| "      | 10,000±2000    | 1                | Barger et al. (1999) | LH_NW; SSA13; SSA17; SSA22 |

a modified and updated from a compilation by Trentham et al. (1998)

Figure 3. Comparison of the 850 µm source counts (solid squares: from Barger et al. 1999) with semi-analytic model counts (see text). Model 1 is equivalent to the “no evolution” model of Blain & Longair (1996). Models 2 and 3 are equivalent to Models A and E respectively from Guiderdoni et al. (1998).

Figure 3 shows that the cumulative 850 µm counts from 2 mJy to 10 mJy can be approximated by a single power law of the form \( N(> S) = 1 \times 10^4 \ S^{-2} \ \text{deg}^{-2} \). The extrapolated value at 1 mJy is consistent with the P(D) results reported in Table 1. This large surface density implies strong evolution in the ULIG population.
Figure 3 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 $60 \mu m$ luminosity function of galaxies (i.e. $\sim 0.001 \text{ ULIGs} \text{ deg}^{-2}$ at $z < 0.08$: Kim & Sanders 1998; see also Soifer et al. 1987; Saunders et al. 1990) assuming no evolution, which underestimates the observed sources by nearly 3 orders of magnitude. Model 2 includes no ULIGs, but instead attempts to account for the fraction of the optical/UV emission absorbed and reradiated by dust in sources observed in optical/near-UV deep fields. Model 2 still substantially underpredicts the $850 \mu m$ source counts by a factor of $\sim 30$. Model 3 includes a strongly evolving population of ULIGs, constrained only by recent measurements of the submillimeter background. Model 3 is a much better match to the observed SCUBA counts, although the particular redshift distribution assumed (Model E of Guiderdoni et al. 1998) was arbitrarily chosen to push most of the ULIGs to $z > 3$, which as described below is at odds with current redshift estimates.

CONTRIBUTION OF SCUBA SOURCES TO THE SUBMM/FAR-IR BACKGROUND

Figure 4 compares the contribution of the $850 \mu m$ sources with the recent model of the EBL determined from COBE data at far-infrared/submillimeter wavelengths (Fixsen et al. 1998; see also Hauser et al. 1998; Puget et al. 1996, 1998). Approximately 25% of the $850 \mu m$ background resides in sources brighter than 2 mJy, and nearly all of the EBL at $850 \mu m$ can be accounted for by sources brighter than 1 mJy, assuming the extrapolation down to 1 mJy given by the straight line fit to the SCUBA data in Figure 3.

![Figure 4](http://www.ifa.hawaii.edu/~cowie/)

Figure 4 makes the important additional point that the average observed temperature of the $850 \mu m$ sources must be low (i.e. $\lesssim 25 \text{ K}$) so that their emission will not exceed the EBL at wavelengths shortward of $200 \mu m$. If the SCUBA sources are indeed distant analogs of local ULIGs whose typical dust temperatures are $\sim 50$–80 K, then a low observed temperature would provide additional evidence that the SCUBA sources lie predominantly at high redshift (i.e. $z > 1$).
SOURCE IDENTIFICATION

Progress in identifying optical/near-IR counterparts of the SCUBA deep-field sources has been frustratingly slow, due in large part to the uncertainty in the 850 μm SCUBA positions, but also to the intrinsic faintness of many of the sources, even at K-band. A prime example is the current controversy surrounding the identified SCUBA counterparts in the HDF. Four of the 5 850 μm SCUBA sources in the HDF, the identifications by Hughes et al. (1998) hinge in large part on plausibility arguments using “template SEDs”. Although these attempts are admirable, they apparently can be misleading, for example the identification of the brightest source, HDF850.1, with a faint counterpart at \(z = 3.4\) is now known to be in error from a more accurate position obtained from millimeter interferometry. Our results for the Lockman Hole are not much more encouraging (see Figure 1): LH NW1 seems to have an identified K-band counterpart, however no emission lines are seen in a deep Keck spectrum, and LH NW2 is a blank field in the current K-band image.

Progress has been somewhat better in the lensed cluster fields, where the 1-2 mags of amplification appears to reduce the number of blank fields (\(< 20\%\) at \(I < 25\); Smail et al. 1998), but uncertainty in the 850 μm positions is still a major problem, plus contamination by cluster members, unless properly accounted for, will artificially inflate the number counts and skew the distribution of redshifts. The wider-area shallower surveys (e.g. Eales et al. 1998; Lilly et al. 1999) preferentially select brighter nearby sources, which are more likely to have brighter optical/near-IR counterparts, but still suffer from position uncertainty at 850 μm.

The net result after combining all current studies is that only \(~20–25\%\) of the 850 μm sources currently have “secure” identifications, and even for these it has been necessary to rely heavily on data at other wavelengths to make a strong case that only the identified source has a high probability of being correct.

TEMPLATE SEDs

Attempts to sort out which of typically 2-3 equally probable sources is more likely to be the true SCUBA counterpart have made use of “template SEDs” to determine which source is most likely to match the known properties of ULIGs. This procedure works best when additional deep-field data are available at several wavelengths, usually deep radio continuum images from the VLA, and high resolution, deep near-IR and optical images from either HST or with adaptive optics from the ground. The most complete and deepest data sets are of the HDF, with shallower multiwavelength data generally available for other SCUBA fields. However, even for the HDF, measurement uncertainties coupled with a real dispersion in ULIG properties can still give ambiguous results.

Figures 5 and 6 illustrate the range of rest-frame SEDs observed for a sample of low-redshift ULIGs, and the corresponding flux ratios that would be observed for these objects at high redshift. It is instructive to briefly review what has (or hasn’t) been learned from trying to identify the correct SCUBA counterpart and/or to set meaningful constraints on redshift using observed flux ratios.

Radio /Far-Infrared Correlation

Perhaps the most promising means of identifying SCUBA positions is from high resolution radio continuum maps, as has been done quite successfully for lower redshift IRAS sources (e.g. Condon et al. 1990). The subarcsecond radio positions coupled with a relatively tight correlation between the radio and the far-infrared emission for infrared galaxies (e.g. Condon et al. 1991) could provide relatively unambiguous identifications of the current SCUBA deep field sources, provided that it is possible to reach a point source sensitivity of \(\lesssim 10 \mu\text{Jy}\) at 3cm or \(\lesssim 30 \mu\text{Jy}\) at 20cm. Unfortunately, although this has been achieved for the HDF (Richards et al. 1998), the majority of the SCUBA sources in the HDF are not detected in the radio continuum at a level which is already at least 3–5 times fainter than even the maximum observed ratios shown on the plot in Figure 6. One possible explanation would be to push the majority of the SCUBA sources to very large redshifts, i.e. \(z > 3\) (e.g. Carilli and Yun 1999), but as shown below, this is in conflict with other best estimates of the range of redshift for the majority of the SCUBA sources. The current situation is bizarre enough to have caused others to attempt interesting explanations such as a substantial underestimate of the pointing error in the JCMT observations of the HDF (Richards 1999). A more likely explanation is that the SCUBA sources are indeed fainter in the radio than ULIGs studied by IRAS, although why this should be is currently not clear. The bottom line is that ultradeep VLA observations are currently incapable of detecting
Figure 5. Measured rest-frame spectral energy distributions (SEDs) from UV-to-radio wavelengths for a representative sample of the most luminous sources detected by *IRAS*.

Figure 6. Left panels: (top) flux ratios as a function of redshift for nearby ULIGs from the *IRAS* Bright Galaxy Sample (Soifer et al. 1987; Sanders et al. 1995); (bottom) Flux versus redshift for Arp 220. Right panels: (top) B–R versus redshift (bottom) B-K versus redshift for three nearby ULIGs (dashed/dotted lines) from the *IRAS* Bright Galaxy Sample compared with the redshifted colors of a standard elliptical galaxy (Trentham et al. 1999).
the majority of SCUBA deep field sources, and thus even deeper ultradeep VLA observations are needed if there is to be any hope of using this potentially powerful diagnostic to pin down the SCUBA positions.

450μm/850μm Spectral Index

In all of the SCUBA deep-fields, only one source has been reliably detected (5σ) at 450 μm, that being SMM02399-0136 in the field of the z = 0.37 cluster, A370; it is the brightest 850 μm source detected in the survey of Smail et al. (1998), and by far, the brightest SCUBA source yet detected in any of the blank field surveys. For all other sources only upper limits can be used to constrain the 450μm/850μm spectral index. Given that the noise at 450 μm is typically 10× that at 850 μm current limits on this ratio are simply not sensitive enough to be of much use. The only caveat might be the HDF where the exceptionally good weather produced a quoted limit at 450 μm of ~25 mJy (Hughes et al. 1998), implying that the two brightest 850 μm sources have $S_{450}/S_{850} < 6 - 7$; however, this sets only a weak constraint of $z > 0.3$ (see Figure 6).

K-band versus 850μm Flux

Figure 6 shows the effects of the large negative K-correction in the submillimeter on the “submillimeter excess” ratio ($\equiv \nu S_\nu(850)/\nu S_\nu(2.2)$). This ratio provides a useful redshift discriminant at $z \lesssim 3$, however at higher redshift the fact that the large positive K-corrections in both the mid-infrared and in the near-UV are similar means that there is little variation in the ratio over the redshift range, $z \sim 3 - 6$.

Optical, Near-Infrared Colors

One of the surprises from the early results from the lensed cluster survey was the finding by Smail et al. (1998) that the optical ($V-I$) colors of the SCUBA counterparts (using only those sources with the highest probability of being correctly identified) are bluer on average than the faint field population, although the spread in colors is relatively large and at least a few objects appear to be extremely red. A priori one might have expected that the majority of the SCUBA sources, given their large infrared excess, should be extremely red objects (e.g. EROS: Hu and Ridgeway 1991; Cimatti et al. 1998; Dey et al. 1998). Although ULIGs are faint at optical wavelengths, either enough UV light escapes from the nuclear dust shroud or is still produced by a slowly decaying starburst in the surrounding disk. Only in the most extreme geometries is it apparently possible to hide all evidence of current and past starburst activity. Unfortunately, given that the optical colors of SCUBA sources bracket those of the faint field population, optical colors may only be of marginal help in identifying SCUBA counterparts.

$L_\text{fit}/L_{CO}$

This ratio differs from the other template measures in that it relies on a line measurement, and thus is only useful once a redshift has been determined. The great majority of ULIGs (at all redshifts) appear to have molecular gas masses in the range $M(H_2) = 0.5 - 10 \times 10^{10} M_\odot$ as inferred from their luminosities in one or more of the lower rotational transitions of CO (e.g. Sanders et al. 1991; Downes et al. 1995; Solomon et al. 1997). The sensitivity of current millimeterwave interferometers is sufficient to detect $>10^{10} M_\odot$ of molecular gas independent of redshift (see Radford 1994), and thus once a redshift has been determined, detection of the source in CO would greatly increase the probability that it indeed was the source of the submillimeter emission. The only drawback is that ULIGs with “warmer” than normal mid- and far-infrared colors can have substantially less molecular gas, e.g. $M(H_2) < 10^9 M_\odot$ (Evans et al. 1998), and thus fall well below current sensitivity limits. Therefore, given that the mid-infrared colors of SCUBA sources are not well-known, non-detection in CO would not necessarily rule out the identification of an otherwise reasonable counterpart.

Despite the above attempts to identify the 850 μm deep-field SCUBA sources, most still do not have secure identifications. Uncertainty in the 850 μm positions remains the major problem. Until submillimeter interferometers start to come on line early in the next decade, the most useful data to obtain would be interferometer measurements at 1 mm to detect the long wavelength tail of the 850 μm emission. Unfortunately the expected 1 mm flux for most of the deep-field SCUBA sources is $< 1$ mJy, which is below the practical sensitivity limits of current mm-wave interferometers. Deeper “ultra-deep” VLA surveys may continue to be the most promising alternative.
**REDSHIFT DISTRIBUTION**

Clearly the most important unknown concerning the SCUBA sources is their redshifts. The relatively small fraction (∼20–25%) of SCUBA sources that have secure identifications has resulted in much speculation about the true redshift distribution. Although it is not possible to rule out distributions that peak at $z \gtrsim 3$ as originally advocated by Hughes *et al.* (1998) for the HDF, or that peak at $z \sim 1$ as advocated by Eales *et al.* (1999) and Lilly *et al.* (1998) for the CFRS fields, there is increasing evidence that the comoving luminosity function of SCUBA sources peaks somewhere in between, i.e. at $z \sim 1 - 3$.

The most comprehensive redshift survey of SCUBA sources is that for the 16 sources in the lensed cluster fields of Smail *et al.* (1998), as recently reported in Barger *et al.* (1999). Of the 16 sources, two are clearly cluster contaminants (i.e. cD galaxies). Of the remaining 14 those with the strongest identifications are an interacting pair at $z = 2.55$ and the previously identified (Ivison *et al.* 1998) type-II AGN/starburst source at $z = 2.8$. The next two most reliable detections, based partly on template SEDs, are at $z = 1.06$ and $z = 1.16$. Eight sources are still highly uncertain, however nearly all plausible nearby counterparts have redshifts in the range $z = 0.18 - 2.11$, with two galaxies at the low end of this range likely being cluster contaminants. Finally, only two sources have no obvious optical counterparts, and therefore might be at higher redshifts (i.e. $z > 3$).

**THE “STAR FORMATION HISTORY” OF THE UNIVERSE**

The past few years has seen a revolution in optical studies of field galaxies, which with the help of 8-10 m-class optical telescopes, has enabled the determination of the UV luminosity density of the Universe out to redshifts $z \gtrsim 4$.

Figure 7. The global “star formation history” of the Universe ($H_0 = 50$ km s$^{-1}$Mpc$^{-1}$, $q_0 = 0.5$ is used for consistency with Madau *et al.* 1996). In the optical/near-UV, the mean co-moving rate of star formation is determined from the total measured rest-frame UV luminosity density of galaxies (solid hexagon: Trayer *et al.* 1998; solid circles: Lilly *et al.* 1996; solid squares: Connolly *et al.* 1997; solid triangles: Madau *et al.* 1996; solid stars: Steidel *et al.* 1998). The optical data points have been corrected upward for extinction; the open symbols shown here are the correction ($\times 4.7$) adopted by Steidel *et al.* (1998). The light shaded region represents a prediction from chemical evolution models (Pei and Fall 1995). The dark shaded region and thick solid line represent the maximum contribution 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 the current observations of 850 µm SCUBA sources (Blain *et al.* 1998).

Figure 7 gives the optical/near-UV determination of the mean co-moving rate of star formation over the redshift range $z = 1 - 4$ following an early analysis of galaxies in the HDF by Madau *et al.* (1996), who also noted that there seemed to be little evidence for substantial amounts of dust obscuration in the optical sources. It is remarkable how quickly this picture has changed.
It is immediately obvious from the large space density of the 850 µm sources, and their large inferred bolometric luminosity in the far-IR/submillimeter (i.e. corresponding to ∼ 30 – 300$L^\odot_{bol}$), that the SCUBA sources could represent a significant and perhaps dominant component of the luminosity emitted by galaxies over cosmic time. It is also clear that a substantial fraction of the “activity” in galaxies at high redshifts (z > 1) is obscured by dust, and, therefore has been missed in optical/UV surveys. This is illustrated in Figure 7, which assuming that all of the far-IR/submm luminosity is due to star formation, plots a range of plausible models of SFR vs. $z$ (Blain et al. 1998) consistent with reasonable assumptions for the redshift distribution of the SCUBA sources. Figure 7 suggests that the SCUBA sources dominate the optical by factors of 5–10 at nearly all redshifts, and that their distribution with redshift is likely to be substantially different than the bias toward low redshifts inferred from the early optical studies.

However, it is naive to assume that the role of dust is negligible in the optical sources, and indeed from studies of the optical/near-UV colors it was quickly realized that dust obscuration could have a substantial effect. Reddening models developed for local starburst galaxies (e.g. Meurer et al. 1997, 1998; Calzetti 1997, 1998) have now been used to correct the optical sources for reddening, resulting in mean model-dependent increases of ∼3–7 in the SFR (e.g. Dickinson 1998; Pettini et al. 1998; Steidel et al. 1998). Better statistical samples at z > 3 have also erased evidence of a turnover in the distribution at $z \sim 1$ (Steidel et al. 1998), and with an additional assumption that mean reddening corrections are relatively constant (at least over the observable redshift range out to $z \sim 4$: e.g. Steidel et al. 1998), the redshift distribution of star formation from the optical samples begins to resemble more closely that determined for the SCUBA sources, although the latter still exceed the former by factors of ∼2–4 at $z > 1$.

THE STARBURST–AGN CONNECTION

Are the SCUBA sources simply powered by starbursts as is the case for the optical-UV selected samples, or could AGN play a significant role in producing their enormous luminosities?

Although relatively little is currently known about the detailed properties of the SCUBA sources, it is interesting to note that the bulk properties of those few sources whose positions and redshifts have been reliably identified with SCUBA detections are in fact quite similar to the mixture of starburst and AGN properties, and merger morphologies observed for ULIGs at low redshift.

The two best studied sources from the sample of Smail et al. (1997) are illustrative. SMM.J02399–0136 at $z \sim 2.8$, with $L_{ir} \gtrsim 10^{13}L^\odot$, is morphologically compact with an optical classification as a narrow-line “type-2” AGN (Ivison et al. 1998), and contains $\sim 10^{10.5}M^\odot$ of molecular gas (Frayer et al. 1998). SMM.J14011+0252 at $z \sim 2.6$ with $L_{ir} \sim 10^{12.3}L^\odot$ (Barger et al. 1999), is a strongly interacting/merger pair, with an HII-like optical spectrum and $\sim 10^{10.7}M^\odot$ of molecular gas (Frayer et al. 1999). These two sources fit remarkably well into the pattern exhibited by ULIGs in the local Universe. In particular their molecular gas masses, optical luminosities, and optical morphologies are very similar to what is observed for local ULIGs (see Sanders and Mirabel 1996 for a review of local ULIGs).

Although there are only two objects, it is interesting to note that their optical spectral types fit the trend with $L_{ir}$ that is observed for local ULIGs, as illustrated in Figure 8 which shows that the importance of AGN appears to increase with increasing $L_{ir}$. At $L_{ir} > 10^{12.0–12.3}L^\odot$ 10–20 % of local ULIGs appear to be predominantly powered by an AGN with the remainder apparently powered by a starburst (although it is still not possible to rule out that a substantial fraction of the luminosity is produced by a heavily dust enshrouded AGN). At $L_{ir} > 10^{12.3}L^\odot$ nearly half of all local ULIGs appear to be powered predominantly by an AGN, while at the highest observed infrared luminosities (i.e. $L_{ir} \gtrsim 10^{13}L^\odot$) all of the currently identified objects are classified as AGN, typically as Sy 2s in direct optical emission (e.g. IRAS F09105+4108: Kleinmann and Keel 1987; IRAS F15307+3252: Cutri et al. 1994; IRAS F10214+4724: Rowan-Robinson et al. 1991), but have been shown to contain hidden broad-line regions in polarized optical light (e.g. Hines et al. 1995), or in direct near-infrared emission (e.g. Veilleux et al. 1997, 1998).

Although Arp 220 (optically classified as a LINER) is often used as the template for ULIGs (see Figure 2) primarily due to the fact that it is the nearest such object by nearly a factor of 2.5, it is not necessarily typical of most UUIGs, in particular those with the largest infrared luminosities. Mrk 231 (optically classified as a Sy 1/BALQSO) may better illustrate the mixture of starburst and AGN found in many ULIGs.
Figure 8. The optical spectral classification of infrared galaxies versus infrared luminosity (Veilleux et al. 1999).

Figure 9 shows the merger morphology apparent in deep optical images of Mrk 231, and the detection by HST of a large population of star clusters in the inner 1-3 kpc, presumably the remnants of a more widespread circumnuclear starburst whose total bolometric luminosity is currently only a very small fraction of the total bolometric luminosity of the system (Surace et al. 1998), nearly all of which originates from the inner few hundred parsecs (e.g. Matthews et al. 1987). The dense knot of molecular gas in the inner \( \sim 1 \) kpc which is centered on the Sy1 nucleus, presumably represents the large reservoir of gas still available to fuel the last phases of the circumnuclear starburst as well as to continue to build and fuel the AGN.

Figure 9. The advanced merger/ULIG/QSO Mrk231 – Left panel: optical image (Sanders et al. 1987) and CO contour (Scoville et al. 1989). Right panel: HST B-band image and identified stellar clusters (‘+’) from Surace et al. (1998). The high resolution CO contours are from Bryant and Scoville (1997).
One of the major questions at this Workshop has been 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. 1998) that on average the more luminous objects in optical samples are also redder, such that after correction for extinction they would have intrinsic luminosities equivalent to that of the SCUBA sources (i.e. \( \gtrsim 10^{12} L_\odot \)). Detect an emerged “star-formation histories” derived for the two populations may have similar shape might suggest that both samples are simply different manifestations of the same general phenomenon.

An alternative view is that the SCUBA sources represent an inherently distinct population, for example the formation of massive spheroids and massive black holes, both of which are triggered by the merger of two large gas-rich disk galaxies (e.g. Kormendy and Sanders 1992; Kormendy and Richstone 1995; see also the review in Sanders and Mirabel 1996). Favoring this view is the fact that the peak in the SCUBA redshift distribution at \( z = 1 - 3 \) is similar to what is observed for QSOs (Schmidt et al. 1995; Warren et al. 1994; Shaver et al. 1998) and radio galaxies (Dunlop 1997). The relatively flat redshift distribution now inferred for the UV starburst population at \( z > 1 \) (Steidel et al. 1998) might then better represent the building of gas-rich disks over a wider range of cosmic time. Also, there is no current evidence to show that the SCUBA detections are indeed related to the most heavily reddened optical sources, plus it is not clear that the far-UV luminosity of SCUBA sources is sufficient to be included in the deepest HST samples, i.e. \( L_\nu(2200\AA)/L_\nu(80\mu m) \sim 10^{-5.5} \), for Arp 220-like objects (see Figure 2).

Finally, in response to questions raised during the AGN Workshop at this COSPAR meeting, we consider the intriguing possibility that the large population of newly discovered SCUBA sources might be responsible for producing a large fraction of the X-Ray background. It is now apparent from the shape of the X-Ray background spectrum that most of the objects contributing to the X-Ray background are heavily absorbed (e.g. Fabian and Barcons 1992; Boyle et al. 1995; Almaini et al. 1998), and that they have largely been missed in optical surveys. Candidates for these obscured sources are the class of “narrow-line X-Ray galaxies” (NLXGs: Hassinger 1996), which have recently been characterized by Maiolino et al. (1998) has having extremely heavy obscuration along the line of sight (e.g. \( N_{H} > 10^{24-25} cm^{-2} \)). SCUBA sources (like local ULIGs) are obvious candidates for having such large absorbing columns, and if a significant fraction of the SCUBA sources prove to have buried AGN, then it seems reasonable to assume that they might indeed be responsible for producing a substantial fraction of the X-Ray background. Deep surveys with soon-to-be-launched X-Ray satellites (e.g. XMM, Chandra, Astro-E) could provide the answer.

Acknowledgments. I am grateful to Karen Teramura for assistance in preparing the figures, and to JPL contract no. 961566 for partial financial support.

References

Almaini, O., Shanks, T., Gunn, K.F., Boyle, B.J., Georgantopoulos, I., et al. 1998, Astr.Nachr., 319, 55
Barger, A.J., Cowie, L.L., Sanders, D.B., Fulton, E., Taniguchi, Y., et al. 1998, Nature, 394, 248
Barger, A.J., Cowie, L.L., and Sanders, D.B., 1999, Ap.J.(Letters), submitted
Blain, A.W., Kneib, J.-P., Ivison, R.J., and Smail, I. 1999, Ap.J.(Letters), in press (astro-ph/9812412)
Blain, A.W., and Longair, M.S. 1996, M.N.R.A.S., 279, 847
Blain, A.W., Smail, I., Ivison, R.J., and Kneib, J.-P. 1998, M.N.R.A.S., in press (astro-ph/980602)
Boyle, B.J., McMahon, R.G., Wilkes, B.J., and Elvis, M. 1995, M.N.R.A.S., 276, 315
Bryant, P.M., and Scoville, N.Z. 1996, Ap.J., 457, 678
Calzetti, D. 1998, in The Ultraviolet Universe at Low and High Redshift: Probing the Progress of Galaxy Evolution, eds. W. Waller, M. Fanelli, J. Hollis, A. Danks, AIP Conference Proceedings 408, (New York: Woodbury), 403
Calzetti, D. 1997, Astron.J., 113, 162
Carilli, C.L., and Yun, M.S. 1998, Ap.J.(Letters), in press (astro-ph/9812251)
Cimatti, A., Andreani, P., Röttgering, H., and Tianus, R. 1998, Nature, 392, 895
Condon, J.J., Helou, G., Sanders, D.B., and Soifer, B.T. 1990, *Ap.J.Suppl.*, 73, 359
Condon, J.J., Huang, Z.-P., Yin, Q.F., and Thuan, T.X. 1991, *Ap.J.*, 378, 65
Connolly, A.J., Szalay, A.S., Dickinson, M., SubbaRao, M.U., and Brunner, R.J. 1997, *Ap.J.(Letters)*, 486, L11
Cutri, R.M., Huchra, J.P., Low, F.J., Brown, R.L., and Vanden Bout, P.A. 1994, *Ap.J.(Letters)*, 424, L65
Dey, A., Graham, J.R., Ivison, R.J., Smail, I., Wright, G.S., et al. 1999, *Ap.J.*, in press (astro-ph/9902041)
Dickinson, M. 1998 in *The Hubble Deep Field*, eds. M. Livio, S.M. Fall, P. Madau, STScI Symposium Series, in press (astro-ph/9802064)
Downes, D., Solomon, P.M., and Radford, S.J.E. 1995, *Ap.J.(Letters)*, 453, L65
Dickinson, M. 1998 in *Cosmology with New Radio Surveys*, eds. M. Bremer, et al. (Dordrecht: Kluwer), in press (astro-ph/9704294)
Eales, S.A., Lilly, S.J., Gear, W., Dunne, L., Bond, J.R., et al. 1998, *Ap.J.*, in press (astro-ph/9808040)
Evans, A.S., Sanders, D.B., Cutri, R., Radford, S.J.E., Solomon, P.M., et al. 1998, *Ap.J.*, 506, 205
Fabian, A.C., and Barcons, X. 1992, *Ann.Rev.Astron.Astroph.* 30, 429
Fixsen, D.J., Dwek, E., Mather, J.C., Bennett, C.L., and Shafer, R.A. 1998, *Ap.J.* 508, 123
Frayer, D.T., Ivison, R.J., Scoville, N.Z., Evans, A.S., Yun, M.S., et al. 1999, *Ap.J.(Letters)*, 514, L13
Frayer, D.T., Ivison, R.J., Scoville, N.Z., Yun, M.S., Evans, A.S., et al. 1998, *Ap.J.Letters* 506, L7
Guiderdoni, B., Hivon, E., Bouchet, F.R., and Maffei, B. 1998, *M.N.R.A.S.*, 295, 877
Hassinger, G. 1996, *Astron.Astrophys.Suppl.*, 120, 607
Hauser, M.G., Arendt, R.G., Kelsall, T., Dweck, E., Odegard, N. et al. 1998, *Ap.J.*, 508, 25
Hines, D.C., Schmidt, G.D., Smith, P.S., Cutri, R.M., and Low, F.J. 1995, *Ap.J.(Letters)*, 450, 1
Holland, W.S., Greaves, J.S., Zuckerman, B., Webb, R.A., McCarthy, C., et al. 1998, *Nature* 392, 788
Holland, W.S., Robson, E.I., Gear, W.K., Cunningham, C.R., Lightfoot, J.F., et al. 1999, *M.N.R.A.S.*, in press (astro-ph/9809122)
Hu, E.M., and Ridgeway, S.E. 1994, *Astron.J.*, 107, 1303
Hughes, D., Serjeant, S., Dunlop, J., Rowan-Robinson, M., Blain, A., et al. 1998, *Nature* 394, 241
Ivison, R.J., Smail, I., LeBorgne, J.-F., Blain, A.W., Kneib, J.-P., et al. 1998, *M.N.R.A.S.*, 298, 583
Kawara, K., Sato, Y., Matsuhara, H., Taniguchi, Y., Okuda, H., et al. 1998, *Astron.Astrophys.* 336, L9
Kim, D.-C., and Sanders, D.B. 1998, *Ap.J.Suppl.*, 119, 41
Kleinmann, S.G., and Keel, W.C. 1987, in *Star Formation in Galaxies*, ed. C.J. Lonsdale-Persson, Wash. DC: US GPO, 559
Kormendy, J., and Richstone, D. 1995, *Ann.Rev.Astron.Astroph.* 33, 581
Kormendy, J., and Sanders, D.B. 1992, *Ap.J.(Letters)*, 390, L53
Lilly, S.J., LeFèvre, O., Hammer, F., and Crampton, D. 1996, *Ap.J.(Letters)*, 460, L1
Lilly, S., Eales, S.A., Gear, W.K.P., Hammer, F., LeFèvre, et al. 1999, *Ap.J.*, in press (astro-ph/9901047)
Madau, P., Ferguson, H.C., Dickinson, M., Giavalisco, M., Steidel, C.C., et al. 1996, *M.N.R.A.S.*, 283, 1388
Maiolino, R., Salvati, M., Bassani, L., Dadina, M., Della Ceca, R., et al. 1998, *Astron.Astrophys.* 338, 781
Matthews, K., Neugebauer, G., McGill, J., and Soifer, B.T. 1987, *A.J.*, 94, 297
Meurer, G.R., Heckman, T.M., Leitherer, C., and Lowenthal, J. 1997, *Astron.J.*, 114, 54
Meurer, G.R., Heckman, T.M., and Calzetti, D. 1998, in *After the Dark Ages: when Galaxies were Young*, eds. S. Holt, E. Smith, in press (astro-ph/9812360)
Pei, Y.C., and Fall, S.M. 1995, *Ap.J.*, 454, 69
Pettini, M., Kellogg, M., Steidel, C.C., Dickinson, M., Adelberger, K.L., et al. 1998, *Ap.J.*, in press (astro-ph/9806219)
Puget, J.-L., Abergel, A., Bernard, J.-P., Boulanger, F., Burton, W.B., et al. 1996, *Astron.Astrophys.* 308, L5
Puget, J.-L., Lagache, G., Clements, D.L.,Reach, W.T., Aussel, H., et al. 1998, *Astron.Astrophys.*, in press (astro-ph/9812039)
Radford, S.J.E. 1994, in *The Cold Universe*, eds. T. Montmerle et al., (Gif-sur-Yvette: Ed. Frontieres), 369
Richards, E.A. 1998, *Ap.J.*, submitted (astro-ph/9811095)
Richards, E.A., Kellermann, K.I., Fomalont, E.B., Windhorst, R.A., and Partridge, R.B. 1998, *Astron.J.*, **116**, 1039

Rowan-Robinson, M., Broadhurst, T., Lawrence, A., McMahon, R.G., Lonsdale, C.J., et al. 1991, *Nature*, **351**, 719

Sanders, D.B., Egan, E., Lipari, S., Mirabel, I.F., and Soifer, B.T. 1995, *Astron.J.*, **110**, 1993

Sanders, D.B., and Mirabel, I.F. 1996, *Ann.Rev.Astron.Astroph.*, **34**, 749

Saunders, W., Rowan-Robinson, M., Lawrence, A., Efstathiou, G., Kaiser, N., et al. 1990, *M.N.R.A.S.*, **242**, 318

Schmidt, M., Schneider, D.P., and Gunn, J.E. 1995, *Astron.J.*, **110**, 68

Scoville, N.Z., Sanders, D.B., Sargent, A.I., Soifer, B.T., and Tinney, C.G. 1989, *Ap.J.(Letters)*, **345**, L25

Shaver, P., Hook, I.M., Jackson, C.A., Wall, J.V., and Kellermann, K.I. 1998, in *Highly Redshifted Radio Lines*, eds. C. Carilli et al., in press (astro-ph/9801211)

Smail, I., Ivison, R.J., and Blain, A.W. 1997, *Ap.J.(Letters)*, **490**, L5

Smail, I., Ivison, R.J., Blain, A.W., and Kneib, J.-P. 1998, *Ap.J.*, **507**, L21

Soifer, B.T., Sanders, D.B., Madore, B.F., Neugebauer, G., Danielson, G.E., et al. 1987, *Ap.J.*, **320**, 238

Solomon, P.M., Downes, D., Radford, S.J.E., and Barrett, J.W. 1997, *Ap.J.*, **478**, 144

Steidel, C.C., Adelberger, K.L., Giavalisco, M., Dickinson, M., and Pettini, M. 1998, *Ap.J.*, in press (astro-ph/9811399)

Surace, J.A., Sanders, D.B., Vacca, W.D., Veilleux, S., and Mazzarella, J.M. 1998, *Ap.J.*, **492**, 116

Taniguchi, Y., Cowie, L., Sato, Y., Sanders, D.B., Kawara, K. et al. 1997, *Astron.Astrophys.*, **328**, L9

Trayer, M.A., Ellis, R.S., Milliard, B., and Donas, J. 1998, in *The Ultraviolet Universe at Low and High Redshift: Probing the Progress of Galaxy Evolution*, eds. W. Waller, et al., AIP Conference Proceedings 408, (Woodbury: AIP), 99

Trentham, N., Blain, A.W., and Goldader, J., 1998, *M.N.R.A.S.*, in press (astro-ph/9812085)

Trentham, N., Kormendy, J.K., and Sanders, D.B. 1999, *Astron.J.*, in press

Veilleux, S., Sanders, D.B., and Kim, D.-C. 1997, *Ap.J.*, **484**, 92

Veilleux, S., Sanders, D.B., and Kim, D.-C. 1998, *Ap.J.*, in press (astro-ph/9904148)

Veilleux, S., Kim, D.-C., and Sanders, D.B. 1999, *Ap.J.*, in press (astro-ph/9904149)

Warren, S.J., Hewett, P.C., and Osmer, P.S. 1994, *Ap.J.*, **421**, 412