THE CANADA–UNITED KINGDOM DEEP SUBMILLIMETER SURVEY. II. FIRST IDENTIFICATIONS, REDSHIFTS, AND IMPLICATIONS FOR GALAXY EVOLUTION

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ABSTRACT

Identifications are sought for 12 submillimeter sources detected in a deep submillimeter survey. Six are securely identified, two have probable identifications, and four remain unidentified with $I_{AB} > 25$. Spectroscopic and estimated photometric redshifts indicate that four of the sources have $z < 1$ and four have $1 < z < 3$, with the remaining four empty-field sources probably lying at $z > 3$. The spectral energy distributions of the identifications, as defined by measurements or upper limits to the flux densities at 8000 Å, at 15, 450, 850 μm, and at 6 cm, are consistent with the spectral energy distributions of high-extinction starbursts such as Arp 220. The far-IR luminosities of the sources at $z > 0.5$ are of order $3 \times 10^{12} h^{-2}c^{2} L_{\odot}$, i.e., slightly larger than that of Arp 220. As with local ultraluminous infrared galaxies, the optical luminosities of the identified galaxies are comparable to present-day $L^{*}$, and the optical morphologies of many of the galaxies show evidence for mergers or highly disruptive interactions. Based on this small sample, the cumulative bolometric luminosity function shows strong evolution to $z \sim 1$, but weaker or possibly even negative evolution beyond. The redshift dependence of the far-IR luminosity density does not appear, at this early stage, to be inconsistent with that seen in the ultraviolet luminosity density. Although the computation of bolometric luminosities is quite uncertain, the population of very luminous galaxies that is detected in the surveys at $z > 1$ is already matching, in the far-IR, the bolometric output in the ultraviolet of the whole optically selected population. Assuming that the energy source in the far-IR is massive stars, this suggests that the total luminous output from star formation in the universe will be dominated by the far-IR emission once the lower luminosity sources, below the current far-IR detection threshold, are included. Furthermore, the detected systems have individual star formation rates (exceeding $300 h^{-2} M_{\odot} \text{yr}^{-1}$) that are much higher than seen in the ultraviolet-selected samples and that are sufficient to form substantial stellar populations on dynamical timescales of $10^{9}$ yr. The association with mergerlike morphologies and the obvious presence of dust makes it attractive to identify these systems as forming the metal-rich spheroid population, in which case we would infer that much of this activity has occurred relatively recently, at $z \sim 2$.

Subject headings: galaxies: distances and redshifts — galaxies: photometry — galaxies: stellar content — submillimeter — surveys

1. INTRODUCTION

The last few years have seen great progress in obtaining a first outline of the evolution of galaxies over a remarkably wide range of cosmic time, corresponding to redshifts $0 < z < 5$. This progress is epitomized by the plot of ultraviolet luminosity density of the universe, $L_{UV}(z)$ (Lilly et al. 1996; Madau et al. 1996; Madau, Pozzetti, & Dickinson 1998; Connolly et al. 1997), which suggests that $L_{UV}(z)$ rises quite rapidly with redshift to a peak in the range $1 < z < 2.5$, declining in a not yet well determined way to higher redshifts. At the higher redshifts, there are still significant uncertainties in the form of $L_{UV}(z)$ associated with the photometry and the application of the “UV-dropout” selection criteria (see, e.g., Sawicki, Lin, & Yee 1997). In translating the ultraviolet luminosity density $L_{UV}(z)$ into a star formation rate (e.g., Madau et al. 1996), there are additional uncertainties regarding the effects of dust obscuration and the initial mass function.

Despite this definite progress, the relationship between the stars produced at different epochs and the present-day morphological components of the galaxy population remains unclear. The evolution to $z \sim 0.8$ appears to be primarily due to relatively small galaxies with irregular morphology and to the disk components of galaxies (see, e.g., the morphological analyses of Brinchmann et al. 1998 and Lilly et al. 1998b; see also Guzman et al. 1998 and references therein). The nature of the galaxies seen at $z > 3$ (Steidel et al. 1996) is still quite controversial (see, e.g., Dickinson 1998; Trager et al. 1997 and references therein), and very little is really known about the nature of galaxies in the crucial intermediate redshift range $1.5 < z < 3$. A major
unsolved problem concerns the origin of the stars seen in the metal-rich spheroid components of galaxies, which today includes one-half to two-thirds of all stars (see Fukugita et al. 1998). There are inconclusive observational arguments both in favor of rapid and homogeneous spheroid formation at very high redshifts (e.g., Ellis et al. 1997) and in favor of a formation through mergers spread over a broad range of epochs (e.g., Kauffmann, Charlot, & White 1996). These alternatives are often viewed as mutually incompatible, although the formation of the bulk of metal-rich spheroid stars in highly dissipational mergers of gas-rich systems at high redshifts would combine the attractive features of both scenarios. A problem, however, with this scenario has been the lack of detection of a substantial population of luminous star-forming high-redshift galaxies with the high star formation rates (several times $10^2$–$10^3 M_\odot$ yr$^{-1}$) that would be required to produce major spheroidal components of galaxies on typical dynamical timescales ($10^8$ yr).

Until very recently, our view of the evolution of typical galaxies at high redshifts has come almost exclusively from studies of starlight in the optical and near-infrared wavebands. Very little has been known about that component of stellar energy that is absorbed by dust and emerges in the far-infrared waveband in the form of thermally reradiated emission from dust. Studies of optically selected galaxies at high redshift (see, e.g., Sawicki et al. 1997; Meurer et al. 1997; Pettini et al. 1998; Dickinson 1998) suggest that dust obscuration is important.

Studies of the local universe indicate that between 30% and 40% of all stellar luminosity emerges as thermally reradiated dust emission (see, e.g., Dwek et al. 1998 and references therein). Furthermore, the recently detected far-IR/submillimeter background seen in the COBE data (Puget et al. 1996; Hauser et al. 1998; Fixsen et al. 1998; Schlegel, Finkbeiner, & Davis 1998) has a $\nu l$ energy content that is as large or larger than the optical/near-IR background that is obtained by integrating the galaxy number counts (see, e.g., Pozzetti et al. 1998; Dwek et al. 1998). This indicates that dust continues to play a major role at high redshifts and that one-half or more of the energy from stellar nucleosynthesis at cosmological redshifts emerges in the far-IR (FIR) [it should be noted that any differences in the redshifts at which these background are produced will change their relative energy content only as $(1 + z)$. In terms of the light from young stars, the balance may be tipped even further in favor of the FIR because a significant fraction of the optical background will be coming from old stars (note that the energy of the background is 3 times higher at $K$ than at $U$; see Pozzetti et al. 1998).

Understanding the nature and redshifts of the sources responsible for the FIR/submillimeter background is therefore vital for an understanding of galaxy evolution. Key questions are (1) whether the redshift dependence of this obscured star formation component follows that of the unobscured component studied hitherto and (2) whether the individual objects emitting in both wavebands are similar, i.e., whether the effects of dust obscuration are uniform across the star-forming population at high redshift.

Several groups (e.g., Smail, Ivison, & Blain 1997; Smail et al. 1998; Hughes et al. 1998; Barger et al. 1998; and ourselves) are pursuing deep surveys in the submillimeter waveband at 450 and 850 mm with the new Submillimetre Common-User Bolometer Array (SCUBA) (Holland et al. 1998; Gear et al. in preparation) on the 15 m James Clerk Maxwell Telescope (JCMT) located on Mauna Kea. The spectral energy distributions of galaxies in the submillimeter waveband rise sharply with frequency up to a peak in the 70–120 $\mu$m range, leading to extremely beneficial $k$-corrections at 850 $\mu$m, a situation quite unlike that seen at all wavelengths $\lambda < 100$ $\mu$m. In consequence, a typical starburst galaxy (with an effective dust temperature of around 30 K and effective emissivity proportional to $\nu^{1.5}$) has a roughly constant observed flux density at 850 $\mu$m over the entire $0.5 < z < 6$ redshift range, especially if $\Omega = 1$ (see Fig. 4) below. Observations at 850 $\mu$m are thus very sensitive to star formation at very high redshifts.

It has recently become clear (Smail, Ivison, & Blain 1997; Hughes et al. 1998; Barger et al. 1998; Eales et al. 1998, hereafter Paper I) that a significant fraction (20%–30%) of the FIR background at 850 $\mu$m can be resolved into relatively bright sources with $S_{850} \geq 3$ mJy. The surface number density of such sources is almost 2 orders of magnitude higher than expected in simple “no-evolution” models for the submillimeter sky (Smail et al. 1997; Paper I). As pointed out by several authors, these sources must have very high FIR luminosities, around $3 \times 10^{12} h_{70}^2 L_{\odot}$, as long as their redshifts lie in the 0.5 $< z < 6$ range where the flux density–redshift relation is flat. This is 50% higher than even the very luminous local source Arp 220. Many of these sources undoubtedly lie at high redshifts (Hughes et al. 1998; Barger et al. 1998; Ivison et al. 1998) although the actual redshift distribution is still far from clear on account of the very small samples studied to date, ambiguities in the identifications (see Richards 1998), and difficulties in measuring redshifts (e.g., Barger et al. 1998). The sources at high redshift are likely responsible for a significant fraction of the integrated extragalactic background and therefore must presumably represent a corresponding fraction of all the stellar luminosity that has ever been emitted in the history of the universe (assuming that stellar nucleosynthetic energy dominates over that released by accretion onto massive black holes). The high individual luminosities (and high implied star formation rates), coupled with the high total output of stars from the population, makes it attractive to identify these sources as producing many of the stars seen in the present-day metal-rich spheroid components of galaxies.

A difficult question concerns the fraction of this energy that comes from hidden active galactic nuclei (AGNs). In the local universe, the evidence (see, e.g., Genzel et al. 1998) is that AGNs provide a significant but not dominant contribution. The observational situation on the high-redshift ultraluminous infrared galaxies (ULIRGs) is open (see Ivison et al. 1998; Frayer et al. 1998). Ascribing a substantial fraction of the energy output of this population to AGNs would require a major upward revision in the total energy output of AGNs (but see Haehnelt, Natarajan, & Rees 1998).

In this paper we report and analyze the identifications of the first 12 submillimeter sources (Paper I) that have been detected in the Canada–United Kingdom Deep Submillimeter Survey. This survey at present covers 24.5 arcmin$^2$ of the sky to a 3 $\sigma$ depth of about 3 mJy at 850 $\mu$m. It is intended to eventually cover at least 120 arcmin$^2$ to this depth. It should be noted that this survey is therefore wider than, but only half as deep as, the Hubble Deep Field (HDF) study reported by Hughes et al. (1998).
We take $H_0 = 50 \, h_0 \, \text{km} \, \text{s}^{-1} \, \text{Mpc}^{-1}$ and assume $\Omega_0 = 1$ unless otherwise noted. We find that almost all the galaxies have spectral energy distributions that are similar to that of Arp 220. Accordingly, we define the bolometric luminosity $L_{\text{bol}}$ as the luminosity integrated over this spectral energy distribution from ultraviolet to radio wavelengths, normalized to the measured brightness at 850 $\mu$m. For comparisons with the extensive literature on IRAS sources, it should be noted that this is 1.5 times larger than the $\nu L_\nu$ luminosity of Arp 220 evaluated at 60 $\mu$m. It should be noted in passing that the ratio between FIR ($3 \, \mu m < \lambda < 1 \, \text{mm}$) and visible ($3000 \, \AA < \lambda < 3 \, \mu m$) luminosities in Arp 220 is $L_{\text{FIR}}/L_{\text{opt}} = 33$, so the contribution from the optical is very small. Nevertheless, even in the FIR the bolometric luminosity of sources detected in the submillimeter is still uncertain because of the poorly defined temperatures and effective emissivities. Correspondingly, there could be systematic uncertainties in $L_{\text{bol}}$ of a factor of 2–3 at $z \sim 1$.

2. IDENTIFICATIONS OF SUBMILLIMETER SOURCES

The 12 submillimeter sources in Paper I are the first to be detected in a UK-Canadian submillimeter survey of fields from the Canada-France Redshift Survey (CFRS) (Lilly et al. 1995a; Le Fèvre et al. 1995 and references therein). The submillimeter survey is carried out with the SCUBA (Holland et al. 1998) on the UK-Canada-Netherlands 15 m JCMT on Mauna Kea. The details of the submillimeter observations and analysis of the number counts are given in Paper I. As noted there, Monte Carlo simulations and other analyses of the submillimeter data indicate that of order 1 of the 12 sources may be spurious.

The CFRS fields were chosen not only because of the extensive redshift data available for galaxies with $I_{AB} < 22.5$, spanning the redshift interval $0 < z < 1.3$, but also because these fields have a wealth of deep imaging data from the Canada-France-Hawaii Telescope (CFHT) and the Hubble Space Telescope (HST), deep $J$ and $15 \, \mu m$ maps taken with the Infrared Space Observatory (ISO) (Flores et al. 1998a, 1998b) and deep radio images from the Very Large Array (VLA\footnotemark) (Fomalont et al. 1991; Hammer et al. 1995b). Furthermore, portions of some of the fields have also been studied by others as part of the Hawaii and Steidel et al. deep survey programs. While the observations at all wavelengths are not as deep as in the Hubble Deep Field, the fields are much larger, allowing us to study a relatively large contiguous area of sky. Our new submillimeter survey is a “field survey” and is not targeted at known objects. It will ultimately cover a good fraction of the 200 arcmin$^2$ of the CFRS 0300+00 (Hammer et al. 1995a) and CFRS 1417+52 fields (Lilly et al. 1995b).

2.1. Optical and Radio Imaging Data

Deep optical images of these fields were searched for identifications of the submillimeter sources. These images included the original $V$, $I$, and $K$ images of the CFRS (Lilly et al. 1995a), supplemented by further deep images of these fields that have been obtained as part of the Canada-France Deep Fields program (CFDF, publications in preparation) using data obtained with the UH8k mosaic camera at CFHT (in $V$ and $I$) and the PF camera at the Kitt Peak National Observatory Mayall 4 m (in $U$). For many of the sources, HST images are available from our earlier studies of these fields or from the “Groth strip” which bisects the 1417+52 field. These optical images are much less deep than the HDF, although this is not necessarily a problem. The high surface density of faint galaxies that lie below our own limit (i.e., at $I_{AB} > 25$) results in many such galaxies lying within the search radius, making it hard to know which, if any, is the correct identification. Our own study ducks this question by simply classifying these sources as “empty fields.”

For the eight submillimeter sources in the 1417+52 field, searches were also made for identifications with radio sources in the Fomalont et al. (1991) deep VLA survey and Flores et al. (1998a, 1998b) deep ISO images of these fields at 7 and 15 $\mu$m.

2.2. Identification Probabilities

Even with a 15 m telescope, the beam size (FWHM) at 850 $\mu$m is 15" and at 450 $\mu$m (for those sources detected at all) it is 8". Thus, until more accurate positions are available from interferometers, identifications of the submillimeter sources at other wavelengths must be based on probabilistic arguments. Our own approach is to do this strictly on the basis of positional coincidence (see, e.g., Browne & Cohen 1978; Downes et al. 1986), allowing us to subsequently examine the properties of the proposed identifications (such as their multielectrode colors) in a way that is independent of the identification procedure.

The identification of the optical galaxies responsible for the submillimeter emission through probabilistic arguments involves a number of subleties. The probability that the nearest member of a population of objects with surface density $n$ is located within a distance $d$ from a random position on the sky is given by $P = 1 - \exp(-\pi n d^2)$.

\begin{equation}
\int_0^d \frac{d}{\pi d^2} = 1
\end{equation}

The $P$-statistic has frequently been used for identifying sources (e.g., Downes et al. 1986). The quantity $P$ tells us the fraction of sources in a sample of size $N$ that would be expected to have an incorrect candidate identification lying within this distance $d$, i.e., $N_{\text{spurious}}(P) = NP$. This $P$-statistic represents a starting point but is not what is really required, which is rather the probability that a particular claimed identification is in fact correct.

For the radio (and ISO) catalogs, $P$ may be simply computed from the number density $n$ of all sources in the catalog, irrespective of their radio (or mid-IR) brightness, since $n$ is sufficiently low that any source within the 5" search radius has a low $P$. On deep optical images, however, the number density of sources is high enough that a 5" search radius may contain a significant number of random galaxies (at $I_{AB} < 25$ the average density is about 0.8 sources per error circle, and at the HDF limit of $I_{AB} > 29$, it is about 10 times larger). Thus, it is advantageous to compute the number density $n'$ of galaxies brighter than the magnitude of the galaxy, i.e., $n' = n(m < m_0)$, decreasing the values of $P$ for the brighter galaxies (since $n$ is much reduced from that of the optical catalog as a whole). However, it should be noted that this procedure introduces a bias toward underestimating the probability of unrelated sources because many almost independent galaxy samples are being searched simultaneously (i.e., the galaxies brighter than 17th magnitude, those brighter than 18th, those brighter than 19th, and so on) so it becomes more likely that one of these samples turns up a low-$P$ positional coin-

\footnotetext{9}{The VLA is a telescope of the National Radio Astronomy Observatory, which is operated by Associated Universities, Inc., under a cooperative agreement with the National Science Foundation.}
cidence. The true fraction of randomly located sources with candidate identifications lying within \( d \) is \( P = \alpha P \). The correction term \( \alpha \) is a function of \( P \), the search cutoff radius, and the magnitude range over which identifications are sought. \( P \) has been determined using Monte Carlo simulations that matched our operational procedure. It should be noted that the correction term \( \alpha \) can be quite large. In our simulations, it is 6.5 for all \( P \lesssim 0.01 \), decreasing to higher \( P \) (\( \alpha \sim 3.5 \) at \( P \sim 0.1 \)). It should be noted that in almost all cases, there is either only one object visible within the search radius of 5" or one object has a \( P \)-value that is so much smaller than the others that it is much more likely to be the identification.

It should be noted that we have computed the separations \( d \) as the distance between the centers of the submillimeter and optical/radio sources and have not considered the size of the optical galaxy. This makes some astrophysical sense in that the energy sources for the submillimeter sources, whether starburst or AGN, are likely to be located at the centers of the galaxies. This procedure also has the merit of being well defined and of avoiding ambiguities in defining the size of the optical galaxies. It is possible in principle, but extremely unlikely in practice, that we have missed off-centered sources in nearby large galaxies.

However, as noted above, the real statistical question that we wish to answer is “what is the probability that a particular identification of some individual source, with some value of \( P \) (or \( P' \)), is actually the correct identification?” As noted above, a sample of \( N \) sources should contain approximately \( NP \) spurious identifications. Thus, a low value of \( P \) for any individual source is not, on its own, enough to make an identification secure. Rather, and perhaps counterintuitively, one has to look at the sample as a whole and determine the number of identifications in the sample (with that value of \( P \)) relative to the number of spurious identifications (with that same \( P \)) that would have been expected if the submillimeter and optical populations were completely unrelated. Only if this ratio is high, i.e., if there are many sources with this value of \( P \) compared with the number expected by chance, can a particular individual source be regarded as securely identified.

This is illustrated in Figure 1, where we show the distribution of (optically determined) \( P \)-values for the identifications in the present program compared with the distribution of \( P \)-values found in the Monte Carlo simulations. This shows that the three identifications with \( P < 0.001 \) are very secure. The three identifications with \( P \leq 0.05 \) are quite secure (especially as one has a \( P < 10^{-3} \) from the radio), although even at this level, one of the identifications could be spurious. The two remaining identifications, with \( P \sim 0.01 \), while possibly correct, could in fact be chance associations. It should be noted that, apart from the radio sources, it is the brighter optical galaxies at lower redshift (see below) that are the most securely identified. The remaining four submillimeter sources have either no candidate identification visible within the error circle or only a faint candidate with high \( P' \), i.e., \( P' \geq 0.5 \). These are regarded as empty fields.

The optical and radio positions for all eight identifications are shown in Table 1, together with the associated values of \( P \) and \( P' \) (submillimeter positions are given in Paper I). At 850 \( \mu \)m, the identifications are generally located within \( 1'' < d < 3'' \), even for the most securely identified sources (e.g., the radio sources). We regard this as acceptable given the size of the 850 \( \mu \)m beam (FWHM = 15") and the low signal-to-noise ratio of the detections, the use of blind pointing on the JCMT, and possible mismatches between the astrometric grids, and it is similar to that found by Smail et al. (1998). We do not see evidence for any systematic offset between the optical/radio and JCMT astrometric systems (cf. Richards 1998). There is no trend of decreasing positional offset with increasing faintness of the optical candidate—a potential indicator of spurious identifications (Browne & Cohen 1978). Furthermore, it should be noted how in the four cases where the source was detected at 450 \( \mu \)m the positional discrepancy is reassuringly smaller at the shorter wavelength. Figure 2 shows a montage of \( HST \) images of seven of the eight identifications (the other one was not observed with \( HST \)).

Positional coincidence offers a simple, robust, and conservative approach to making identifications. Problems could obviously arise if the submillimeter sources were not in fact randomly located relative to physically unrelated galaxies—an obvious possibility being if they are gravitationally lensed by foreground galaxies (cf. the discussion by Hughes et al. 1998). Our procedure would tend to identify the bright foreground lens rather than the real background source. Clustering effects could also bias the results, although at least in this case the redshifts would be correctly estimated.
Fig. 2.—Montage of HST images of the seven (of eight) securely identified sources in our submillimeter survey. These are arranged in order of ascending redshift. Each image shows an area $10'' \times 10''$, except that for 03B (= CFRS 10.1411), a spiral galaxy at $z = 0.074$ which is $22'' \times 22''$. The small insets for the four smallest galaxies show the central $1 \times 1$ arcsec$^2$ area magnified by a factor of 3. All of the galaxies except CFRS 10.1411 show some evidence for disturbed morphologies, and in some cases there is clear evidence for mergerlike activity.
It should be noted that our estimates of \( P \) and \( P^\prime \) do not take into account other unusual characteristics (i.e., photometric, spectral, or morphological) that the correct identifications are likely to exhibit, which could in principle further reduce the effective density \( n \) and thus reduce \( P \) and \( P^\prime \).

Many of the galaxies claimed as identifications had already been cataloged in the CFRS program, and two already had spectroscopic redshift measurements. One bright galaxy was subsequently observed spectroscopically in 1998 June with the OSIS spectrograph on CFHT, yielding \( z = 0.074 \). For the remainder, we have estimated likely redshifts on the basis of their optical-infrared \( \text{AB} \) colors (see Fig. 3). Photometric data for the identifications are given in Table 2. The \( \text{VIK} \) colors span a large baseline in color and offer a relatively clean separation between galaxies at \( z < 1.5 \) and \( z > 1.5 \). For the latter sources, detection in \( U \) limits the redshift to \( z < 3 \). An additional advantage is that the effect of reddening is to move galaxies in the \((V-I)/(I-K)\) plane in a direction that is largely orthogonal to the direction produced by varying the redshift (see Fig. 3).

The following represents notes on individual sources, in order of decreasing reliability of the identification. Photometric data for the identifications are given in Table 2.

### 2.3. Identifications and Redshifts

#### 2.3.1. The Six Sources Considered Most Securely Identified

**CFRS 10B.**—This source is securely identified with CFRS 10.1141, a bright \( I_{160} \) = 17 spiral galaxy with a newly determined spectroscopic redshift of \( z = 0.074 \). The spectrum shows strong H\( \alpha \) with equivalent width \( \text{EW}_0 \approx 26 \, \text{Å} \). Our CFHT and \( HST \) images show a relatively normal looking face-on spiral galaxy. It should be noted that the FIR luminosity of this source is a factor of 10 smaller than that of the others in the sample, but is still substantial, \( L_{\text{boul}} \approx 2 \times 10^{11} \, h_{50}^{-2} L_{\odot} \).

**CFRS 14F.**—This source is the faintest submillimeter source in the sample but nevertheless one of the most securely identified. It is identified with CFRS 14.1139, an \( I_{160} = 20.5 \) galaxy with measured \( z = 0.660 \) (Lilly et al. 1995b). This galaxy is itself securely identified (Hammer et al. 1995a) with a 79 \( \mu \)Jy radio source (Fomalont et al. 1991) and is also detected at 7 and 15 \( \mu \)m by \( I\text{SO} \) (Flores et al. 1998a, 1998b). The \( HST \) images show a dramatic and chaotic morphology indicative of a major merger event. The spectrum shows moderately strong \([ \text{O II} \] \( \lambda 3727 \) in emission (\( \text{EW}_0 = 13 \, \text{Å} \)) and the Balmer lines (\( \text{H}\delta \) and \( \text{He} \)) in absorp-

### Table 1

**Source Identifications**

| Submillimeter Source | CFRS | FWKK | R.A. (2000) | \( \delta \) (2000) | \( 850/450 \) | \( P \) | \( P^\prime \) |
|---------------------|------|------|------------|----------------|----------------|------|------|
| 10B                 | 10.1411 | ... | 10 00 37.21 | +24 14 59.7 | 2.8/1.8 | <10^-4 | <10^-3 |
| 14F                 | 14.1139 | 15V.24 | 14 17 42.04 | +52 30 25.7 | 2.0/0.6 | <10^-3 | 0.002 |
| 14A                 | ... | 15V.18 | 14 17 40.21 | +52 29 06.5 | 1.7/... | 0.05 | 0.18 |
| 10A                 | 10.1153 | ... | 10 00 38.27 | +25 14 50.4 | 1.2/0.8 | <10^-3 | 0.007 |
| 03A                 | 03.1054 | ... | 03 02 36.35 | +00 08 14.1 | 2.8/2.0 | 0.04 | 0.14 |
| 10D                 | 10.1167 | ... | 10 00 36.86 | +25 14 44.0 | 2.8/... | 0.04 | 0.15 |
| 14C                 | ... | ... | 14 17 33.81 | +52 30 49.9 | 2.1/... | 0.07 | 0.22 |
| 14B                 | ... | ... | 14 17 51.92 | +52 30 27.5 | 1.9/... | 0.14 | 0.32 |

*Note:* Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

| As cataloged in Paper I.
| CFRS catalog number if cataloged.
| Positional offset from nominal submillimeter position (second figure for 450 \( \mu \)m where available).
| Corrected probability that identification is not associated with submillimeter source.

### Table 2

**Photometry of Identifications**

| Submillimeter Source | CFRS | \( z^c \) | \( U_{160} \) | \( V \) | \( I_{160} \) | \( K_{160} \) | \( S^c_{\text{850/450}} \) | \( S_{\gamma \text{pm}} \) | \( S_{\lambda \text{pm}} \) |
|---------------------|------|--------|------------|------|------|------|----------------|-----------|-----------|
| 10B                 | 10.1411 | 0.074 | 18.2 ± 0.1 | 17.3 ± 0.1 | 16.4 ± 0.1 | ... | ... | ... | ... |
| 14F                 | 14.1139 | 0.660 | 22.7 ± 0.1 | 21.6 ± 0.1 | 20.3 ± 0.1 | 18.6 ± 0.1 | 79 ± 6 | 115 ± 34 | 562 ± 50 |
| 14A                 | (2.0) | 26.5 ± 0.5 | 25.5 ± 0.8 | 24.1 ± 0.3 | 20.8 ± 0.1 | 44 ± 4 | 150 | 200 |
| 10A                 | 10.1153 | 0.550 | 23.3 ± 0.1 | 21.2 ± 0.1 | 18.9 ± 0.1 | 18.9 ± 0.1 | 56 ± 15 | 90 ± 45 | 150 ± 100 |
| 03A                 | 03.1054 | (1.5) | 25.8 ± 0.4 | 24.5 ± 0.4 | 23.4 ± 0.2 | 21.1 ± 0.1 | 16 | 150 | 200 |
| 10D                 | 10.1167 | (0.8) | 24.1 ± 0.3 | 22.6 ± 0.1 | 20.5 ± 0.2 | 20.5 ± 0.2 | 16 | 150 | 200 |
| 14C                 | (2.5) | 25.7 ± 0.3 | 24.8 ± 0.3 | 23.8 ± 0.2 | 21.1 ± 0.1 | 16 | 150 | 200 |
| 14B                 | (2.5) | 27.6 ± 0.8 | 26.0 ± 0.5 | 25.2 ± 0.4 | 22 (2 \sigma) | 16 | 150 | 200 |

*As cataloged in Paper I and Table 1.

b CFRS catalog number if cataloged.

c Redshift. In parentheses are crude photometric estimated from \( \text{VIK} \) photometry.

d From Fomalont et al. 1991 and Hammer et al. 1995b.

e From Flores et al. 1998a.

f From Flores et al. 1998b.
The optical-infrared colors are of a relatively unobscured late-type galaxy, and the large FIR luminosity doubtless comes from a highly embedded region.

**CFRS 14A.**—This is the brightest submillimeter source in the sample. It is 2′ from the 44 µJy radio source FWKK V15 18, which is itself identified (Hammer et al. 1995a) with a faint galaxy. This galaxy is thus a secure identification despite the faintness of the optical galaxy. As noted by Hammer et al., the galaxy is very red, and the source was identified by them only in the K band at $K_{AB} \sim 19$. The galaxy is detected on our F814W HST images and can also be made out on our ground-based V-band and I-band images (especially once the new CFDF data are added). The galaxy has $I_{AB} \sim 24$. The VIK colors suggest a redshift $z \sim 2$. There is a 2 σ photometric detection at $U$, requiring $z < 3$. The HST morphology is rather distinct, being quite compact, but even so, it is not completely symmetrical.

**CFRS 10A.**—This source is identified with CFRS 10.1153, an $I_{AB} = 21.5$ galaxy with previously measured $z = 0.550$ (Le Fèvre et al. 1995b). The optical spectrum shows only absorption features (but does not extend as far as Hα), but the VIK colors indicate a color excess of 0.5 mag in $I - K$ relative to an early-type galaxy at this redshift. The HST morphology is unspectacular (it was classified by Brinchmann et al. 1998 as a midspiral) but the galaxy has a strong barlike feature with a prominent secondary maximum at one end. There is also some evidence for irregular outer isophotes, so it is possible that this is some kind of merger, perhaps viewed from an unfavorable angle.

**CFRS 03A.**—This source is likely associated with the $I_{AB} \sim 23.4$ galaxy cataloged as CFRS 03.1055. The positional discrepancy (2′′8 and 2′0 at 850 and 450 µm, respectively) is acceptable, and only the faintness of the galaxy increases $P$ to 0.14. The F814W HST image shows a flattened system (possibly an edge-on disk) with multiple components in the center. There is again evidence for some asymmetry in the outer isophotes. There is at present no K photometry, or optical spectroscopy, on this object, but the UVI colors suggest that this galaxy has the colors of a midspiral at $z \sim 1.5$. It must be at $z < 3$ on the basis of a good detection at U.

**CFRS 10D.**—This source is almost certainly identified with CFRS 10.1167, an $I_{AB} = 22.6$ galaxy. Although $P \sim 0.15$ (the separation from the 850 µm position is 2′7 and there is no 450 µm position), the F814W HST morphology is very unusual with two high surface brightness components separated by 0′9 with surrounding asymmetric nebulosity that is suggestive of tidal features. The morphology is highly indicative of some form of merger or strong interaction, and this substantially increases our confidence in the reality of this identification. The redshift is estimated from the $VIK$ colors as $z \sim 0.8$, almost irrespective of the degree of reddening.

### 2.3.2. The Two Less Secure Identifications

Two sources have candidate identifications with faint galaxies. The values of $P$ for these galaxies suggest that there is a significant chance that these are not individually associated with the submillimeter sources.

**CFRS 14C.**—This source is plausibly identified ($P \sim 0.22$) with a faint galaxy with $I_{AB} \sim 24$ located 2′ away from the nominal 850 µm position. The $VIK$ colors lie in the area of $z = 2$–3 galaxies almost irrespective of reddening. The good detection in the $U$ band at $U_{AB} \sim 25.8$ constrains the redshift of this galaxy to be $z < 3$. There is no HST image available and the morphology on the CFHT images is unremarkable.

**CFRS 14B.**—This source is 2′ away from a faint galaxy with $I_{AB} \sim 25$ ($P = 0.32$). The HST morphology of this faint galaxy is compact but distinctly asymmetric. The colors are similar to the possible identification of CFRS 14C, albeit a magnitude fainter, leading to a slightly estimated redshift. The $U$-band photometric detection is more marginal (about 1.5 σ), so the $z < 3$ constraint is correspondingly slightly weaker and the redshift less certain.

### 2.3.3. The Empty Fields

The remaining four sources, CFRS 10C, CFRS 14D, CFRS 14E, CFRS 14G, are empty to the reliable limits of our ground-based images, i.e., $I_{AB} > 25$, and in any case the density of sources at such optical levels is rising sufficiently that the reliability of such identifications would be highly questionable. We therefore regard these four sources as empty fields. Nature conspires to make very high redshift sources least detectable in the visible, ISO and radio bands, and at 450 µm, and so these faintest optical sources would not be expected to be detectable at these other wavelengths, and indeed are not. With no supporting detections at other wavelengths, it is always possible that one or more of these sources is spurious (see the discussion in Paper I), but most of them are probably real.

### 2.4. Discussion: Properties of the Identifications and Empty Fields

Having made the identifications on the basis of positional coincidence alone and estimated the redshifts of the galaxies...
from spectroscopic observations or from photometric colors, we can now examine the properties of the spectral energy distributions (SEDs) of the galaxies as defined by the flux density ratios between the visible, midinfrared (15 μm), submillimeter (450 and 850 μm), and radio (5 GHz) wavebands. Because of the large uncertainties in the redshifts of many of the galaxies, the SEDs are studied by means of color-redshift relations (comparing the galaxies to a series of standard SEDs) rather than by attempting to construct rest frame SEDs. We have computed “colors,” defined as \( \log \left( \frac{S_1}{S_2} \right) \), between 850 μm and the observed \( I \) band, 15 μm, 450 μm, and 5 GHz wavebands for the six SEDs given by Schmitt et al. (1997), using modeled interpolations between the points given in that work. In particular, the submillimeter SEDs at \( \lambda > 100 \) μm are constructed using a 30 K radiation component with an effective emissivity \( \epsilon \propto \nu^{1.5} \). We have also constructed a final template SED representing Arp 220 interpolating between the photometric measurements given by Rowan-Robinson & Efstathiou (1993) and references therein. These SEDs exhibit a wide range of the ratio between FIR and visible luminosities.

### 2.4.1. The Submillimeter Luminosities of the Galaxies

As expected from the flat flux-density redshift relation, the 850 μm flux densities do not correlate with the estimated or measured redshifts. This is shown in Figure 4, which also shows the expected track of Arp 220 (with no evolution) under two different cosmologies. The lack of correlation suggests that the redshift distribution of our sample is unlikely to be affected by any incompleteness in detecting sources above the nominal flux density limit (see Paper I) since any missing sources are unlikely to be biased toward any particular redshifts.

Figure 4 makes the point (see also Barger et al. 1998) that any submillimeter source that is detected at the \( S_{850} > 3 \ \text{mJy} \) level at \( z > 1 \) is likely to have a bolometric luminosity that is significantly larger than that of Arp 220 (\( z = 0.018 \)), widely regarded as the archetypal ULIRG in the local universe.

#### 2.4.2. The Optical Luminosities of the Galaxies

In contrast, the \( I_{AB} \) magnitudes of the identifications do correlate well with the estimated and measured redshifts (see Fig. 5). This suggests that the identified galaxies are generally luminous optical galaxies with roughly \( L^* \) or greater optical luminosities. As seen in Figure 2, many of the galaxies have highly disturbed or multiple morphologies. These are both characteristics of ULIRGs at low redshifts (see Sanders & Mirabel 1996 and references therein). The empty-field sources are consistent with either being similar galaxies at very high redshifts \( z > 3 \), or less luminous systems at lower redshifts.

#### 2.4.3. The 0.8–850 μm Colors

For all sources we have measurements or limits to the \( I \)-band magnitudes. The 0.8–850 μm colors, defined as \( \log \left( \frac{S_{0.8}}{S_{850}} \right) \), are shown in Figure 6. These track well the colors expected for Arp 220 (and for the highly obscured SBH starburst SED from Schmitt et al. 1997).

The limits to the empty-field sources are consistent with these being similar objects at any \( z > 2 \), and they could be at even lower redshifts if they were more heavily obscured and consequently had higher \( L_{\text{FIR}}/L_{\text{opt}} \).

#### 2.4.4. The 450–850 μm Colors

The 450 and 850 μm bolometer arrays on SCUBA operate simultaneously, and so measurements or limits to

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**Figure 4.** Flux density at 850 μm plotted against measured or estimated redshift. Solid squares are three securely identified sources with spectroscopically determined redshifts; open squares are three securely identified sources with photometrically estimated redshifts; open circles are two probable identifications with estimated redshifts; and the four stars are the four empty fields arbitrarily assigned redshifts \( z \sim 4 \) for display purposes. The lines show the flux density that Arp 220 \( (z = 0.018) \) would have as a function of redshift for \( \Omega_0 = 1 \) (solid line) and \( \Omega_0 = 0.2 \) (dotted line). All of the detected sources except the one at \( z < 0.1 \) have luminosities comparable to or larger than that of Arp 220. There is no correlation between \( S_{850} \) and redshift, as expected given the flat flux density-redshift relation at \( z > 0.5 \).

**Figure 5.** \( I \)-band magnitudes vs. redshift (measured or estimated) for the eight identified sources and limits to the empty-field sources (plotted at arbitrary redshift \( z \sim 4 \)), compared with an unevolving Sbc galaxy from Coleman et al. (1980) with present-day \( L^* \) luminosity. Symbols as in Fig. 4. The identified galaxies are generally luminous \( L^* \) galaxies at visible wavelengths.
the 450 µm flux density are available for all sources except one (CFRS 14G is near the edge of the field, and the 450 µm camera has a slightly smaller field of view). The 450–850 color is often regarded as a good redshift indicator and, in contrast to the HDF sample of Hughes et al. (1998), four of our 12 sources are detected at 450 µm. Gratifyingly, these are four of the five sources with the lowest measured or estimated redshifts. The measurements and limits track well the predicted 450–850 “colors,” as defined above, for the standard template SEDs (Fig. 7), assuming that the estimated redshifts are roughly right. Lowering the effective emissivity to $\epsilon \propto \nu^l$ (see, e.g., Dunne et al., in preparation) would make all of the sources consistent. It can be seen that, with this quality of data, the three empty-field sources with 450 µm upper limits are consistent with lying at almost any redshift.

2.4.5. The 15–850 µm Colors

The 15–850 µm colors were extensively used by Hughes et al. (1998) in their analysis of the HDF. The $S_{15}/S_{850}$ ratio drops strongly with redshift since the bands lie on either side of the thermal peak at $\lambda \sim 100$ µm. Unfortunately, deep 15 µm data are only available at the moment for the seven sources in the 1417+52 field, only one of which was detected. The one submillimeter source detected by ISO at 15 µm is at low redshift ($z = 0.66$), and the limits to the colors of the remaining submillimeter sources are again consistent with the Arp 220 and SBH SEDs at their estimated or measured redshifts (Fig. 8). The empty-field sources have limits to the colors that are consistent with these SEDs at any $z > 1.5$.

We can also look at the properties of the 15 µm sources that were detected by ISO but which were not detected in the submillimeter survey. There are five such sources, all with measured or estimated redshifts in the 0.7 < $z$ < 1.1 range (Flores et al. 1998b). The lower limits to the $S_{15}/S_{850}$ flux density ratio for these sources are consistent with having the same SEDs at these lower redshifts (Fig. 8). They
are probably not detected at 850 μm simply because they have slightly lower luminosities.

2.4.6. The 850–Radio Colors

In the CFRS 1417+52 field, we have measurements or limits to the flux densities at 5 GHz (Fomalont et al. 1991; Hammer et al. 1995b). Figure 9 shows the 850 μm to 5 GHz colors of the 7 μJy level radio sources that were detected by SCUBA. The colors of the detected sources track very well the Arp 220 SED, and the lower limits for the remaining five are not too discrepant.

Interestingly, the two radio sources detected by SCUBA have the steepest radio spectra (consistent with star formation) whereas the remaining four radio sources in our surveyed area that were not detected in the submillimeter have flat or inverted radio spectra (more indicative of AGNs).

2.5. Summary: The Nature of the Sources and Their Redshift Distribution

From the above discussion the following can be concluded:

1. The eight identified galaxies are optically luminous galaxies (comparable to present-day \(L^*\)) spanning a broad range of redshifts 0.08 < z < 3 as measured or estimated from their optical colors.

2. For all the identified sources, the broad SED as defined from the optical through to the radio (from measurements or limits at 0.8, 15, 450, and 850 μm and at 5 GHz) is consistent with the measured/estimated redshift and a rest frame SED that matches that of Arp 220 or the heavily obscured starburst SED from Schmitt et al. (1997). This SED has a luminosity ratio of approximately 35 between the FIR and the optical.

3. With the present limited data, the observed properties of the currently unidentified empty-field sources would be broadly consistent with those of the identified galaxies if placed anywhere over a wide range of redshifts, 2 < z < 10. Redshifts as low as z ~ 1 are not excluded by the present data but would require an even higher \(L_{\text{FIR}}/L_{\text{opt}}\).
4. The redshift distribution of the submillimeter sources is thus broad, extending from very low \( z \) to redshifts that are likely to reach \( z \sim 3 \) or greater. However, at least three (and probably four) of the 12 sources have \( z < 1 \) (and these are among the most securely identified sources in the sample). Based on the \( U \)-band detections of the faintest identified sources, it is quite likely that no more than four of the 12 sources have \( z > 3 \). The median redshift of the sample as a whole is thus unlikely to be much larger than \( z \sim 2.5 \). The implied redshift distribution is shown in Figure 10a and compared with the smaller HDF sample of Hughes et al. (1998). In broad terms they appear consistent (but see also Richards 1998). The larger lensed sample of Smail et al. (1998) does not have redshift estimates (except for constraints based on detection in \( B \) or \( V \)) but appears to have a similar distribution in \( I_{AB} \) magnitude (Fig. 10b).

3. HIGH-LUMINOSITY SOURCES AT HIGH REDSHIFTS: THE HIDDEN PHASES OF GALAXY EVOLUTION AND THE RELATION TO THE OPTICAL PICTURE

It has been clear since the initial results of Smail et al. (1997; see also Paper I) that the submillimeter source counts require evolution in the FIR population. Clearly a key question is to what extent the implied redshift evolution in the submillimeter population is similar to, or different from, that inferred from optical studies (Lilly et al. 1996; Maddalena et al. 1996, 1998). As noted in Paper I, the submillimeter source number counts can in fact be successfully matched by a local 850 \( \mu \)m luminosity function undergoing luminosity evolution such that the luminosity density has the same redshift dependence as in the optical (Maddalena et al. 1996). Furthermore, this model also reproduces (Paper I) the spectral shape of the FIRAS background if the effective emissivity of the population is relatively flat, i.e., near \( \nu^1 \).

3.1. The Redshift Distribution—Similarities with the Optical Picture

In this section we examine the implications of the direct redshift information obtained from the optical identifications reported above. The most obvious discrepancy between recently published IRAS-based models (Blain et al. 1998) and the present data is the relatively large fraction of sources found in the present study at \( z < 1 \). As noted above, there are at least two and probably three sources in our sample at \( 0.5 < z < 1.0 \), as well as a single less luminous galaxy at \( z = 0.076 \). It should be noted that two of the three \( 0.5 < z < 1.0 \) sources are very secure identifications with supporting evidence (in the shape of highly disturbed or multiple morphologies and/or radio and ISO detections) that they are indeed the associated with the submillimeter sources. None of the models considered by Blain et al. (1998) appear to have more than about 1% of the sources at these flux densities at \( z < 1 \). It should be appreciated, however, that models for the 850 \( \mu \)m sky are still quite uncertain, being generally based (e.g., Blair & Longair 1993; Eales & Edmunds 1997; Blair et al. 1998) on extrapolations from the IRAS 60 \( \mu \)m population. This represents a factor of 13 in wavelength straddling the thermal peak at \( \lambda \sim 100 \) \( \mu \)m, and this extrapolation is therefore highly sensitive to assumptions about the temperature and effective emissivity of the dust. In the near future, SCUBA observations of nearby optically selected and IRAS-selected galaxies (e.g., Dunne et al. in preparation) will lead to a big improvement in the models.

3.1.1. Constraints on the Cumulative Bolometric Luminosity Function

In order to look more directly at the implications of the redshift distribution inferred for our sample, we have constructed the cumulative bolometric luminosity function (CBLF) for sources in our sample. The primary motivation is to compare samples selected at very different wavelengths, and it should be remembered that the bolometric luminosities are uncertain by a factor of at least 2. Given the limited redshift information and these considerable uncertainties in estimating the bolometric luminosities, \textit{this exercise is intended to be primarily illustrative.} The calculation is done for \( \Omega = 1 \), but the offset in other cosmologies largely parallels the local luminosity function, so the choice of \( \Omega \) is in the end largely immaterial given the other uncertainties. The CBLF for our sources has been computed in three redshift bins: (1) \( 0.5 < z < 1.0 \), (2) \( 1.0 < z < 3.0 \), and (3) \( 3.0 < z < 8.0 \). It should be recalled that the flux density redshift relation is almost flat in the range \( 0.5 < z < 8.0 \) (Fig. 4) so flux density–limited samples will approximate volume-limited samples within these broad redshift bins. These redshift bins are chosen so that bin 1 represents objects for which we have good redshift constraints from our spectroscopy and from photometric redshifts of bright galaxies; bin 2 represents fainter identified sources which are constrained to \( z < 3 \) from their detections in the \( U \) band. The four empty-field sources for which we have essentially no redshift information are then alternatively assigned either to the very high redshift bin 3 or to bin 4.

As noted above, the bolometric luminosities for these sources are estimated by integrating over the Arp 220 SED normalized to the observed 850 \( \mu \)m flux density, a procedure that may be uncertain at the factor of 2–3 level. In the \( 0.5 < z < 1.0 \) bin there are two sources with \( L_{bol} > 2 \times 10^{12} h_{50}^{-2} L_\odot \) (the third, CFRS 14H, falls below this limit). These are shown in Figure 11 with a Poisson error bar. In the next bin, there are between four and eight sources (depending on whether the four empty-field sources are included) with \( L_{bol} > 3 \times 10^{12} h_{50}^{-2} L_\odot \). This range, with associated Poisson error bars, is shown in Figure 11. Finally, there are between zero and four sources at \( z > 3 \) (depending on the redshifts of the empty-field sources), again with \( L_{bol} > 3 \times 10^{12} h_{50}^{-2} L_\odot \). These are shown as an upper limit in Figure 11. This last bin reaches to \( z \sim 8 \), since this is the maximum accessible redshift for such sources. If all such sources were at the lower end of this bin, because of evolutionary effects, then the CBLF at \( z \sim 3 \) would effectively be raised by the ratio of volumes (e.g., a factor of 2 for \( 3 < z < 5 \) or \( \Omega = 1 \)). These estimates of the CBLF are compared in Figure 11 with that of local IRAS galaxies given by Soifer et al. (1987) and Saunders et al. (1990), which differ only at high luminosities, correcting for different \( H_0 \) and different definitions of \( L_{bol} \) used in these analyses. We also show (and discuss in § 3.2) the CBLF of the ultraviolet-selected sample given by Dickinson (1998), computing bolometric luminosities in this case as \( \nu L_\nu \) at 1500 \( \AA \). It should be noted that the vertical normalization of this luminosity function is based on the ground-based samples and is lower than that seen in the (very small) HDF.

Looking at the FIR CBLF in Figure 11, there is a need for quite strong evolution to \( z \sim 1 \). In terms of density this is a large factor, about 300, but the CBLF at low redshift is so steep that, viewed in terms of luminosity, the effect is smaller—possibly as low as a factor of 10. This number is, of
course, quite uncertain, as it effectively relies on the validity of the computation of bolometric luminosity based on the Arp 220 SED. These could easily represent a factor of 2-3 uncertainty. However, a luminosity change of a factor of 10 to z ~ 1 is of the same order as the changes in the ultraviolet luminosity density of the universe to z ~ 1 (Lilly et al. 1996), i.e., (1 + z)^3.5.

Depending on the redshifts of the empty-field sources [and on the slope of the CBLF over the range 2 × 10^{12} < h_0 \, L_{bol} / L_\odot < 3 × 10^{12}], the evolution at higher redshifts is quite uncertain. However, there is little evidence at this stage for a further dramatic increase in the CBLF at z > 1. Putting all the empty-field sources at 1 < z < 3 would allow an increase of a factor of up to 3 from 0.5 < z < 1.0 but would then require a drastic reduction at z > 3. If the empty-field sources are at z > 3, as we suspect, then the data are consistent with a roughly flat redshift dependence of the CBLF at z > 1. The main point to stress is that the fact that only a third of the sources can lie at z > 3 already constrains the CBLF at those redshifts to be comparable to that at z ~ 1. We return to this point below.

3.1.2. Constraints on the Bolometric Luminosity Density as a Function of Redshift

In the same way, it is easy to calculate the FIR bolometric luminosity density, L_{bol,FIR}, above 2 × 10^{12} h_0^{-2} L_\odot for 0.5 < z < 1.0 and above 3 × 10^{12} h_0^{-2} L_\odot at higher redshifts. These are shown compared with the ultraviolet bolometric luminosity density in Figure 12. Faint blue galaxies typically have a spectral index f_s \propto \nu^{-1}, so the bolometric luminosity density in the ultraviolet has been computed simply using νL_ν using various estimates of L_\nu(z) over 1500 Å < λ < 2800 Å, themselves based on spectroscopic and photometric redshifts (Lilly et al. 1996; Connolly et al. 1997; Treyer et al. 1998; Madau et al. 1998; Sawicki et al. 1997).

In terms of a global star formation history, this diagram should be interpreted with extreme caution. There are several issues. In the first place, individual bolometric luminosities are uncertain at least at the factor of 2 level. More importantly, we know that only 20% of the 850 μm submillimeter background is represented in the FIR points in Figure 12, so an estimate of a total luminosity density, integrated over all luminosities, would on average be higher, by up to a factor of 5, while, in contrast, the ultraviolet luminosity density estimates already approximate “total” estimates. Also, because the luminosity threshold is lower in the 0.5 < z < 1.0 FIR bin, this point is biased high relative to the two higher redshift FIR points, probably by a factor of about 2. Finally, whereas the far-ultraviolet bolometric luminosity density (particularly as sampled at λ < 2000 Å) is dominated by young stars, some fraction of the FIR bolometric luminosity density (particularly at the lower luminosities “missing” from Fig. 12) will be due to energy emitted by older stellar populations, and some may be due to nuclear (AGN) activity. We have no real way of addressing the question of AGN contamination at this stage. In the local universe it is likely (Genzel et al. 1998) that stellar emission dominates the energy of ULIRGs (with a signifi-
cant contribution from AGNs). There are mixed indications from the few observations available at high redshift (Ivison et al. 1998; Frayer et al. 1998).

With all these very important caveats in mind, two important points are worth noting. First, even though we are so far considering those brightest sources which produce only 20% of the background (Paper I)—we refer to this loosely as the “top 20%” of the background—the bolometric luminosity density in the FIR due to “obscured” star formation activity already appears (with our assumption of an Arp 220 SED) to be comparable to all that seen “unobscured” in the ultraviolet (see also Hughes et al. 1998). When the extra star formation seen in the FIR at lower luminosities is added (plausibly raising the luminosity density by a factor of up to 5), it is likely that most of the energy from star formation at $1 < z < 3$ emerges in the FIR. Second, there is no evidence, as yet, that the redshift dependence of the luminosity density in the FIR is different from that seen in the ultraviolet. We look at this further in the next section.

3.1.3. The Production of the Integrated Background in Redshift Space

Another way to look at the redshift distribution of the sources is in terms of the redshift distribution of the light in the extragalactic 850 μm background. For an idealized population of star-forming galaxies whose SED is flat (i.e., $f_{\nu} \propto \nu^0$) and dominated by young stars, it is easy to show (following Lilly & Cowie 1987) that the cumulative distribution in redshift of the light in the extragalactic background is formally identical to the cumulative distribution in redshift of the production of stars in the universe. This result is independent of the cosmology, the nature of the star formation (i.e., constant or sporadic), possible number nonconservation of galaxies, and so on. However, at 850 μm, we have an SED that rises as $\nu^{1.5}$ (i.e., for emissivity $\propto \nu^{1.5}$ in the Rayleigh-Jeans tail) so there is a strong weighting of high-redshift star formation activity in the production of the 850 μm background. The weighting will be simply $\int f_{\nu}(v_{\text{em}})/f_{\nu}(v_{\text{obs}}) \, dv_{\nu}$ or $(1 + z)^{3.5}$ over much of the redshift range of interest $0 < z < 6$.

Our data suggest that two-thirds or more of the light in the top 20%–30% of the 850 μm background (Eales et al. 1998) is emitted at $z < 3$, implying that at least 15% of the whole background is emitted at $z < 3$.

In Figure 13 we have computed the redshift distribution of the background light for a number of different star formation histories, assuming that the energy of this star formation emerges with the SED of an obscured starburst, e.g., Arp 220 (see above). The distribution of observed light at $S_{850} > 2.8$ mJy in our identified source sample is also shown. This does not reach unity because the unidentified sources have been omitted—their redshifts are unconstrained, but it is assumed for this purpose that they have $z > 2.5$. The contribution from the two less securely identified galaxies estimated to lie at around $z \sim 2.5$ is shown as a dotted line.

As is clear in Figure 13, the weighting effect of the $k$-corrections is such that a galaxy formation/evolution scenario in which 50% of all dust-enshrouded star formation in the universe occurred prior to $z = 3$ would predict that 85% of the 850 μm background had been produced at $z > 3$! Such an evolutionary scenario would represent a picture in which all spheroidal stars formed very early in the universe.
3.2. Individual Luminosities and Space Densities: Differences with the Optical Picture

The analyses above suggest that the redshift dependence of the star formation producing the FIR/submillimeter background may be similar to that inferred in the optical, or at least that there is no compelling evidence at this time for any differences. On the other hand, it is clear from Figure 11 that the individual submillimeter sources are much more luminous than their optically selected counterparts. The characteristic bolometric luminosity (in the ultraviolet) of the optically selected samples at $z = 3$ (computed for $\Omega = 1$ from $v_L$, at 1500 Å) is about $6 \times 10^{10} \, h_5^{-2} \, L_\odot$ (Dickinson 1998), a factor of 50 below the sources detected in the submillimeter in the present survey. But these submillimeter-selected ULIRG galaxies have number densities of order $3 \times 10^{-5} \, h_5^{-3} \, \text{Mpc}^{-3}$ at $z \sim 2$, considerably less than the $(3-5) \times 10^{-4} \, h_5^{-2} \, \text{Mpc}^{-3}$ of the $L^*$ ultraviolet-selected galaxies. Thus, the submillimeter sources are rarer but very much more luminous than the optically selected sources.

3.3. The Formation of the Metal-rich Spheroids?

The identification of a population of galaxies at high redshift that are producing a substantial fraction of present-day stars in high-luminosity systems is important because it is then attractive to identify these as producing the spheroidal components of galaxies (or possibly old Population I disks). Local ultraluminous IR galaxies have long been proposed as being triggered by major mergers and resulting in the production of massive spheroids (see Sanders & Mirabel 1997 and references therein). The high individual luminosities and implied starformation rates are consistent with making substantial stellar populations on dynamical timescales.

The population revealed in the submillimeter surveys at high redshift has a sufficiently high number density (more than 100 times higher than in the present-day universe; Fig. 11) that they must be responsible for producing a significant fraction of all stars that have been formed in the universe (see Fig. 12). Not least, the high-luminosity submillimeter galaxies detected in the present survey at $S_{550} > 3$ mJy (i.e., with luminosities $L_{\text{bou}} > 3 \times 10^{12} \, h_5^{-2} \, L_\odot$) are responsible for producing, in the FIR, a bolometric luminosity density in the universe that is as large as the bolometric luminosity produced in the ultraviolet by the whole population (integrated over essentially all luminosities); see Figure 12. So, the population sampled by these sources is presumably responsible for the generation of at least 20% of all stars produced in the universe, a fraction that would presumably rise rapidly as lower luminosities are considered. It should be recalled (e.g., Fukugita et al. 1998) that the spheroids contain one-half to two-thirds of all stars in the universe.

The combination of the high integrated production of stars, the high star formation rates, the incidence of merger-like morphologies, and the obvious presence of substantial amounts of dust make it attractive, although still speculative, to associate these galaxies with the production of the metal-rich spheroid component of galaxies. In this case, these first data from our survey suggest that much of this activity, conservatively, at least 50%, has happened at relatively recent epochs, i.e., $z < 3$ (Figs. 12 and 13). We suspect that this could be equally well be accommodated within either hierarchical or monolithic collapse scenarios of galaxy formation.

4. SUMMARY

We have searched for identifications of the 12 submillimeter sources ($S_{850} > 2.8$ mJy) reported in Paper I at optical, midinfrared, and radio wavelengths with the following results:

1. Six sources can be securely identified, two have probable identifications, and four remain unidentified with $I_{AB} > 25$ (for such faint galaxies the chance of random positional coincidences also becomes quite large).

2. Three of the identifications have measured redshifts (0.08 < $z$ < 0.66), and redshifts for the remainder have been estimated from $UVIK$ photometry. Based on these, four of the identifications are likely to have $z < 1$, with the remaining four identifications likely lying in the 1.5 < $z$ < 3.0 redshift interval.

3. The SEDs as defined by measurements or upper limits to the flux densities at 8000 Å, at 15, 450, and 850 μm and at 6 cm are consistent with the SEDs of high-extinction starbursts such as Arp 220. The bolometric luminosities of the sources at $z > 0.5$ are of order $3 \times 10^{12} \, h_5^{-2} \, L_\odot$, i.e., slightly larger than that of Arp 220. The lowest redshift source at $z \sim 0.08$ is about a factor of 10 less luminous. As with local ULIRGs, the optical luminosities of the identified galaxies are comparable to present-day $L^*$, and the optical morphologies of many of the galaxies show evidence for mergers or highly disruptive interactions. Thus, in all respects studied so far, the individual sources appear to be similar to the most extreme starbursts seen locally.

4. Our unidentified sources could be similar galaxies anywhere in a broad range of redshifts at $z > 2$ (possibly extending to very high redshifts). But they could also be at redshifts as low as $z \sim 1$ if they have significantly higher $L_{\text{FIR}}/L_{\text{opt}}$ ratios.

5. The bolometric luminosity function at 0.5 < $z$ < 1.0 shows strong evolution relative to that defined by local IRAS galaxies at 60 μm, although the comparison is rendered imprecise by the large difference in wavelengths. While the strength of this evolution is thus uncertain, it likely corresponds to a factor of 10 in luminosity, roughly the change seen in the ultraviolet luminosity density of the universe as a whole, or a factor of order 300 in density. The evolution likely flattens off or possibly even reverses at higher redshifts.

6. The analysis of the relationship between the star formation history of the universe and the redshift distribution of the light in the background suggests that the observed redshift distribution in the sample is broadly consistent with a redshift evolution of the FIR luminosity density that matches that in the ultraviolet, i.e., rising to a peak in the 1.2 < $z$ < 2 range and falling thereafter. This is supported by direct computation of the FIR luminosity density. The number of sources is still small, and the uncertainties large, but we can at least say that we see no strong evidence in the present data for significant differences in the redshift dependence.

7. With the caveat that our estimates of the FIR bolometric luminosities are based on the Arp 220 SED (and are thus uncertain by a factor of 2–3), the population of high-redshift ULIRGs detected in the survey at $z > 1$ already appears to be producing a bolometric luminosity in the FIR that matches that produced in the ultraviolet by the whole optically selected population. Thus, these high-redshift ULIRGs and the lower luminosity systems presently below
the detection threshold are likely to be producing a significant fraction of all stars that have ever formed. Furthermore, they are doing so in systems with high star formation rates, exceeding $300 \, h_{50}^{-2} \, M_\odot \, \text{yr}^{-1}$, with indications of mergerlike activity and in the presence of large amounts of dust (i.e., metals). It is therefore attractive to identify these as forming the metal-rich spheroid population, in which case we would infer that much of this activity has occurred relatively recently, at $z \sim 2$.

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