MID-INFRARED IDENTIFICATION OF FAINT SUBMILLIMETER SOURCES
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ABSTRACT

Faint submillimeter sources detected with the Submillimeter Common-User Bolometer Array on the James Clerk Maxwell Telescope have faced an identification problem due to the telescope’s broad beam profile. Here we propose a new method to identify such submillimeter sources with a mid-infrared image having a finer point-spread function. The Infrared Space Observatory has provided a very deep 6.7 μm image of the Hawaii Deep Field SSA13. All three faint 850 μm sources in this field have their 6.7 μm counterparts. They have been identified with interacting galaxy pairs in optical images. These pairs are also detected in the radio. Two of them are optically faint and very red (I > 24, I - K > 4), one of which has a hard X-ray detection with the Chandra satellite. As these observing properties are similar to those of local ultraluminous infrared galaxies, their photometric redshifts are derived based on submillimeter-to-mid-infrared flux ratios assuming a spectral energy distribution (SED) of Arp 220. Other photometric redshifts are obtained via χ²-minimization between the available photometry data and template SEDs. Both estimates are in the range z = 1–2, in good agreement with a spectroscopic redshift and a millimetric one. The reconstructed Arp 220 SEDs with these redshift estimates are consistent with all the photometry data except Chandra’s hard X-ray detection. The sources would be a few times more luminous than Arp 220. With an assumption that contributions from active galactic nuclei are negligible, it appears that extremely high star formation rates are occurring in galaxies at high redshifts with massive stellar contents already in place.

1.INTRODUCTION

The installation of the Submillimeter Common-User Bolometer Array (SCUBA) on the 15 m James Clerk Maxwell Telescope has brought us the discovery of a new population of faint submillimeter sources (Smail, Ivison, & Blain 1997; Barger et al. 1998; Hughes et al. 1998; Eales et al. 1999). Meanwhile, the far-infrared background (FIRB) was detected with the Far-Infrared Absolute Spectrometer (FIRAS) and the Diffuse Infrared Background Experiment (DIRBE) on the COBE satellite (Puget et al. 1996; Schlegel, Finkbeiner, & Davis 1998; Hauser et al. 1998; Fixsen et al. 1998). The FIRB is comparable to or larger than that in the optical wavelengths, and much of it could be explained by integrating individual submillimeter sources down to the faintest limit (Blain et al. 1999). Thus, it is indispensable to investigate the faint submillimeter population in order to understand overall history of energy production in the universe.

Although SCUBA has unveiled the faint submillimeter population, its beam is too broad (15" FWHM at 850 μm) to pinpoint their optical counterparts (e.g., Barger, Cowie, & Richards 2000). The high density of the submillimeter sources also raises a problem of source confusion (Eales et al. 2000; Hogg 2001). Up until now, methods to bypass the broad submillimeter beam have included centimetric radio interferometry with the Very Large Array (VLA; Ivison et al. 1998; Richards 1999; Smail et al. 1999; Barger et al. 2000) and millimetric interferometry with the IRAM interferometer or the Owens Valley Millimeter Array (Downes et al. 1999; Gear et al. 2000; Bertoldi et al. 2000; Frayer et al. 2000). Most recently, an attempt to observe at a longer wavelength has started at the IRAM 30 m telescope (Bertoldi et al. 2000). The larger dish provides a slightly smaller beam (10" at 1.3 mm).

Here we investigate the identification of SCUBA sources with a mid-infrared deep image having a relatively small beam (7" at 6.7 μm). Faint submillimeter sources, presumably dusty systems at high redshifts, could be bright in the mid-infrared regardless of their energy sources. If the submillimeter emission was produced by dust heated by star-forming activity, there should be stellar systems following the stellar initial mass function. The stellar systems could be luminous at the rest-frame near-infrared (>1 μm) even in the presence of dust. In the case that the source was powered by an active galactic nucleus (AGN), very hot dust surrounding the AGN could emit its reprocessed energy at wavelengths longer than 2 μm. For both cases, the emitted light could be received at the mid-infrared, even though the sources were at high redshifts.

2. SOURCE IDENTIFICATION

A sensitive mid-infrared camera ISOCAM (Cesarsky et al. 1996) on board the ISO (Kessler et al. 1996) provided us with the first opportunity to identify faint submillimeter sources at the mid-infrared. In the Hawaii Deep Field SSA13, a very deep mid-infrared map was obtained with the LW2 (6.7 μm) filter (Sato et al. 2002). This field was also surveyed extensively with SCUBA (Barger et al. 1998; Barger, Cowie, & Sanders 1999a). In the upper left panel of Figure 1, we plot both 6.7 and...
850 μm sources detected within the SCUBA field of view. All three 850 μm sources A, B, and C (these identifiers are used throughout this Letter; see Table 1) are found to be located very close to certain 6.7 μm sources. Monte Carlo simulations of source detection suggest that displacement of the detected position as large as the beam size could happen in low signal-to-noise ratio (S/N) ranges (Eales et al. 2000; Hogg 2001). We estimate the probability of random alignments between the 6.7 and 850 μm sources. As the surface density of 6.7 μm sources at this depth is larger than that of 850 μm sources, we assume a Poisson distribution for 6.7 μm sources. Then, the chance alignment probability can be defined as \( P = \exp \left[ -\pi r^2 N(6.7 \, \mu m) \right] \), where \( r \) is the distance between 6.7 and 850 μm sources and \( N(6.7 \, \mu m) \) is a 6.7 μm integral number count at the flux of the corresponding 6.7 μm source. The chance probability became only 0.9%, 16%, and 4.1% for sources A, B, and C, respectively. Then, we associate the closest 6.7 μm sources with the corresponding submillimeter sources.

The optical counterparts of the sources were identified in deep Hubble Space Telescope (HST) images taken with the Wide Field Planetary Camera 2 (WFPC2) F814W filter (Cowie, Hu, & Songaila 1995). Interacting galaxy pairs were found at the peaks of the 6.7 μm contours for all the 850 μm sources (Fig. 1). The occurrence of an irregular morphology is consistent with the results of ultraluminous infrared galaxies (ULIGs) discovered with IRAS (Sanders & Mirabel 1996). Within 1′ from all the optical counterparts, faint 1.4 GHz sources are detected (E. A. Richards 2001, private communication). Source B also has a hard X-ray (2–10 keV) detection with Chandra (Mushotzky et al. 2000). The small rate of AGNs in submillimeter sources (one-third) is similar to the previous results (Almaini, Lawrence, & Boyle 1999; Fabian et al. 2000; Hornschemeier et al. 2000; Severgnini et al. 2000; Barger et al. 2001). Magnitudes at the \( K \), \( I \), and \( B \) bands were measured with additional data taken from the ground (Cowie et al. 1996). Two of the three sources are optically faint and very red (Table 1). Here are notes for the individual sources. Source A: This is the most significant SCUBA detection in this sample (4.7 \( \sigma \)). The ISOCAM contour reduces the uncertainty of the SCUBA position. In the middle of the 6.7 μm contour, there is a faint (\( I \sim 25 \)) interacting galaxy pair having a very red color of \( I-K > 4 \). Source B: One of the 6.7 μm peaks matches a colliding galaxy pair with \( I \sim 24 \) and \( I-K > 4 \). The ISOCAM source appears somewhat extended probably due to confusion of faint sources. Source C: A bright merger (\( I \sim 22 \)) with tidal tails is located at the edge of the beam centered at the nominal SCUBA position. The original SCUBA image shows a sign of elongation, suggesting a lower position accuracy (see Fig. 1 in Barger et al. 1998).

### 3. Redshift Estimates

The three SCUBA sources detected at 6.7 μm share the same observational properties as those of local ULIGs, i.e., an irregular morphology, a red color, and optical and X-ray faintness. Therefore, it seems possible to estimate their redshifts with an assumption that their spectral energy distributions (SEDs) are similar to that of Arp 220, an archetypal ULIG in the local universe. We adopt a UV-to-submillimeter SED in the GRASIL library to represent Arp 220 (Silva et al. 1998).\(^7\) Applying a convolution with two bandpass filters at 850 and 6.7 μm, we derive flux ratios \( f_6(850 \, \mu m)/f_6(6.7 \, \mu m) \) as a function of redshift (Fig. 2, \( \sim \)).

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### TABLE 1

| ID | Name\(^a\) | R.A. (J2000.0) | Decl. (J2000.0) | 2–10 keV\(^b\) | \( B \) (mag) | \( I \) (mag) | \( K \) (mag) | \( 6.7 \, \mu m \) (mJy) | \( 850 \, \mu m \) (mJy) | 1.4 GHz\(^d\) (mJy) |
|----|------------|---------------|---------------|---------------|-------------|-------------|-------------|----------------|----------------|----------------|
| A  | [BCS99] J131232.1+424430 | 13 12 31.94 | +42 44 29.7 | <3.2 | >25.5 | >24.7 | 19.7 | 18 | 3.8 | ... |
| B  | [BCS99] J131228.0+424458 | 13 12 28.29 | +42 44 54.6 | 5.67 | >25.5 | 24.0 | 19.9 | 14 | 2.3 | 39 |
| C  | [BCS99] J131225.7+424350 | 13 12 25.18 | +42 43 44.9 | <3.2 | 24.3 | 21.6 | 18.5 | 27 | 2.4 | ... |

\( ^a \) From Barger et al. 1999a.
\( ^b \) From Mushotzky et al. 2000.
\( ^c \) From Sato et al. 2002.
\( ^d \) From Barger et al. 2001.

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\( ^7 \) See [http://grana.pd.astro.it/grasils/](http://grana.pd.astro.it/grasils/).
et al. 2000; Barger et al. 1998).

Based on this relation, photometric redshifts $z_{\text{ph}}(6.7 \mu m)$ are derived for the three submillimeter sources A, B, and C. With these redshift estimates, Arp 220 SEDs are reconstructed to fit the 850 and 6.7 $\mu m$ measurements. We adopt the GRASIL SED (Silva et al. 1998), complemented with radio and X-ray data (Carilli & Yun 2000; Iwasawa 1999). Reconstructed SEDs are consistent with other photometry data.

The hard X-ray detection of source B is beyond the wavelength span of the SED. The fluxes and upper limits (3 $\sigma$) are measured at 2–10 keV, 0.5–2 keV, $I$, $J$, $K$, 6.7 $\mu m$, 450 $\mu m$, 850 $\mu m$, and 1.4 GHz (Table 1; Mushotzky et al. 2000; Barger et al. 1998).

upper left panel). Because of a monotonic increase with redshift, this relation can be used to estimate redshifts, analogous to the redshift estimator based on a submillimeter-to-radio flux ratio (Carilli & Yun 1999; Carilli & Yun 2000; Barger et al. 2000).

The derived estimates were in the range $z_{\text{ph}}(6.7 \mu m) = 1–2$ (Table 2). The reconstructed SEDs are consistent with other photometry data, suggesting the usefulness of this redshift estimator (Fig. 2).

With the identification results above, we could omit the assumption of an Arp 220 SED to obtain photometric redshifts. Other estimates $z_{\text{ph}}(6.7 \mu m)$ were derived via $\chi^2$-minimization between all the photometry data and SED templates. We here adopt the GRASIL SED library (Silva et al. 1998), UV-to-submillimeter SEDs of local templates (starbursts: M82, NGC 6090, and Arp 220; normal galaxies: M51, M100, and NGC 6946; and a giant elliptical) and UV-to-radio SEDs of evolving E, Sa, Sb, and Sc galaxies. We add an X-ray–to–radio SED of a heavily obscured AGN, NGC 6240, compiled by Hasinger (2000). The best scaling factor for a certain SED at each redshift was determined by minimizing $\chi^2$. The $\chi^2$-value was summed up at the wavelengths where the model predictions could be evaluated. Upper limits were used as restrictions. Thus, the number of degrees of freedom is the number of detections (within the wavelength range of the SED) minus one (for a scaling factor). The smallest reduced $\chi^2$ was achieved with the Arp 220 SED for sources A and B, and with the 13 Gyr Sc SED for source C. The resulting $z_{\text{ph}}(6.7 \mu m)$-values are similar to $z_{\text{ph}}(1.4 \text{ GHz}) = 1.8$ derived for source B (Barger et al. 2001).

All of these are consistent in the range $z = 1–2$ (Table 2). Source C gives a minimum $\chi^2$ at $z \sim 1$ for many SEDs including the Arp 220 SED. The hard X-ray flux for the Chandra source B was not used in the $\chi^2$ calculations except in the case with the NGC 6240 SED. An overall fit to the hard X-ray–to–radio data turned out to be not so good; the NGC 6240 SED suggests $z = 1.9$, but with a reduced $\chi^2 = 5.9$. (cf. Fig. 11 in Barger et al. 2001). If we admit such a level of reduced $\chi^2$, there could be some room for a higher redshift for the optically faint sources A and B. Source A could be at $z = 5.3$ with the 0.8 Gyr E SED (a reduced $\chi^2 = 1.9$). For source B, the 0.2 Gyr E SED gives $z = 3.1$ with a reduced $\chi^2 = 3.2$ (for the UV-to-radio data only). Both E SEDs represent a dusty elliptical before the galactic wind blows.

4. DISCUSSION

We identified source C with a galaxy offsetting 6′4 from the nominal SCUBA position. Such sizes of offsets were observed in simulations of the source detection in a crowded field (Eales et al. 2000; Hogg 2001). SCUBA observations of radio-selected sources actually found such offsets at the submillimeter flux level of 2–4 mJy with S/N = 3–5 (Barger et al. 2000). The expected large offsets and optical faintness suggest that the mid-infrared identification of SCUBA sources could be an effective way to find their optical counterparts. For the submillimeter sample presented here, their counterparts are as faint as 14 $\mu$mJy at 6.7 $\mu$m, $K = 20$, or $I = 25$. Integral galaxy counts at the corresponding depths are $1 \times 10^4$, $3 \times 10^4$, and $8 \times 10^4$ $\text{deg}^{-2}$, respectively (Sato et al. 2002; Maihara et al. 2001; Metcalfe et al. 2001). Thus, the probability of finding spurious associations by chance would be smaller by a factor of 3–8 at 6.7 $\mu$m.

Our ISOCAM map taken with a pixel field of view (PFOV) of 6′ still has a low-resolution problem. The 6.7 $\mu$m contour for source C extends to the east to include an edge-on spiral. The extended appearance is also seen for source B. Although their fluxes were corrected to be one point source statistically (Sato et al. 2002), effects of the extension to the corrected flux for a particular source remain uncertain. A mid-infrared imaging with a finer PFOV ($1′′$–$2′$) with the SIRTF’s InfraRed Array Camera (IRAC) or the ASTRO-F’s Infrared Camera (IRC) would clarify such ambiguities. The high sensitivity of these detectors will also strengthen redshift estimates for the mJy 850 $\mu$m sources. They can be detected even at $z = 5$, and their redshifts could be determined, provided that the Arp 220 SED is a representative for them. For cases of other SEDs, multiband mid-infrared fluxes should be required to estimate photometric redshifts because such high-redshift sources are likely to be faint in the optical, or even in the near-infrared.

The estimated range of redshift for the three sources in the SSA13 field is $z = 1–2$. Given a cosmology with $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$ and $\Omega_m = 0.1$, the sources would be 2–4 times more luminous than Arp 220. These properties are similar to other submillimeter sources (Lilly et al. 1999; Barger et al. 1999b, 2000). A simple scaling of the model parameters for the GRASIL Arp 220 SED gives star formation rates in the range

\begin{table}[h]
\centering
\caption{Redshifts of the Submillimeter Sources}
\begin{tabular}{|c|c|c|c|}
\hline
ID & $z_{\text{ph}}(6.7 \mu m)$ & $z_{\text{ph}}(1.4 \text{ GHz})$ & Note. \\
\hline
A & $2.0^{+0.4}_{-0.4}$ & $2.0^{+0.4}_{-0.4}$ & 1. \text{From Cowie et al. 1996.} \\
B & $1.6^{+0.2}_{-0.2}$ & $1.6^{+0.2}_{-0.2}$ & 2. \text{From Barger et al. 2001.} \\
C & $1.038^{+0.9}_{-0.9}$ & $1.0^{+0.3}_{-0.3}$ & 3. \text{From Sato et al. 2002; Maihara et al. 2001; Metcalfe et al. 2001.} \\
\hline
\end{tabular}
\end{table}
(1–2) \times 10^3 \, M_\odot \, \text{yr}^{-1} \) and stellar masses in the range \((3–7) \times 10^{11} \, M_\odot\). While the peak of the dust emission was not observed directly, the 6.7 \, \mu m flux originated from the rest-frame near-infrared. Because rest-frame near-infrared emission has a good correlation with stellar mass, it would be accurate to assume that these submillimeter sources have massive stellar populations in them. With signs of a major merger in all the optical counterparts, similar to the irregular morphologies already reported (Smail et al. 1999), it is suggested that less massive galaxies identified at \(z \sim 3\) (Pettini et al. 1998) would evolve into local massive galaxies via major merging with the submillimeter bright phase.

5. CONCLUSIONS

All three of the faint 850 \, \mu m sources (2–4 mJy) in the SCUBA SSA13 deep field have been found to have ISOCAM 6.7 \, \mu m counterparts (10–30 \, \mu m). Utilizing the smaller beam size at 6.7 \, \mu m, we find that all the three sources are coincident with interacting galaxy pairs in the HST I-band images. They all have VLA 1.4 GHz counterparts, and only one of them is detected with Chandra at the 2–10 keV band. Based on the properties similar to local ULIGs, we used submillimeter–to–mid-infrared flux ratios to estimate photometric redshifts. We derived other photometric redshifts utilizing the X-ray–to–radio photometry data. Both estimates are consistent with a spectroscopic redshift and a millimetric one. An Arp 220 SED at \(z = 1–2\) provides a good fit to the available data. With an assumption that AGN contributions are negligible, the implied star formation rates are in the range \((1–2) \times 10^3 \, M_\odot \, \text{yr}^{-1}\) and the mid-infrared emission requires stellar masses in the range \((3–7) \times 10^{11} \, M_\odot\).

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REFERENCES

Almaini, O., Lawrence, A., & Boyle, B. J. 1999, MNRAS, 305, L59
Barger, A. J., Cowie, L. L., Mushotzky, R. F., & Richards, E. A. 2001, AJ, 121, 662
Barger, A. J., Cowie, L. L., & Richards, E. A. 2000, AJ, 119, 2092
Barger, A. J., Cowie, L. L., & Sanders, D. B. 1999a, ApJ, 518, L5
Barger, A. J., Cowie, L. L., Sanders, D. B., Fulton, E., Taniguchi, Y., Sato, Y., Kawara, K., & Okuda, H. 1998, Nature, 394, 248
Barger, A. J., Cowie, L. L., Smail, I., Ivison, R. J., Blain, A. W., & Kneib, J.-P. 1999b, AJ, 117, 2656
Bertoldi, F., et al. 2000, A&A, 360, 92
Blain, A. W., Kneib, J.-P., Ivison, R. J., & Smail, I. 1999, ApJ, 512, L87
Carilli, C. L., & Yun, M. S. 1999, ApJ, 513, L13
———. 2000, ApJ, 530, 618 (erratum 539, 1024)
Cesarsky, C. J., et al. 1996, A&A, 315, L32
Cowie, L. L., Hu, E. M., & Songaila, A. 1995, AJ, 110, 1576
Cowie, L. L., Songaila, A., Hu, E. M., & Cohen, J. G. 1996, AJ, 112, 839
Downes, D., et al. 1999, A&A, 347, 809
Eales, S., Lilly, S., Gear, W., Dunne, L., Bond, J. R., Hammer, F., Le Fevre, O., & Crampton, D. 1999, ApJ, 515, 518
Eales, S., Lilly, S., Webb, T., Dunne, L., Gear, W., Clements, D., & Yun, M. 2000, AJ, 120, 2244
Fabian, A. C., et al. 2000, MNRAS, 315, L8
Fixsen, D. J., Dwek, E., Mathee, J. C., Bennett, C. L., & Shafer, R. A. 1998, ApJ, 508, 123
Frayer, D. T., Smail, I., Ivison, R. J., & Scoville, N. Z. 2000, AJ, 120, 1668
Gear, W. K., Lilly, S. J., Stevens, J. A., Clements, D. L., Webb, T. M., Eales, S. A., & Dunne, L. 2000, MNRAS, 316, L51
Hasinger, G. 2000, in Lect. Notes Phys. 548, ISO Survey of a Dusty Universe, ed. D. Lemke, M. Stickel, & K. Wilke (Berlin: Springer), 423
Hauser, M. G., et al. 1998, ApJ, 508, 25
Hogg, D. W. 2001, AJ, 121, 1207
Hornschemeier, A. E., et al. 2000, ApJ, 541, 49
Hughes, D. H., et al. 1998, Nature, 394, 241
Ivison, R. J., Smail, I., Le Borgne, J.-F., Blain, A. W., Kneib, J.-P., Bézecourt, J., Kerr, T. H., & Davies, J. K. 1998, MNRAS, 298, 583
Iwasawa, K. 1999, MNRAS, 302, 96
Kessler, M. F., et al. 1996, A&A, 315, L27
Lilly, S. J., Eales, S. A., Gear, W. K. P., Hammer, F., Le Fèvre, O., Crampton, D., Bond, J. R., & Dunne, L. 1999, ApJ, 518, 641
Maihara, T., et al. 2001, PASJ, 53, 25
Metcalf, N., Shanks, T., Campos, A., McCracken, H. J., & Fong, R. 2001, MNRAS, 323, 795
Mushotzky, R. F., Cowie, L. L., Barger, A. J., & Arnaud, K. A. 2000, Nature, 404, 459
Pettini, M., Kellogg, M., Steidel, C. C., Dickinson, M., Adelberger, K. L., & Giavalisco, M. 1998, ApJ, 508, 539
Puget, J.-L., Abergel, A., Bernard, J.-P., Boulanger, F., Burton, W. B., Desert, F.-X., & Hartmann, D. 1996, A&A, 308, L5
Richards, E. A. 1999, ApJ, 513, L9
Sanders, D. B., & Mirabel, I. F. 1996, ARA&A, 34, 749
Sato, Y., et al. 2002, A&A, submitted
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Severgnini, P., et al. 2000, A&A, 360, 457 (erratum 364, 348)
Silva, L., Granato, G. L., Bressan, A., & Danese, L. 1998, ApJ, 508, 25
Smail, I., Ivison, R. J., & Blain, A. W. 1997, ApJ, 490, L5
Smail, I., Ivison, R. J., Blain, A. W., & Kneib, J.-P. 1998, ApJ, 507, L21
Smail, I., Ivison, R. J., Kneib, J.-P., Cowie, L. L., Blain, A. W., Barger, A. J., Owen, F. N., & Morrison, G. 1999, MNRAS, 308, 1061