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RADIO IDENTIFICATION OF SUBMILLIMETER SOURCES IN THE HUBBLE DEEP FIELD

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ABSTRACT

Determination of the epoch-dependent star formation rate of field galaxies is one of the principal goals of observational cosmology. Recently, Hughes et al., using the Submillimeter Common-User Bolometer Array instrument on the James Clerk Maxwell Telescope, reported the detection of a new population of heavily dust enshrouded, star-forming galaxies at high redshifts ($z > 2$), dramatically altering the picture of galaxy evolution. However, we show that this interpretation must be treated with caution because of ambiguities in the identification of the host galaxies. Based on our deep, high-resolution 1.4 GHz observations of the Hubble Deep Field, we suggest alternate identifications to the submillimeter detections. These identifications argue for a lower redshift to the submillimeter population with a consequential lowering of the $z > 2$ submillimeter/far-infrared luminosity density and global star formation rate.

Subject headings: cosmology: observations — galaxies: evolution — galaxies: starburst — radio continuum: galaxies

1. INTRODUCTION

An 850 μm survey of the Hubble Deep Field (HDF) with the Submillimeter Common-User Bolometer Array (SCUBA) detector on the James Clerk Maxwell Telescope (JCMT) found five sources in a confusion-limited image (Hughes et al. 1998) with 15″ resolution. Tentative optical identifications are all with putative starbursts at $z \gtrsim 1$ and with star formation rates (SFRs) of 400–1200 $M_{\odot}$ yr^{-1} (we assume $h = 0.5$, $q_0 = 0.5$). In this Letter, we compare our deep radio images of the HDF with the SCUBA images and suggest alternate optical counterparts to the submillimeter sources.

Closely related to the far-infrared (FIR) emission in starburst galaxies is the radio continuum. In normal galaxies (i.e., without a powerful active galactic nucleus), the centimeter radio luminosity is dominated by diffuse synchrotron emission believed to be produced by relativistic electrons accelerated in supernovae remnants. At shorter wavelengths, free-free emission from H II regions may contribute substantially. Although the radio emission is linked to active star formation by different physical mechanisms than that of the FIR, there is a tight correlation between the FIR and radio luminosity of a starburst (Helou, Soifer, & Rowan-Robinson 1985; Condon, Anderson, & Helou 1991). Radio observations are only sensitive to recent starburst activity in a galaxy (and the formation of its O and B stellar populations), since the thermal and synchrotron radiation dissipate on physical timescales of 10^7–10^8 yr. In this sense, the radio luminosity of a starburst is a true measure of the instantaneous rate of star formation in a galaxy, uncontaminated by older stellar populations. Because galaxies and the intergalactic medium are transparent at centimeter wavelengths, radio emission is a sensitive measure of star formation in distant galaxies. The current deep Very Large Array (VLA) radio surveys with sensitivities of a few microjanskys are capable of detecting star-forming galaxies to $z \sim 2$ (Richards et al. 1998).

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2. RADIO OBSERVATIONS

A 5′.4 (FWHM) field containing the HDF has been imaged at 8.5 GHz with the VLA with an rms sensitivity of 1.8 μJy. The observing technique and data reduction are discussed in Richards et al. (1998). We collected 40 additional hours of data at 8.5 GHz in 1997 June. The new combined image has an rms sensitivity near the field center of about 1.6 μJy with a resolution of 3″.5.

During 1996 November, we obtained 42 hr of VLA data in its A array on the HDF at 1.4 GHz. The subsequent 1.4 GHz image of the HDF has an effective resolution of 1″.9 and an rms sensitivity of 7.5 μJy with a firm detection limit of 40 μJy. A total of 380 radio sources at 1.4 GHz have been cataloged within 20′ of the HDF and are reported on elsewhere (Richards 1999). Within the HDF, there are nine radio sources detected in complete samples at either 1.4 GHz and/or 8.5 GHz, while an additional seven 8.5 GHz sources constitute a supplementary sample as described by Richards et al. (1998).[2]

3. ASSOCIATION OF SUBMILLIMETER AND RADIO SOURCES

We inspected our radio images to determine if any of the SCUBA sources have possible radio counterparts. Our first step was to align the radio and SCUBA position frames. The VLA coordinate grid is within 0″.1 of the J2000/FK5 reference frame at both 8.5 and 1.4 GHz (Richards et al. 1998). In order to tie the JCMT coordinate grid to this system, we have assumed that the radio and submillimeter sources are associated with the same galaxy, as discussed in § 1.

The relative rms positional errors for the submillimeter sources should be of order 1″–2″ (based on the 15″ SCUBA beam size and the signal-to-noise ratio of individual detections); however, the uncertain effects of source confusion in the submillimeter images likely makes this an underestimate. In addition, the absolute registration of the SCUBA image is unknown a priori, although Hughes et al. (1998) quote a value of 0″.5, while Smail et al. (1998) report typical values of 3″ for their SCUBA images. Thus, we chose to search for any radio

[2] The 8.5 and 1.4 GHz images of the HDF are available at www.cv.nrao.edu/~jkempner/vla-hdf.

TABLE 1
RADIO IDENTIFICATIONS OF SUBMILLIMETER SOURCES

Name	R.A.[a]	Decl.[a]	HDF Identification	$S_{8.5\,\mathrm{GHz}}$ (μJy)	$S_{1.4\,\mathrm{GHz}}$[c] (μJy)	I_{AB}[d] (mag)	z[e]
HDF850.1	12 36 51.63 ± 0.10	62 12 22.5 ± 0.7	…	…	…	…	…
VLA J123651+621221	12 36 51.653 ± 0.021	62 12 21.41 ± 0.15	3-633.1?	17	49	25.9	(1.72)?
HDF850.2	12 36 55.99 ± 0.20	62 12 00.0 ± 1.4	…	…	…	…	…
VLA J123655+621159	12 36 55.859 ± 0.033	62 12 01.57 ± 0.23	…	<6	26	23.9	…
VLA J123656+621207	12 36 56.605 ± 0.025	62 12 07.58 ± 0.17	…	<6	46	>28	…
HDF850.3	12 36 44.06 ± 0.21	62 12 59.5 ± 1.5	…	…	…	…	…
VLA J123644+621258	12 36 44.627 ± 0.028	62 12 58.15 ± 0.19	…	<5	32	>27	…
VLA J123644+621304	12 36 44.612 ± 0.036	62 13 04.73 ± 0.25	1-34.0	<5	23	22.1	0.485
HDF850.4	12 36 49.68 ± 0.23	62 13 12.1 ± 1.6	…	…	…	…	…
VLA J123649+621313	12 36 49.656 ± 0.019	62 13 13.16 ± 0.13	2-264.1	14	49	21.4	0.475
HDF850.5	12 36 51.29 ± 0.25	62 13 15.4 ± 1.8	…	…	…	…	…

NOTE.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.
[a] SCUBA positions are given after translation to the VLA coordinate frame.
[b] The most probable optical identification of the radio source in the HDF catalog (Williams et al. 1996) based on positional coincidence.
[c] The integrated flux density corrected for the attenuation of the VLA primary beam. In a few places, upper limits are given.
[d] The integrated *I*-magnitude of the identification as taken from the HDF catalog (Williams et al. 1996).
[e] The spectroscopic redshift (Cohen et al. 1996; Lowenthal et al. 1997) of the identification. Values within parentheses are photometric estimates of the redshift (Fernandez-Soto et al. 1998).

object either in the 1.4 GHz complete sample or in the 8.5 GHz catalog of Richards et al. (1998) within a 10″ error circle around each of the submillimeter source positions. Possible radio associations were apparent for HDF 850.1 (VLA J123651+621226 and VLA J123651+621221), HDF 850.2 (VLA J123656+621207), and HDF 850.4 (VLA J123649+621313). Two of these radio sources were detected at both 1.4 and 8.5 GHz as part of independent and complete samples (VLA J123651+621221 and VLA J123649+621313). These two radio sources in particular also have high-significance *Infrared Space Observatory* (*ISO*) 15 μm counterparts (Aussel et al. 1999), indicating that these systems may contain substantial amounts of dust and hence be luminous FIR galaxies. Based on the association of VLA J123656+621207 and VLA J123649+621313 with HDF 850.1 and HDF 850.4, respectively, we suggest a SCUBA coordinate frame shift of 4″.8 west and 3″.8 south. This position shift is tentative and could be overestimated based on the uncertain positions of the heavily confused SCUBA sources.

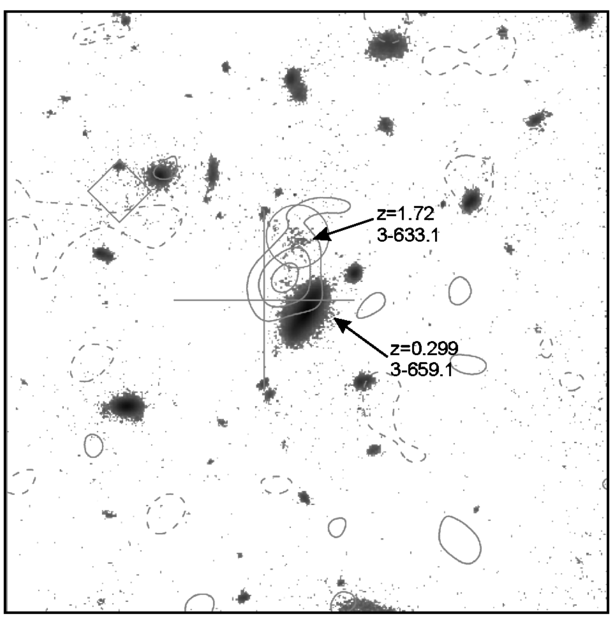

FIG. 1.—The gray scale shows a 20″ × 20″ HDF *I*-band image (Williams et al. 1996) containing the SCUBA detection HDF 850.1. The contours correspond to 1.4 GHz emission at the −2, 2, 4 and 6 σ level (σ = 7.5 μJy). The 3 σ position error circle for HDF 850.1 is shown after shifting to the VLA coordinate frame. The original position of HDF 850.1 taken from Hughes et al. (1998) is denoted by the diamond. The *ISO* detection is marked with a cross with 3 σ position errors (Aussel et al. 1999). The radio emission is clearly confined to the optical feature north of the bright spiral, which also has a reported NICMOS detection (M. Dickinson 1998, private communication). Radio source VLA 123651+621221 may be the most obscured part of a larger galaxy 3-633.1 at z = 1.72 (Fernandez-Soto et al. 1998).

4. OPTICAL IDENTIFICATION OF RADIO/SUBMILLIMETER SOURCES

Since the radio source positions are much more accurate (0″.1–0″.2) than the submillimeter positions and since the HDF contains a high surface density of optical objects (typically 20 per SCUBA beam), we now use the radio data to make secure identifications with optical counterparts. Table 1 presents plausible radio counterparts to the submillimeter sources of Hughes et al. (1998). In several cases, the submillimeter source is obviously confused and its emission may not be limited to the discrete radio identification. The first line gives the position of the SCUBA source after translation to the radio coordinate frame with suggested radio counterparts and their optical identifications given in following lines.

1. HDF 850.1.—We present in Figure 1 the 1.4 GHz overlay of the HDF centered on the shifted SCUBA position. The precise 1.4 GHz radio position suggests the optical identification is with the faint low surface brightness object to the immediate north of the brighter foreground disk system. Richards et al. (1998) suggested that this optical feature might be associated with the z = 0.299 galaxy 3-659.1 (Williams et al. 1996). M. Dickinson (1998, private communication) report a *J*/*H*-band detection at the position of the radio source which suggests a galaxy at high redshift. However, we note the presence of a separate low surface brightness galaxy at z = 1.72 (3-633.1; Fernandez-Soto, Lanzetta, & Yahill 1998) located approximately 2″ to the northwest.

Radio source VLA J123651+621221 is a firm 15 μm *ISO* detection (Aussel et al. 1999), which is consistent with the presence of a dusty galaxy. If 3651+1221 is the most obscured part of a larger galaxy 3-633.1 at z = 1.72, the implied star formation rate is 1500 $M_{\odot}$ yr^{-1} (Salpeter initial mass function

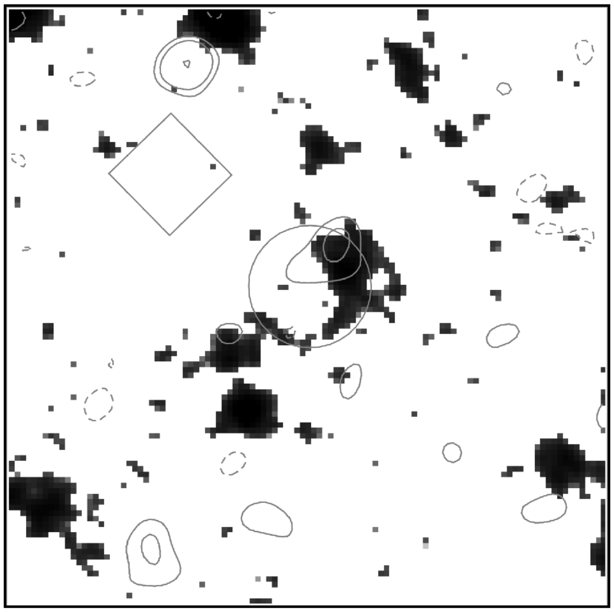

FIG. 2.—The gray scale shows a 20″ × 20″ ground-based *I*-band image taken from Barger et al. (1999) centered on the position of SCUBA source HDF 850.2. The 1.4 GHz radio contours are drawn at −2, 2, 3, and 5 σ. The symbols are as in Fig. 1. We identify HDF 850.2 with the 3.5 σ radio source VLA J123657+621159.

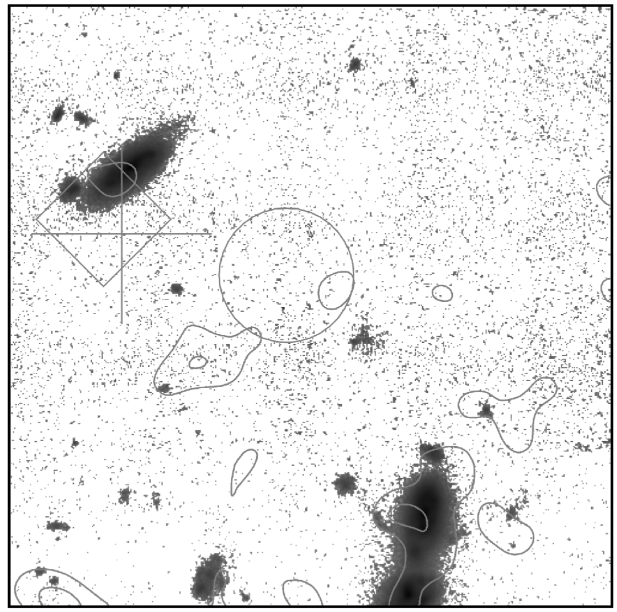

FIG. 3.—The gray scale corresponds to optical *I*-band emission in the field of SCUBA source HDF 850.3 (20″ on a side) as taken from the HDF. Radio contours at 1.4 GHz are drawn at the −2, 2, and 4 σ level. Intriguingly, there is a 4.2 σ radio "source" located 4″ from HDF 850.3. The probability of this being a chance coincidence is 20% based on the surface density of 4 σ radio sources in the field. If HDF 850.3 is associated with the radio source, then this is a blank field object to $I_{AB} = 27$ (object lies in the less sensitive Planetary Camera). However, an *ISO* source from the supplemental catalog of Aussel et al. (1999) is also in the field and associated with the bright disk galaxy 1-34.0 (Williams et al. 1996). It is difficult to discriminate between these two possible submillimeter identifications with the present data. The symbols are as in Fig. 1.

integrated over 0.1–100 $M_\odot$). Assuming a graybody dust model with an emissivity $\epsilon = 1.5$ ($\epsilon \propto \nu^\alpha$) and dust temperature 30 K, the FIR-radio flux density ratio is about 200, in good agreement with values found locally.

2. HDF 850.2.—Based on the optical/radio positional coincidence, the 3.5 σ radio source VLA J123655+621159 has a 90% reliability of being associated with a $I = 23.7$ distorted galaxy (Barger et al. 1999), according to the analysis of Richards et al. (1998). We identify the 850 μm detection with this same galaxy of unknown redshift. The *UGR* band photometry (Hogg 1998) on this galaxy suggests that it is likely at $z < 3$. Figure 2 shows the 1.4 GHz overlay of the optical field. However, we also note the presence of an optically unidentified radio source (VLA J123656+621207) located 4″ to the north of the unshifted SCUBA position. This radio source is detected independently at 1.4 GHz by a deep MERLIN image of the area (Muxlow et al. 1999). Based on its nondetection in the HDF and in deep infrared imaging (M. Dickinson 1998, private communication), VLA J123656+621207 is likely located at $z > 2$ and hence associated with a low-luminosity active galactic nucleus (AGN; $L > 10^{24.5}$ W Hz^{-1}).

3. HDF 850.3.—The radio data does little to clarify the identification of the submillimeter source in this field. Figure 3 shows a 4 σ radio source (VLA J123644+621258) located 4″ from the position of the 850 μm detection. However, before the shift the SCUBA source position is in good agreement with the position of the bright disk system 1-34.0, which is also included in the supplemental 15 μm *ISO* catalog of Aussel et al. (1999). This galaxy also has a 3 σ radio detection (VLA J123644+621304). The 0.485 redshift of this object implies a star formation rate of 40 $M_\odot$ yr^{-1} from the radio luminosity, although the presence of an AGN cannot be ruled out. At present, the data cannot discriminate between these two possible radio/submillimeter associations.

If the submillimeter detection is associated with 1-34.0, the FIR-radio correlation predicts a 1.4 GHz flux density of about 260 μJy (assuming the dust model used for HDF 850.1), in clear excess of our observed value of 23 μJy. One can bring the radio and submillimeter data into agreement with the FIR-radio correlation if the dust temperature is lowered to about 20 K.

4. HDF 850.4.—The radio source VLA J123649+621313 is associated with the spiral galaxy 2-264.1 at a redshift of 0.475. Both 7 and 15 μm *ISO* sources from the complete catalogs of Aussel et al. (1999) and Rowan-Robinson et al. (1997) have been associated with this radio source. This galaxy is likely part of the larger structure at 0.475, which contains 16 galaxies with spectroscopic redshifts (Cohen et al. 1996). At least one of these galaxies (2-264.2) lies at a small projected distance (less than 30 kpc) and suggests that dynamic interactions may be triggering the radio/submillimeter activity. Although the SCUBA and *ISO* detection may be a blend of emission from several galaxies in this crowded field (see Fig. 4), the radio emission is clearly confined to the central galaxy 2-264.1. Richards et al. (1998) estimate SFR = 80 $M_\odot$ yr^{-1}.

Can the SCUBA source HDF 850.4 plausibly be associated instead with the HDF optical galaxy 2-399.0 as claimed by Hughes et al.? If we take those authors' estimate of the FIR luminosity, $\log_{10} L_{60\mu m} = 12.47\ L_\odot$, for this galaxy, the FIR-radio relation (Condon et al. 1991) predicts an observed 1.4 GHz flux density of about 300 μJy, clearly in excess of our upper limit of 23 μJy (3 σ). We find the identification of SCUBA source HDF 850.4 with HDF galaxy 2-399 to be dubious and instead identify HDF 850.4 with 2-264.1.

Similar to the arguments for HDF 850.3, if we require the

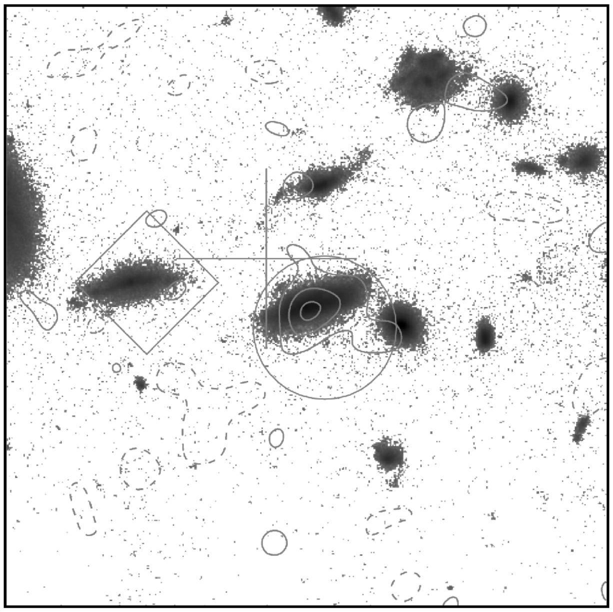

FIG. 4.—Radio 1.4 GHz contours drawn at the −2, 2, 4 and 6 σ level are overlaid on the HDF *I*-band image centered on the position of HDF 850.4 (20″ on a side). A 15 μm detection from the complete catalog of Aussel et al. (1999) has been associated with this radio source and suggests likely starburst activity in the disk galaxy. The symbols are as in Fig. 1.

FIR-radio correlation to not be violated, then the dust in HDF galaxy 2-264.1 must have a temperature $T \sim 20$ K.

5. HDF 850.5.—There is no 1.4 GHz radio emission apparent to the 2 σ limit of 15 μJy in this field. Optically there are only two plausible identifications for the 850 μm source: HDF galaxies 2-395.0 and 2-349.0. The redshift of 2-395.0 is 0.72 (Fernandez-Soto et al. 1998). The radio flux limit on this galaxy excludes an SFR $\geq 100\ M_\odot\ \mathrm{yr}^{-1}$. The other possible identification (2-349.0) is at an unknown redshift. The nondetection of this submillimeter source at radio or optical wavelengths coupled with the fact that this is the weakest source in the Hughes et al. (1998) catalog suggests that this source may be spurious. We also note that this submillimeter source is located only 12″ from submillimeter detection HDF 850.4 and hence suffers from confusion.

5. CONCLUSIONS

Of the five 850 μm sources in the HDF, two are solidly detected at radio wavelengths, while two are probable detections. Two of these identifications are possibly with $z \sim 0.5$ starbursts (HDF 850.3 and HDF 850.4). The other two detections (HDF 850.1 and HDF 850.2) must have redshifts less than 2 or be contaminated by an AGN in order to not have implausible radio implied star formation rates (SFR $\gtrsim 1000\ M_\odot\ \mathrm{yr}^{-1}$). This radio analysis suggests the claim, based on submillimeter observations alone, that the optical surveys underestimate the $z > 2$ global star formation rate are premature. On the other hand, the $z < 1$ star formation history may have been underestimated if a significant fraction of the submillimeter population lies at relatively low redshift. The submillimeter emission from these low-z systems must predominately be from cold dust ($T \lesssim 30$ K) in order to obey the radio-FIR relation.

In the absence of high-resolution submillimeter imaging capability, it is necessary to rely on plausible radio counterparts of submillimeter sources in order to provide the astrometric accuracy needed to make the proper optical identifications. Only complete redshift samples of the submillimeter population coupled with diagnostic spectroscopy and high-resolution radio data will allow for calculation of the epoch-dependent submillimeter luminosity function and its implication for the star formation history of the universe.

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