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A POPULATION OF HOT, DUSTY ULTRALUMINOUS GALAXIES AT $z \approx 2$

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ABSTRACT

We report spectroscopic redshifts for 18 μJy radio galaxies at a mean redshift of $z = 2.2$ that are faint at both submillimeter and optical wavelengths. While the radio fluxes of these galaxies could indicate far-IR luminosities comparable to high-redshift submillimeter-selected galaxies ($\gtrsim 10^{12}\ L_\odot$), none are detected in the submillimeter. We propose that this new population of galaxies represents an extension of the high-redshift submillimeter galaxy population but with hotter characteristic dust temperatures that shift the peak of their far-IR emission to shorter wavelengths, reducing the submillimeter flux below the sensitivity of current instruments. Therefore, surveys in the submillimeter waveband may miss up to half of the most luminous, dusty galaxies at $z \approx 2$. Mid-infrared observations with the *Spitzer Space Telescope* will be a powerful tool to test this hypothesis.

Subject headings: cosmology: observations — galaxies: evolution — galaxies: formation — galaxies: starburst

Online material: color figures

1. INTRODUCTION

The microjansky radio population ($S_{1.4\,\mathrm{GHz}} > 30\ \mu$Jy) has been the key to pinpointing and studying the submillimeter galaxies (SMGs; Ivison et al. 1998, 2002; Barger et al. 2000; Smail et al. 2000; Chapman et al. 2001, 2002, 2003c). Approximately 40% of μJy radio sources with optical magnitudes $R > 23.5$ (the optically faint radio galaxies or OFRGs) are detected at $S_{850\,\mu\mathrm{m}} \gtrsim 5$ mJy with the Submillimeter Common-User Bolometric Array (SCUBA) on the James Clerk Maxwell Telescope (JCMT), and conversely 65%–70% of SMGs brighter than this flux limit have reliable radio identifications. A spectroscopic survey of radio-identified SMGs has measured redshifts for 73 SMGs (Chapman et al. 2003a, 2004a), allowing us to constrain their dust temperatures, luminosities, star formation rates, evolution, clustering strength, and dynamical and gas masses (Chapman et al. 2003a, 2004a; Blain et al. 2004a, 2004b; Neri et al. 2003; T. Greve et al. 2004, in preparation; Smail et al. 2003, 2004; Swinbank et al. 2004). With these measurements for a representative sample of submillimeter-bright galaxies, we can now study the properties of obscured galaxies at $z \approx 2$ as easily as the typically less obscured UV-selected population (Steidel et al. 2004).

However, there remains the question of the nature of the ~60% of the OFRGs that are not bright submillimeter sources. Chapman et al. (2003c) attempted a comprehensive study of the whole microjansky radio population but could not constrain the nature of those OFRGs without submillimeter detections. This was mostly due to a lack of spectroscopic redshifts for these galaxies, which could thus either be interpreted as moderate-luminosity star-forming galaxies at intermediate redshifts, $z \approx 0.5$, or alternatively, bolometrically luminous galaxies at similar redshifts to the SMG population but that are not detectable in the submillimeter waveband. The latter possibility exists because submillimeter flux is a relatively poor proxy for the bolometric luminosity of a galaxy, being strongly sensitive to the characteristic dust temperature (Blain 1999; Eales et al. 2000). The dependence for galaxies at $z \approx 2$ follows the approximate form $S_{850\,\mu\mathrm{m}} \simeq T_d^{-3.5} L_{\mathrm{TIR}}$; even a small increase in T_d implies a large decrease in observed submillimeter flux density (see Fig. 1).

To investigate the nature of the submillimeter-faint OFRGs, we have undertaken a spectroscopic survey of this population in parallel with the SMG redshift survey of Chapman et al. (2004a, hereafter C04). In § 2 we describe the sample and our observations. § 3 presents our findings, and § 4 discusses these and gives our conclusions. All calculations assume a flat, ΛCDM cosmology with $\Omega_\Lambda = 0.7$ and $H_0 = 72$ km s^{-1} Mpc^{-1}.

2. SAMPLE AND OBSERVATIONS

The sample studied here is defined by selecting all radio sources in seven separate fields (CFRS-03, Lockman Hole, HDF, SSA 13, Westphal-14, ELAIS N2, and SSA 22) that have either been targeted with SCUBA (Holland et al. 1999) in photometry mode or lie within existing SCUBA maps in these regions and that lack an optical counterpart brighter than $R = 23.5$. The latter criteria has the effect of eliminating the lowest redshift, low-luminosity sources as well as optically bright active galactic nuclei (AGNs) at high redshifts (the $R > 23.5$ condition implies that stellar-luminosity quasars and optical AGNs are excluded from our sample for $z \approx 2$; Boyle et al. 2000). For comparison to earlier work on OFRGs, we note that the typical color of galaxies at $R > 23.5$ is $(R - I) \approx 0.5$ (Smail et al. 1995). We note that a less stringent cut in optical faintness ($R > 23$) leads to a significantly larger number of broad-line QSOs and low-redshift star-forming systems in the sample.

The radio data in CFRS-03, Lockman Hole, Westphal-14, ELAIS N2, and SSA 22 were obtained and reduced as part of our own programs (C04) and reaches rms sensitivities of 4–10 μJy. Details of the Lockman Hole and ELAIS N2 radio data and their reduction can be found in Ivison et al. (2002), and this description is applicable to the other data sets. The HDF and

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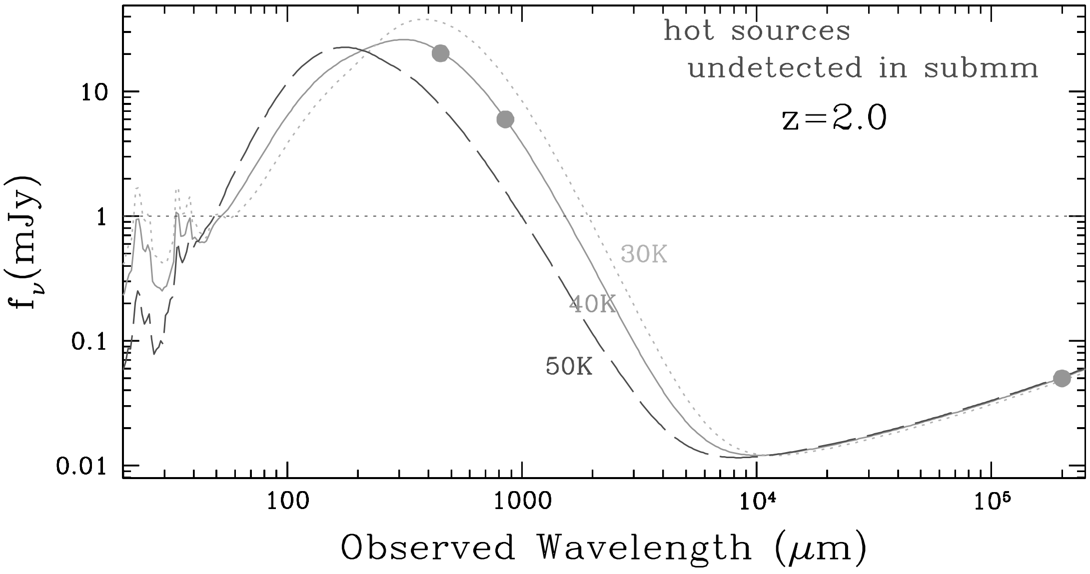

FIG. 1.—Far-IR/radio spectral energy distributions (SEDs) for galaxy templates with identical far-IR luminosities but characteristic dust temperatures corresponding to 30, 40, and 50 K graybodies with dust emissivities $\beta = 1.60$, 1.55, and 1.50, respectively (Dale et al. 2001). The points represent a typical 6 mJy SCUBA galaxy at 850 and 450 μm (*filled circles*) from the SMG sample of C04 with a dust temperature of 40 K. As can be seen, galaxies with similar luminosities and similar radio fluxes but with SEDs that are characterized by a dust temperature hotter than $\sim$50 K will have 850 μm fluxes less than $\sim$1 mJy at $z = 2$ and thus will be undetectable in current submillimeter surveys. Note that 24 μm emission is definitely detectable by *Spitzer* at a level of 0.1 mJy. [*See the electronic edition of the Journal for a color version of this figure.*]

SSA 13 radio data were obtained from E. A. Richards (2004, private communication), and reach rms sensitivities of 8 and 5 μJy, respectively. The HDF data is described in Richards (2000), while the SSA 13 data is so far unpublished (a subsequent reduction of the SSA 13 data is described in E. Fomalont et al. 2004, in preparation). Submillimeter fluxes were measured for all optically faint radio sources in these regions from either targeted photometry-mode observations with SCUBA in these fields by our group (the technique is described in Chapman et al. 2001) or from our reduced SCUBA maps of these fields taken and reduced from the JCMT archive, using a weighted 3 beam extraction. In the latter case, to avoid contamination from bright submillimeter sources unrelated to the OFRGs, the maps were first cleaned of all other sources brighter than 3 σ before the fluxes were measured. Original presentations of some of the submillimeter maps in these fields are given in the following papers: CFRS-03 (Webb et al. 2003), Westphal-14 (Eales et al. 2000), Lockman Hole and ELAIS N2 (Scott et al. 2002), HDF, SSA 13, and SSA 22 (Barger et al. 1999, 2000).

We then refine our sample further by discarding any sources that are either nominally detected in the submillimeter at $\geq$2.5 σ or have 2.5 σ limits on their submillimeter fluxes that are consistent with them being brighter than 5 mJy at 850 μm. This guarantees that the final sample is much fainter in the submillimeter than the C04 sample, which has a mean submillimeter flux of $S_{850\,\mu\mathrm{m}} = 6.6$ mJy, with two-thirds brighter than 5 mJy. As we show later, the typical submillimeter flux for the OFRGs in our survey is only $\sim$0.5 mJy, and so most of these galaxies lie far below the confusion limit of current blank-field submillimeter surveys.

These selection criteria result in a parent catalog of 60 submillimeter-faint and optically faint radio galaxies. We note that there is a comparably sized sample of OFRGs that are not formally detected in the submillimeter but whose submillimeter limits are still consistent with detections, with an average $S_{850\,\mu\mathrm{m}} = 2.1$ mJy, which are discussed in C04. Note that of the 169 radio sources whose redshifts were used in the analysis of Chapman et al. (2003b), none satisfy the criteria for inclusion in this catalog, as they all have $R < 23.5$.

A random subset of 36 of the 60 submillimeter-faint OFRGs were spectroscopically observed with LRIS (Oke et al. 1995; Steidel et al. 2004) on Keck in several observing runs throughout 2002, 2003, and 2004 under generally good conditions ($\sim0\farcs8$–$1\farcs0$ seeing). All the spectra cover the observed wavelength range from 0.3 μm out to as much as 0.8 μm (depending on the slit position in the mask and the grating used on the red arm of LRIS: 400 or 600 lines mm^{-1}). Exposure times were 1.5–4.5 hr split into 30 minute integrations. Data reduction followed standard techniques using custom IRAF scripts. One-dimensional spectra were extracted and compared with template spectra and emission-line catalogs to identify redshifts. All identifications are based on multiple features, most prominently the Lyα line, along with weaker stellar/interstellar/AGN features and/or continuum breaks (Fig. 2).

We obtain secure redshifts for 18 submillimeter-faint OFRGs in our sample, giving a spectroscopic completeness for this sample of only 50%. While relatively low, this completeness level is sufficient to elucidate some of the basic properties of this population. We note that all the OFRGs in our sample from the HDF and SSA 13 fields (including both the sources presented in Table 1 and the sources we exclude from the present sample because their submillimeter limits are consistent with marginal detections) were included in the OFRG samples in Chapman et al. (2003c). However, spectroscopic identifications have not been previously presented for any of these galaxies. The OFRGs in the remaining five fields are presented for the first time here.

We stress that this "secure" spectroscopic sample is conservatively restricted to those galaxies with the very best spectral identifications (with two or more reliable features). Of the remaining 18 nominally *unidentified* sources in our sample, many have either solitary bright emission lines or several weak features that would put them into the same redshift range as

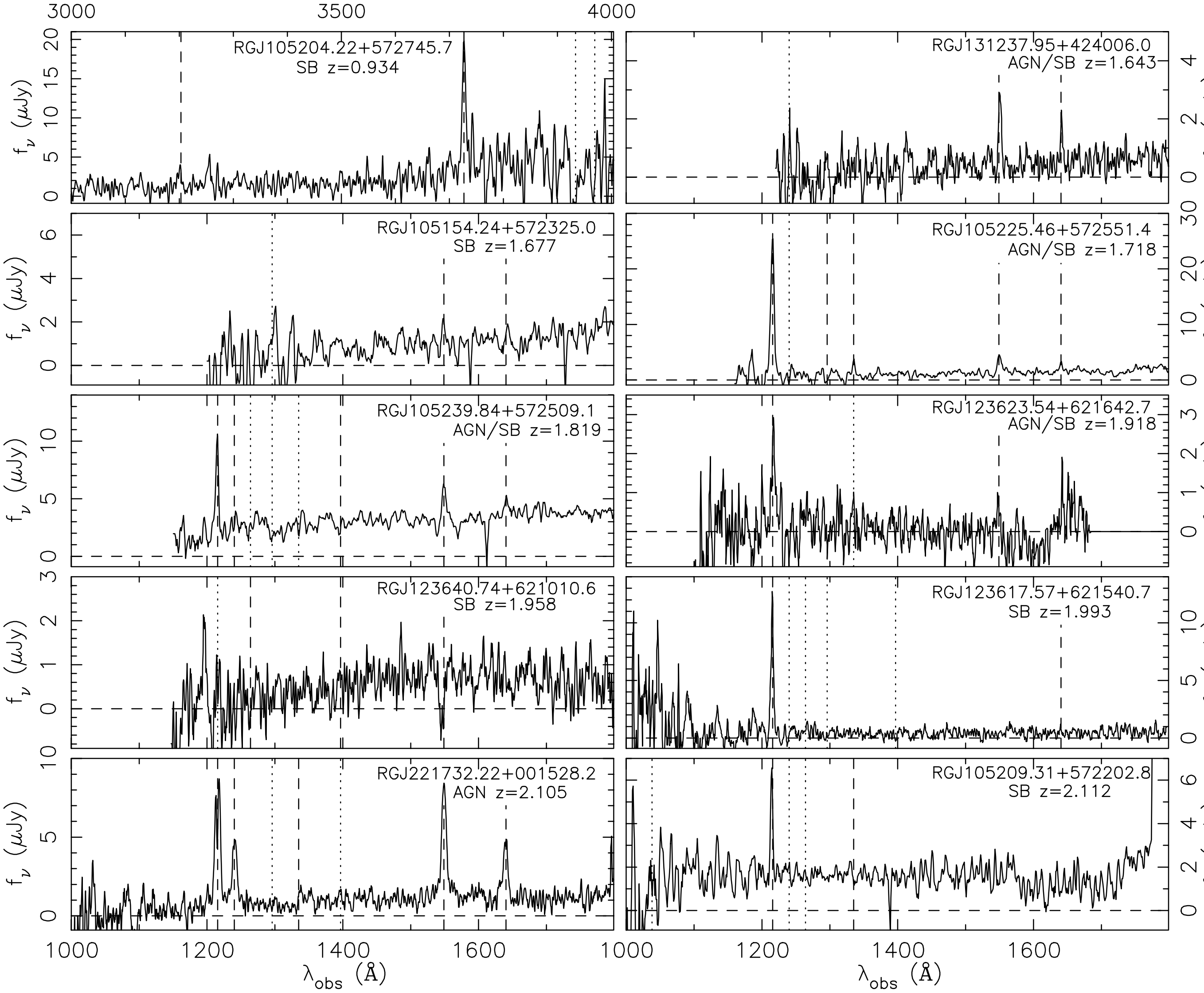

FIG. 2.—Spectra of all sources from our sample, showing the typical spectral characteristics of our observations and this class of galaxies. The spectral features used to measure the redshifts and classify the spectra, either starburst (SB) or AGN, are marked. The identified lines are: O VI $\lambda1038$, Lyα $\lambda1215$, N V $\lambda1240$, Si II $\lambda1264$, C III] $\lambda1296$, C II $\lambda1335$, Si IV $\lambda1396$, C IV $\lambda1549$, He II $\lambda1640$, and (for RG J105204.22+572745.7) He II $\lambda3203$, [O II] $\lambda3727$, and Ca H and K. We use dashed lines for primary line identifications and dotted ones for supporting identifications. The reader should note the close similarity between these spectra and those measured for the SMG population by C03 and C04.

those presented in this paper. The emission lines are likely to be either Lyα, when no continuum was detected and the wavelength was <4500 Å, or [O II] $\lambda3727$ if continuum was detected on both sides of the line and the wavelength was $\gg$4500 Å. We illustrate the spectra for the securely identified sample in Figure 2 and in Table 1 list their observational properties: their positions, redshifts, submillimeter and radio fluxes and optical magnitudes, limits on their dust temperatures T_d, total infrared luminosities $L_{\rm TIR}$, and spectral class (divided into starburst [SB], AGN/SB, or AGN). $L_{\rm TIR}$ was calculated based on the redshift and radio flux densities, *K*-correcting the synchrotron spectrum with an index $\alpha = 0.8$ (Richards 2000), and assuming the local far-IR–radio correlation (Condon et al. 1991; Helou et al. 1985). The derived T_d and $L_{\rm TIR}$ are plotted in Figure 3.

Our spectral classes are derived from the UV spectral properties as follows: SB, no C IV $\lambda1549$ emission detected at ≥3 σ above the noise; AGN/SB, detectable C IV $\lambda1549$ emission but also robust interstellar absorption lines (most notably Si II $\lambda1264$, O I/S I $\lambda1303$, and C II $\lambda1335$), which would be heavily diluted/undetected if an AGN dominated the UV continuum emission; AGN, showing significant C IV $\lambda1549$ emission with no detectable interstellar absorption features. The C IV/Lyα ratio has been used as an AGN diagnostic in previous studies of high-redshift galaxies. This ratio has a mean of 0.2 for the AGN subsample of $z \approx 3$ Lyman break galaxies (LBGs) selected by Steidel et al. (2002) and a value of 0.12 for the composite radio galaxy spectrum presented by McCarthy (1993). McCarthy (1993) and references therein argue that the ensemble properties of high-redshift radio galaxies (indications of a hard photoionizing spectrum, alignment of emission-line and radio major axes, and possible correlation between $L_{\rm radio}$ and $L_{\rm [O\,III]}$) suggest they are predominantly AGN powered. All of our OFRGs with AGN or AGN/SB classifications have C IV/Lyα > 0.12. We also note that strong C IV $\lambda1549$ emission is present in some *classical* luminous radio galaxies that also exhibit interstellar absorption lines in the UV (e.g., 4C 41.17;

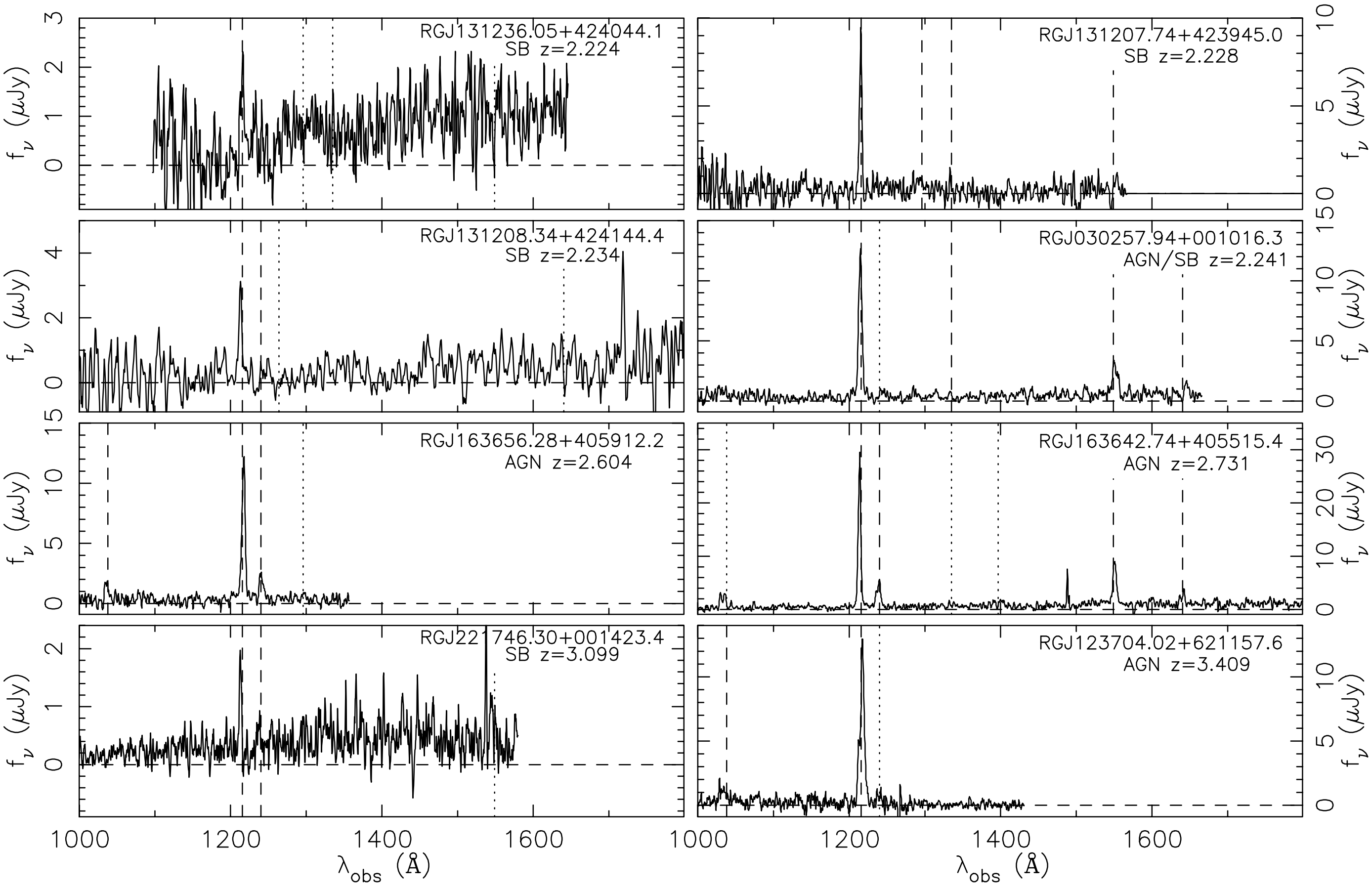

Fig. 2.—*Continued*

TABLE 1

Properties of Submillimeter-Quiet OFRGs

ID	$S_{1.4\ \mathrm{GHz}}$ (μJy)	R	$S_{850\ \mu\mathrm{m}}$ (mJy)	z	T_d (K)	L_{TIR} ($10^{12}\ L_\odot$)	Spectral Type
RG J030257.94+001016.3.....	55.1 ± 9.8	25.7	0.2 ± 1.5	2.241	≥46	7.7	AGN/SB
RG J105209.31+572202.8.....	39.4 ± 5.4	24.6	1.6 ± 1.3	2.112	≥40	7.6	SB
RG J105239.84+572509.1.....	43.6 ± 5.1	23.5	−1.0 ± 1.4	1.819	≥38	3.5	AGN/SB
RG J105225.46+572551.4.....	36.1 ± 5.4	24.4	−0.6 ± 1.7	1.718	≥34	2.4	AGN/SB
RG J105154.24+572325.0.....	46.7 ± 5.2	24.4	−0.1 ± 1.3	1.677	≥34	2.8	SB
RG J105204.22+572745.7.....	42.9 ± 6.1	23.9	−2.1 ± 1.7	0.934	≥29	0.5	SB
RG J123617.57+621540.7.....	200.0 ± 12.8	24.7	2.1 ± 1.0	1.993	≥66	20.3	SB
RG J123623.54+621642.7.....	481.0 ± 25.4	24.1	1.6 ± 1.1	1.918	≥79	43.8	AGN/SB
RG J123640.74+621010.6.....	86.8 ± 8.8	25.8	−1.5 ± 1.7	1.958	≥45	8.4	SB
RG J123704.02+621157.6.....	41.1 ± 8.9	26.2	−1.4 ± 0.8	3.409	≥55	16.3	AGN
RG J131207.74+423945.0.....	44.9 ± 2.4	24.8	−1.1 ± 1.9	2.228	≥40	6.2	SB
RG J131208.34+424144.4.....	37.6 ± 4.0	25.2	1.8 ± 1.5	2.234	≥41	5.2	SB
RG J131236.05+424044.1.....	48.7 ± 4.3	24.1	0.4 ± 1.1	2.224	≥48	6.7	SB
RG J131237.95+424006.0.....	39.9 ± 4.3	24.1	−0.1 ± 0.9	1.643	≥39	2.4	AGN/SB
RG J163642.74+405515.4.....	55.1 ± 8.6	24.7	1.2 ± 1.5	2.731	≥44	6.7	AGN
RG J163656.28+405912.2.....	30.9 ± 8.6	25.3	−0.5 ± 1.4	2.604	≥41	6.6	AGN
RG J221732.22+001528.2.....	49.8 ± 5.6	24.5	−0.1 ± 1.1	2.105	≥46	5.9	AGN
RG J221746.30+001423.4.....	38.8 ± 8.6	24.2	1.0 ± 1.4	3.099	≥54	13.6	SB

Notes.—T_d limits derived using 2 σ limits from the submillimeter. L_{TIR} was calculated assuming the local far-IR/radio correlation (Helou et al. 1985) with a total infrared color correction term calculated at the T_d limit.

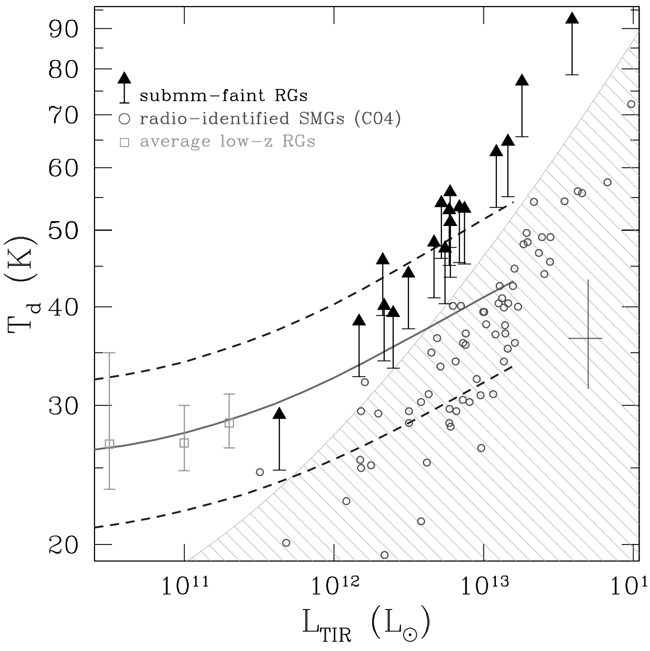

FIG. 3.—Distribution of dust temperature, T_d, versus total infrared luminosity ($L_{\rm TIR}$, 8–1100 μm) for submillimeter-faint radio sources with spectroscopic redshifts from our sample. A lower limit on T_d has been calculated assuming a 2 σ upper limit to the submillimeter flux of each source. For comparison, we show the radio-submillimeter galaxies from Chapman et al. (2003c) and C04, with the average error bar shown to the right. The typical sensitivity limit of surveys precludes detection in the submillimeter waveband of sources in the unshaded region. The C03 derivation of the range of local *IRAS* galaxies from the 1.2 Jy 60 μm catalog are shown as a ± 2 σ envelope. The average T_d for optically bright radio sources at $z = 0.3$–1 from Chapman et al. (2003b) are shown as open squares, lying well within the local ± 2 σ distribution. [*See the electronic edition of the Journal for a color version of this figure.*]

Dey et al. 1997). Both of these facts mean that our classifications should be interpreted with caution.

3. ANALYSIS AND RESULTS

Our survey shows that the submillimeter-faint OFRGs are a high-redshift galaxy population; the mean redshift of our sample is $z = 2.2$ with an interquartile range of ± 0.3 and a full range spanning $z = 0.9$–3.4. At such high redshifts, these galaxies are bolometrically luminous, all but one with $L_{\rm TIR} > 10^{12}$ $L_\odot$ and four with $L_{\rm TIR} > 10^{13}$ $L_\odot$ (Table 1, Fig. 3), assuming the local far-IR–radio correlation holds. These luminosities are comparable to those estimated for the submillimeter-detected population uncovered by SCUBA (Chapman et al. 2003a, hereafter C03), as shown in Figure 3. Moreover, the redshift range populated by the submillimeter-faint OFRGs is the same as that inhabited by SMGs (C03; C04), which have a median of $z = 2.3 \pm 0.4$. The two populations also have very similar optical and radio characteristics; the 18 spectroscopically identified, submillimeter-faint OFRGs have a median R-band magnitude of $R = 24.6 \pm 0.2$ and a median radio flux of $S_{1.4\,\rm GHz} = 79 \pm 26$ μJy, comparable to the values seen for the submillimeter-detected radio sources in the C04 sample: $R = 24.1 \pm 0.2$ and $S_{1.4\,\rm GHz} = 74 \pm 6$ μJy (although with the caveat that SMGs are not restricted to $R > 23.5$).

The similarity of the OFRG and SMG populations extends to their UV spectral properties, where a comparison of Figure 2 and the spectra presented in C03 and C04 shows that the spectral characteristics of both submillimeter-bright and submillimeter-faint radio galaxies are very similar. The spectra of the submillimeter-faint OFRGs span a range from pure starburst (similar to the $z \approx 2$–3 population selected in the rest-frame UV; Shapley et al. 2003) to low-luminosity narrow-line or type II AGN with enhanced N V λ1240 and/or C IV λ1549 emission. Although we see no broad-line type I AGN, this is not particularly surprising given our optical limit was chosen to exclude them. The galaxy spectra in which AGN signatures dominate comprise about 20% of the submillimeter-faint OFRG sample, with the SMG sample of C04 exhibiting a similar fraction. These AGNs are spectrally similar to the rest-frame UV-selected AGN at $z \approx 3$ described in Steidel et al. (2002), although those galaxies are typically undetected in the radio. An additional quarter of our OFRGs exhibit interstellar absorption features in the UV continuum but also show significant AGN emission lines (e.g., C IV λ1549, He II λ1640), which we classify as hybrid AGN/SB. The UV spectra of the remainder of our spectroscopically identified OFRGs, consisting of half of the sample, show no detectable signs of AGN. An Hα survey of OFRGs and SMGs (Swinbank et al. 2004) broadly supports the pure-starburst classification from the UV; galaxies identified as SB from the UV typically show narrow Hα line widths ($<$500 km s^{-1}) and low [N II]/Hα ratios typical of star-forming galaxies. Moreover, we note that those galaxies for which we failed to identify a redshift were either undetected on the slit, showed no obvious features in the weakly detected continuum, or showed only a single spectral feature as described above. Some of these galaxies are likely to be high-redshift starbursts, since AGN lines would likely have been identified even with the faint continuum magnitudes. However, a low-redshift starburst interpretation would still be consistent with several of these galaxies. We can conclude that less than half of the OFRG sample are likely to show any spectral signatures of an AGN, similar to the spectroscopically classified SMG population.

In fact, there is only one characteristic that differs substantially between our submillimeter-faint OFRG sample and the SMGs in C03 and C04: the average 850 μm flux of the galaxies. The C04 sample has an average flux of 6.6 mJy, whereas the submillimeter-faint OFRGs have a variance-weighted average of only $S_{850\,\mu\rm m} = 0.5 \pm 0.3$ mJy, an order of magnitude fainter. Why are these apparently ultraluminous galaxies, which share many features with the submillimeter-bright, high-redshift SMG population, so faint in the submillimeter waveband? As illustrated in Figure 1, this could either reflect enhanced radio emission, relative to the far-IR, compared to that normally seen in star-forming galaxies, or a hotter characteristic dust temperature than that of the submillimeter-detected population at these redshifts. We discuss these alternatives in turn.

Radio emission from an AGN is one possible route to increase the radio fluxes of these galaxies but not increase their far-IR luminosities, and thus leave them undetectable in the submillimeter waveband. We see some signatures of an AGN in half of our sample with robust redshifts; however, to significantly perturb the radio fluxes of these systems we would require a substantial contribution from the AGN and hence a luminous, central AGN. The spectral features we see can arise at a relatively large radius (for instance, in the outer parts of the accretion disk around the AGN and beyond; e.g., Hutchings et al. 1998), and so it is possible that dust in the very central regions is obscuring the true luminosity of the AGN in the rest-frame UV. Optically thin radio emission could still escape from these regions, and hence high spatial resolution radio observations would identify a strong central point source. Moreover, X-ray emission from the AGN can also escape, and hence sensitive X-ray observations can be used to search for luminous but highly obscured AGN in these galaxies. Both of these observational tests can be applied to the OFRGs lying in the well-studied HDF region.

Of the four OFRGs lying in the HDF region, two have rest-frame UV spectra that are classed as starbursts, one is an AGN/SB, and one is classed as an AGN. None of the galaxies spectrally classified as starbursts or AGN/SB are detected in the 2 Ms *Chandra* HDF observation, while the AGN is (Alexander et al. 2003). To provide a more general comparison, we take advantage of the spectral similarity of SMG and submillimeter-faint OFRGs to combine our sample with that of C04 to provide 12 luminous, dusty, high-redshift galaxies with AGN signatures and 20 with starburst spectra within the *Chandra* HDF. In the 2 Ms *Chandra* image, the 12 sources showing AGN signatures in their UV spectra are all detected in the X-ray data, whereas only nine of the sources showing starburst spectra are detected. Moreover, the average 2–8 keV X-ray flux of those SMGs/OFRGs with AGN-like spectra are roughly an order of magnitude greater than the galaxies with starburst spectra, whose X-ray fluxes are more consistent with that expected from the X-ray binary star emission from a $\sim 10^3\ M_\odot\ \mathrm{yr}^{-1}$ starburst (see D. Alexander et al. 2004, in preparation).

The high-resolution radio observations of the sources in the HDF come from the MERLIN/Very Large Array (VLA) map of this region (T. Muxlow et al. 2004, in preparation; see also Chapman et al. 2004b) and have 0.″3 resolution, sufficient to identify nuclear radio sources on sub-kiloparsec scales. These data show that the radio morphologies for the starburst-classified OFRGs are often extended and clumpy on $\sim 1''$ (~ 8 kpc) scales, while some galaxies with signs of AGN in their UV spectra also show similar radio morphologies (Chapman et al. 2004b). This indicates that the majority of the radio emission from these galaxies is not coming from a central point source or from low-luminosity analogs of classical radio jets. Hence, we conclude that the majority of these galaxies do not have AGN-enhanced radio emission and thus they must be bolometrically luminous systems.

Why then are these galaxies undetected in the submillimeter, where we detect comparably luminous dusty galaxies at these redshifts (C04)? The answer must lie in the characteristic temperature of the dust emission in these galaxies. This is shown in Figure 3, which depicts the distribution on the T_d-L_{TIR} plane of the local *IRAS* galaxy distribution (Chapman et al. 2003b) and the locations of the radio-detected SMGs at $z > 1$ from C04. A representative flux limit for current submillimeter surveys is shown by the shaded region. This demonstrates that hot, high-luminosity dusty galaxies could be at similar redshifts to the SMGs, $z > 2$ and detectable in the radio but not at 850 μm with SCUBA (see also Blain et al. 2004b). Using the average error-weighted flux for the submillimeter-faint OFRG sample, we can estimate the characteristic dust temperature these galaxies must have, $\gtrsim 50$ K, rather than the ~ 36 K of the submillimeter-detected population. While the dust-temperature distributions of the SMG and OFRG populations overlap, Figure 3 shows that the samples are distinct in $T_d/(1+z)$. The total range in T_d spanned by luminous galaxies at high redshift could be a factor of two larger than that implied by submillimeter-selected galaxies alone (Blain et al. 2004a; C04).

We conclude that the submillimeter-faint OFRGs are most likely *hotter* relatives of the SMGs detected at high redshift. These galaxies have far-IR luminosities of $>10^{12}\ L_\odot$ and appear to be predominantly powered by starbursts, as shown by the relative weakness of AGN signatures in the UV, X-ray, or radio wavebands. While our L_{TIR} estimates rely on the validity of the local far-IR–radio correlation (Condon et al. 1991; Helou et al. 1985), if the correlation is very different at $z \approx 2$, then it would affect the luminosity calculations for the SMGs and submillimeter-faint OFRGs in a similar manner, and they would still remain comparably luminous populations.

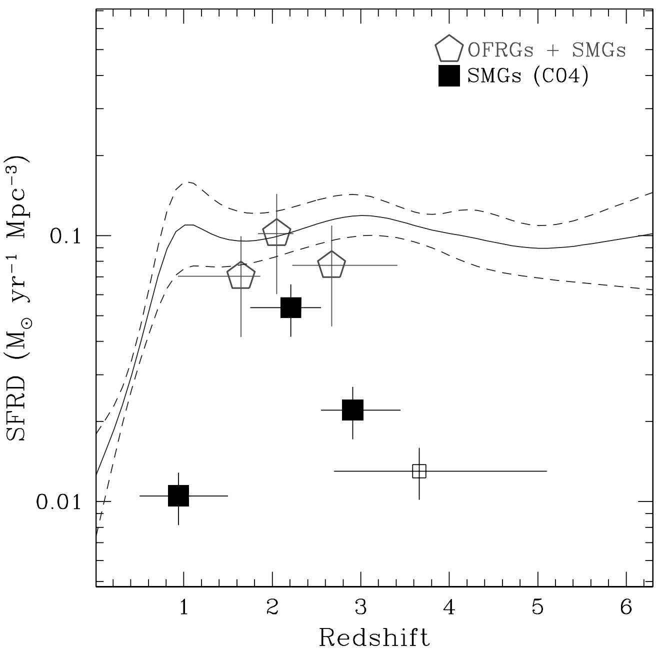

FIG. 4.—Evolution of the energy density (parametrized by SFRD) in the universe with epoch. Submillimeter measurements ($S_{850\,\mu\mathrm{m}} > 5$ mJy) from C04 are shown at the median value for each redshift bin. Radio-identified SMGs with spectroscopic redshifts are shown with filled squares, while an estimate for the 35% of SMGs undetected in the radio is shown with an open square. The new OFRG measurements are added to the submillimeter-inferred fitted values to demonstrate the current lower limits on the extent of obscured star formation activity at high redshifts from populations that are fully quantified and detected. This observed radio+submillimeter total SFRD is compared to a fit to the published estimates from optical/UV surveys corrected for dust extinction of the star formation density (short dashed lines show the ±1 σ envelope; the fit is derived by C04 from a compilation from Blain et al. 2002 and includes data from Giavalisco et al. 2004, Steidel et al. 1999, Connolly et al. 1997, Yan et al. 1999, Flores et al. 1999, and Yun et al. 2001). [*See the electronic edition of the Journal for a color version of this figure.*]

The volume density of submillimeter-faint OFRGs at $z \approx 2.2$ are comparable to that of the SMGs (C03; C04), with $\rho = (6.2 \pm 2.3) \times 10^{-6}\ \mathrm{Mpc}^{-3}$ for $1 < z < 3$. This suggests that around half of the ultraluminous infrared galaxies at $z \approx 2.2$ are missed by existing submillimeter selection criterion and that the total volume density of $\gtrsim 4 \times 10^{12}\ L_\odot$ galaxies at this epoch is $1.3 \times 10^{-5}\ \mathrm{Mpc}^{-3}$. We illustrate this by calculating the star formation rate densities (SFRD) for our sample of 18 OFRGs divided into three redshift bins (Fig. 4). We note that the far-IR emission from between 20%–50% of our sample may include a contribution from an AGN; however, this downward revision in the estimated SFRD would be compensated by including those (predominantly star-forming) OFRGs for which we have only obtained single-feature redshifts and which therefore are not included in this estimate. We translate our luminosity-density measurements into a star formation density using the average standard calibration of $1.9 \times 10^9\ L_\odot\ (M_\odot\ \mathrm{yr}^{-1})^{-1}$ (Kennicutt 1998) and add the results to the SFRDs of submillimeter galaxies in Figure 4. This reveals that the *observed* OFRG and submillimeter galaxy samples have a SFRD at $z \approx 2$, comparable to rest-frame-UV–selected galaxies after correcting the latter for dust extinction by a factor of 5. The space density of these luminous galaxies has decreased a thousandfold over the last 11 Gyr to just $\sim 10^{-8}$ Mpc^{-3} at the present-day where the *IRAS* survey selected all the most luminous, low-redshift, dusty galaxies regardless of dust temperature. This evolution is far stronger than is seen in less luminous galaxies and underlines the importance of tracing obscured activity to understand the earliest phases of galaxy formation in the universe.

We can further demonstrate the decoupling of the unobscured and obscured surveys of distant, star-forming galaxies by investigating the limited extent to which the huge infrared luminosities of the OFRGs are traced by their rest-frame UV emission. By design, these galaxies are faint in the optical and typically very faint in the UV. Using the deep *UBR* photometry of OFRGs lying in the HDF, Lockman, and SA 22 fields, we determine that there is some overlap of the colors and UV luminosities of the OFRGs with populations of $z \approx 2$ galaxies selected in the UV (Steidel et al. 2004). Hence, some OFRGs have UV-predicted SFRs similar to those of the Steidel et al. galaxies (Reddy & Steidel 2004). However, these are well below the star formation rates implied by the radio emission ($\sim 10^3\ M_\odot$ yr^{-1}). A similar mismatch arises locally when one considers the faint UV emission and blue colors of some dusty ultraluminous infrared galaxies (ULIRGs; e.g., Goldader et al. 2002).

4. DISCUSSION AND CONCLUSIONS

Looking at the similarity in the median redshifts of the SMG and submillimeter-faint OFRG samples, it is tempting to conclude that the evolution of these two populations must be similar. However, there are substantial differences in the *K*-corrections between submillimeter- and radio-selected samples. While the SMG redshift survey (C03; C04) includes a radio-selection criteria, the total SMG population is constrained by both a knowledge of the underlying parent population (C04) and the benefits of a negative submillimeter-wave *K*-correction that maps a flux limited survey into a luminosity-limited survey. Unfortunately, at $z \gtrsim 3$ the radio fluxes of the submillimeter-faint OFRGs begin to fall below the current sensitivity limits of the VLA. Hence for the submillimeter-faint OFRGs, we are unable to state whether the population seen at $z \approx 2$–3 can extend to much higher redshifts with a comparable luminosity density (analogous to the apparently constant comoving luminosity density in UV-selected populations at $z \gtrsim 2$–4; Steidel et al. 1999; Giavalisco et al. 2004).

Understanding the relationship between the submillimeter-faint OFRGs, the submillimeter-brighter galaxies (C04), and other high-redshift populations (Franx et al. 2003; Daddi et al. 2003; Steidel et al. 2004) will be helped by comparing the strength of the clustering, both within and between the different classes. Unfortunately, this will require substantially larger samples than are currently available. However, it is worth pointing out that the statistics of pairs of submillimeter-faint OFRGs within 1200 km s^{-1} of each other in these fields are comparable to those found for SMGs by Blain et al. (2004a), and similar calculations for the OFRG sample would yield an estimate of the correlation length $r_0 \approx 8\ h_{100}^{-1}$ Mpc, among the highest clustering amplitudes seen for any high-*z* population. In addition, several of these submillimeter-faint OFRGs lie within the SMG *associations* described in Blain et al. (2004a), suggesting a close relationship between SMGs and OFRGs. These arguments provide circumstantial support for our claim that we have indeed found a new population of extremely luminous galaxies comparable to the SMGs.

Our discovery of this new, luminous galaxy population at $z \approx 2$ could have several implications. The most important is that the census of the most luminous star formation at the peak epoch in quasar activity ($z \approx 2.2$) is seriously incomplete when only the submillimeter-bright fraction is considered. We suggest therefore that the $z \approx 2$ star formation rate density has been underestimated in studies to date (Steidel et al. 1999; Smail et al. 2002; C03). At least out to $z \approx 2$, the radio selection provides us with a less biased assessment of the total energetic budget. This conclusion is not changed qualitatively if we remove the half of the new sample that exhibit signs of an AGN in their UV spectra (especially if we consider that the half of the parent sample that have only single-feature redshifts, and hence are not included here, are likely to be starburst systems at similar redshifts). However, the current sensitivities achievable in the radio cannot detect such hot, luminous galaxies beyond $z \approx 3$, and we therefore are not in a position to assess the incompleteness of current estimates of the obscured star formation rate density at higher redshifts. Observations from *Spitzer* and the extended VLA may complete the picture initiated in this study.

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