RADIO AND INFRARED SELECTED OPTICALLY INVISIBLE SOURCES IN THE BOÖTES NDWFS

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ABSTRACT

We have combined data from the NOAO Deep Wide-Field Survey in Boötes and the Spitzer Space Telescope to determine basic properties for 16 optically “invisible” MIPS 24 μm and 35 optically invisible radio sources (OIMSs and OIRSs, respectively), including their spectral energy distributions (SEDs) and luminosities. Most OIMSs possess steep power-law SEDs over \( \lambda_{\text{rest}} = 1-10 \) μm, indicating the presence of obscured AGNs in agreement with Spitzer spectroscopy. These objects are extremely luminous at rest-frame near- and mid-IR \( [\nu_L, (5 \, \mu m) = 10^{38}-10^{39} \, W] \), consistent with accretion near the Eddington limit and further implying that they host buried QSOs. The majority of the IRAC-detected OIRSs have flat 3.6–24 μm SEDs, implying comparable emission from stellar photospheres and hot AGN-illuminated dust. This may reflect relatively small amounts of dust close to the central engine or current low mass accretion rates. A small subset of OIRSs appear to be starburst-dominated with photometric redshifts from 1.0 to 4.5. The OIMSs and OIRSs with significant starburst components have similar \( L_X \) and stellar masses \( (M_* \approx 10^{11} \, M_\odot) \) assuming minimal AGN contribution. Roughly half of the OIRSs are not detected by Spitzer IRAC or MIPS. These are most likely \( z \gtrsim 2 \) radio galaxies. The IRAC-detected OIRSs are more likely than OIMSs to appear nonpointlike in the 3.6 and 4.5 μm images, suggesting that interactions play a role in triggering their activity. The AGN-powered OIMSs may represent submillimeter galaxies making the transition from starburst to accretion dominance in their evolution to current-epoch massive ellipticals.

Subject headings: galaxies: active — galaxies: high-redshift — galaxies: starburst — infrared: galaxies — radio continuum: galaxies

Online material: color figures

1. INTRODUCTION

Sensitive multiband surveys in the optical and near-infrared portion of the electromagnetic spectrum have proven extremely successful in identifying large and diverse galaxy populations in the high-redshift universe. Deep images obtained through optical \( u' , g' , r' , i' , z' \) filters, for example, readily find \( z \gtrsim 3 \) galaxies by the presence of a strong 912 Å Lyman break (e.g., Steidel et al. 1996). Lyman break galaxies (LBGs) tend to be massive galaxies with star formation rates (SFRs) in the range \( \approx 4-25 \, M_\odot \, yr^{-1} \) and relatively low dust obscuration. Similarly, unobscured star-forming disk galaxies (S-BzK galaxies) and passively evolving spheroidal galaxies at \( z \approx 1.4 \) can be discerned from the myriad background sources by their optical/near-infrared colors or other magnitude-color criteria (see, e.g., Daddi et al. 2004; Adelberger et al. 2004). The S-BzK galaxies, in particular, tend to possess large stellar masses \( (M_* \approx 10^{11} \, M_\odot) \) with SFR \( \approx 200 \, M_\odot \, yr^{-1} \). Nevertheless, it had been long suspected that a substantial fraction of luminous \( z > 1 \) galaxies powered by star formation or accretion onto supermassive black holes would not be identified using these and related techniques because of heavy dust obscuration, but would turn up instead at infrared, submillimeter, and radio wavelengths (see, e.g., Chary & Elbaz 2001 and references within). Indeed, deep but small-area surveys at submillimeter wavelengths by SCUBA (e.g., Smail et al. 1997) revealed a population of extremely dusty galaxies at \( z \approx 1-3 \), whose high luminosities are generally thought to originate primarily in star formation \( (SFR \gtrsim 1000 \, M_\odot \, yr^{-1}) \), although a small fraction may be dominated by active galactic nuclei (AGNs). Galaxies powered by starbursts or AGNs can also be strong emitters at radio wavelengths through either large populations of supernova remnants or accretion disk phenomena. Even though this emission is unaffected by obscuration, roughly 10%–15% of compact radio sources identified in deep radio surveys have either extremely faint optical counterparts or none at all (e.g., Richards et al. 1999; Fomalont et al. 2002), and may represent distant luminous obscured starburst- or AGN-powered galaxies. Such objects make a still unknown contribution to the luminosity, chemical, and accretion history of the universe. Determining an accurate census of heavily obscured sources—their redshifts, luminosities, space densities, and dominant power source—is one of the key issues in observational astrophysics and a primary objective of the Spitzer Space Telescope (Werner et al. 2004).7

A number of ambitious large-area multiwavelength surveys incorporating Spitzer data have been conducted to date. These include the Great Observatories Origins Deep Survey (GOODS), the Spitzer Wide-area InfraRed Extragalactic (SWIRE) survey, and the First Look Survey (FLS). This paper is concerned with the nature of infrared- and radio-selected sources with extremely faint optical counterparts originally selected from the NOAO Deep Wide-Field Survey (NDWFS) in Boötes (Jannuzi & Dey 1999)8 with the expectation that they are either heavily extincted, luminous, and radio-selected objects.

7 The Spitzer Space Telescope is operated by JPL, California Institute of Technology, for the National Aeronautics and Space Administration. Information on Spitzer can be found at http://ssc.spitzer.caltech.edu/.
8 The NOAO Deep Wide-Field Survey is supported by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under a cooperative agreement with the National Science Foundation. Information on the NDWFS can be found at http://www.noao.edu/noao/ndwfs/.

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at high redshift, or both. Higdon et al. (2005; hereafter Hig05) identified 36 optically “invisible” radio sources (OIRSs) out of 377 compact or unresolved radio sources found in a VLA A-configuration 20 cm survey covering 0.5 deg² in the NDWFS Boötes field.⁹,¹⁰ These observations reached a flux density limit of ≈80 µJy (5 σ) at the three overlapping pointing centers. To be considered optically invisible, a radio source must have no $B_R$, $R$, or $I$ counterpart within a 1.5′′ radius. This corresponds to limiting 3 $σ$ magnitudes of approximately 26.9, 25.6, and 24.9 (Vega; 2″ aperture), respectively, with the precise value depending on location within the optical survey. The NDWFS region was surveyed at 24 and 70 µm with the Multibanding Imaging Photometer for Spitzer (MIPS; Rieke et al. 2004). Analysis of the OIRSs’ $q$-parameter led Hig05 to conclude that they are a population powered by relatively unobscured radio-loud active nuclei.¹¹ While none of the OIRSs have measured redshifts, Hig05 argued that they are likely to be at $z > 1$ based on the faint optical limits set by the NDWFS survey. An independently defined sample of seven optically faint ($R \geq 24.5$) and 10 optically invisible sources from the NDWFS Boötes region, subject to the additional constraints that $F_{24,µm} > 0.75$ mJy and $v_f/(24,µm)/v_f,(0.8 µm) > 100$, was observed using Spitzer’s Infrared Spectrometer (IRS; Houck et al. 2004). These optically invisible MIPS sources (OIMSs) are a high-$z$ population, with $z \sim 1.6$–2.7. Comparisons with mid-IR spectra of local starburst- and AGN-dominated galaxies suggested that the primary energy source in 13 of the 17 OIMSs is a heavily obscured active nucleus (Houck et al. 2005, hereafter Hou05). All 17 have inferred 8–1000 µm luminosities of $\approx 10^{13}$ $L_\odot$, placing them in the hyperluminous class.

It is not known how the radio- and infrared-selected invisible populations in Hig05 and Hou05 are related, apart from the fact that the majority of both appear to possess powerful AGNs. We do not know, for example, if the OIRS population lies at systematically higher redshifts than the OIMSs with similar $L_R$ or, for that matter, if they are a sub-L* population at $z \sim 0.5$. Key to addressing these issues is estimating photometric redshifts for the OIRSs, which are generally too faint for Spitzer’s IRS. In this paper we present results obtained by combining optical $B_R$, $R$, and $I$, and MIPS 24, 70, and 160 µm flux densities (or limits) with data from the Spitzer IRAC (Fazio et al. 2004) Shallow Survey of the NDWFS Boötes field (Eisenhardt et al. 2004). The IRAC Shallow Survey covers 8.5 deg² in four bands centered at 3.6, 4.5, 5.8, and 8.0 µm. For $z \approx 1$–3, these bands measure emission in the rest-frame near-infrared. Because this wavelength regime is much less sensitive to extinction relative to the optical, the IRAC data can constrain the evolved stellar content of galaxies at this epoch. Photometric redshifts are also possible by virtue of the rest-frame 1.6 µm peak arising from the H⁻ opacity minimum in the photospheres of evolved stars. It is our aim to derive basic properties for both optically invisible source populations, including rest-frame near-infrared luminosities and SEDs, and to determine, for example, if their rest-frame near-infrared emission is dominated by starlight or an AGN. Only then would it be possible to relate OIMSs and OIRSs to other high-$z$ populations. It is also our intent to use the IRAC images to explore the near environments of OIMSs and OIRSs for additional clues to their nature and evolution.

A brief description of the extraction of IRAC flux densities for the infrared- and radio-selected invisible sources is given in § 2. Photometric redshift estimates for selected OIRSs are presented in § 3, along with determinations of the average rest-frame SEDs, luminosities, and near environments of the OIMS and OIRS samples detected with IRAC. The nature of these two populations is discussed in § 4. These results are summarized in § 5. Throughout this paper we refer to the OIRSs and OIMSs by number (i.e., OIRS 97 or OIMS 13), corresponding to their entries in Table 2 of Hig05 and Table 1 of Hou05. Source coordinates can be found from those papers directly, or through their SIMBAD designations, [HHW2005] No. and [HSW2005] No. for the OIRSs and OIMSs, respectively. We assume a flat ΛCDM cosmology, with $\Omega_M = 0.27$, $\Omega_\Lambda = 0.73$, and a Hubble constant of 71 km s⁻¹ Mpc⁻¹.

### 2. OBSERVATIONS AND SOURCE EXTRACTION

Flux densities or limits at 3.6, 4.5, 5.8, and 8.0 µm for the OIRSs and OIMSs were extracted from the final IRAC Shallow Survey mosaics (pipeline ver. S11) using SExtractor (Bertin & Arnouts 1996) with 4.8″ diameter apertures. All sources are nearly pointlike, and point-source aperture corrections were applied. The 3.6 µm images were used for matching the radio- and 24 µm–selected source positions since they had the highest point-source sensitivity ($F_{3.6,µm} = 6.4$ µJy [5 σ] in a 4″ diameter aperture) and angular resolution (1.7″ FWHM). To qualify as a “match” the coordinates of an OIMS or OIRS had to agree with an IRAC 3.6 µm source to within 2″. We decided on this match radius after comparing the radio and $F_{24,µm} > 0.75$ mJy MIPS catalogs with the IRAC Shallow Survey catalog. For example, 2/3 of the compact 20 cm radio sources (excluding the OIRSs) had a 3.6 µm source counterpart centered within 0.65″. Since the great majority of these matches are real we took 0.65″ to represent the 1 σ relative positional accuracy between the radio and IRAC 3.6 µm catalogs. A similar value (0.71″) was found for the 1 σ relative positional accuracy between the $F_{24,µm} > 0.75$ mJy MIPS sources and 3.6 µm counterparts in the Shallow Survey. The match radius of 2″, while seemingly small, represents essentially a 3 σ criterion, i.e., we would expect ±1 radio/IRAC mismatch out of the full 377 compact radio source sample. As a consequence, OIMSs and OIRSs can be said to lack IRAC counterparts at the 3 σ level if no 3.6 µm sources are within 2″, and at the 5 σ level if there are none within 3.3″.

The original count of OIRSs in Hig05 was 36. However, we are no longer confident that No. 362 is a clear-cut OIRS. As a result, we do not include it in the following analysis. Of the remaining 35 OIRSs within the IRAC Shallow Survey, 19 (54%) were unambiguously detected at 3.6 µm, as shown in Figure 1. Even when a potential optical counterpart exists within ±2″–3″ (e.g., OIRS 97 and 410) the compact radio source sits squarely on an IRAC source. Of these, six (17%) were detected in three IRAC bands to ≥3 σ (OIRS 79, 176, 208, 245, 346, and 349), and two (OIRS 176 and 349) in all four. The median 3.6 and 4.5 µm flux densities for these 19 objects are 18.3 and 22.5 µJy, respectively. Sixteen OIRSs were found to lack IRAC counterparts within 2″ and are shown in Figure 2. Note that in four instances (OIRS 9, 305, 430, and 441) possible IRAC counterparts are present roughly 3″–5″ away. OIRS 9, 305, and 441 are particularly suspicious as their candidate IRAC matches are also optically invisible, i.e., like the 19 OIRSs with clear IRAC counterparts. The coordinate mismatches in these instances, however, equal or exceed the radio/IRAC relative positional accuracy at the 5 σ level. Moreover, the expected number of OIRSs in Figure 2

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⁹ The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

¹⁰ The VLA radio source catalog, consisting of positions, flux densities, morphologies, and $B_R$, $R$ and $I$ magnitudes or limits, is available at http://cheller.phy.georgiasouthern.edu/works/bootes.html.

¹¹ Here $q = \log(F_{24,µm}/F_{20,µm})$. Systems powered by star formation or radio-quiet active nuclei possess $q = 0.5$–1.1. Smaller and, in particular, negative values of $q$ indicate the presence of increasingly radio-loud active nuclei (Appleton et al. 2004).
with an optically invisible IRAC source 3′′-5′′ away due to chance is ≈3, given the estimated density of 3.6 μm sources with no optical counterparts (3.3 arcmin⁻²) in the Shallow Survey. We conclude that these four OIRSs are unlikely to be physically associated with the relatively nearby IRAC sources. However, even if we allow these four matches, it remains true that a significant fraction (at least 12/35 or 34%) of the OIRSs lack clear 3.6 μm counterparts in the IRAC Shallow Survey.

It should also be noted that while the radio source morphologies in Figures 1 and 2 are for the most part quite simple, extended radio emission may have been lost due to a lack of short spacings (although the 4.5 hr spent at each pointing center in the A-configuration observations should reliably represent emission up to 12′′ scale sizes) or (1+z)⁻⁴ surface brightness dimming that might otherwise have connected an OIRS to an optical or infrared source. Observations in more compact array configurations...
will be needed to resolve this issue. With these caveats in mind, stack averages of the 3.6, 4.5, 5.8, and 8.0 μm images at the radio source positions led to flux density upper limits of 1.5, 2.0, 10.1, and 11.0 μJy (3σ) for the 16 OIRSs with no apparent IRAC counterparts.

OIMS 11 was not included in this study due to its uncertain redshift.12 All of the 16 remaining OIMSs were detected by IRAC, although OIMS 17 was only observed at 3.6 and 5.8 μm. These are shown in Figure 3, and their flux densities or limits are listed in Table 2. The median 3.6 and 4.5 μm flux densities for the 15 OIMSs observed in all four IRAC bands are 17.0 and 26.1 μJy, i.e., quite similar to that of the 19 IRAC-detected OIRSs. However, a much higher fraction of these OIMSs (12/15 or 80%) were detected in all four IRAC bands. The OIMSs are also significantly brighter at 8.0 μm than the OIRSs: the median OIMS $F_{8.0\,\mu m}$ is 136 μJy, while the median $F_{8.0\,\mu m}$ for the nine OIRSs detected in this band is 37 μJy.

The OIMSs were chosen from the MIPS 24 μm catalog to satisfy $F_{24\,\mu m} > 0.75$ mJy, and the sources in Table 2 have a median $F_{24\,\mu m}$ of 1.1 mJy. By contrast, only four OIRSs were detected at 24 μm at 3σ or higher (OIRS 97, 176, 245, and 363), with a mean $F_{24\,\mu m}$ of 0.38 mJy. Two additional OIRSs were detected at the 3σ level (OIRS 208 and 349), with a mean $F_{24\,\mu m}$ of 0.24 mJy. We stack-averaged MIPS 24 μm subimages centered on the 11 nondetected OIRSs in an attempt to recover faint emission from these sources. No significant signal was found, allowing us to set a flux density upper limit of 67 μJy (3σ) at 24 μm for these sources as a group. No OIRSs or OIMSs were detected with MIPS at 70 or 160 μm, placing 3σ upper limits of 24 and 60 mJy at these two wavelengths.

The IRAC and MIPS flux densities (or 3σ limits) for the two source populations are listed in Tables 1 and 2. To these have been added flux densities (or limits) in $B_W$, $R$, and $I$ from the NDWFS catalog,13 and at 20 cm from either Hig05 for the OIRSs or de Vries et al. (2002) for the OIMSs.

3. PROPERTIES OF THE OPTICALLY INVISIBLE POPULATIONS

3.1. Photometric Redshifts

Photometric redshifts ($z_{phot}$) were calculated using a set of galaxy templates corresponding to starburst (M82, from Xu et al.

12 The S/N for this source’s IRS spectrum is low. While Hou05 gives $z_{spec} = 0.70 \pm 0.24$, a redshift of ≈2.5 is just as feasible using the same galaxy template.

13 If not already published, new 3σ limits were calculated using $m_0 - 2.5 \log \left[ 3 \sigma_{pix} \left( N_{pix} \right)^{1/2} \right]$, where $\sigma_{pix}$ is the rms per pixel, $N_{pix}$ is the number of pixels within the 4' diameter aperture, and $m_0$ is the appropriate zero-point constant.
2001), composite starburst plus AGN (Arp 220, from Devriendt et al. [1999], modified using IRS spectra to better represent its polycyclic aromatic hydrocarbon [PAH] emission and silicate absorption), AGN-dominated (I Zw 1, from Xu et al. 2001), and elliptical (Silva et al. 1998) galaxies. For each OIRS, the templates were redshifted from $z = 0.1$ to 6.0 in steps of 0.05, re-gridded and scaled to the observed flux densities. Redshifts were determined by minimizing the reduced $\chi^2$, defined as

$$\chi^2 = N_{\text{dof}}^{-1} \sum \frac{[O_\lambda - \alpha_\lambda T_{(1+z)}]^2}{\sigma^2_\lambda},$$

FIG. 2.—OIRSs with no obvious counterparts in the IRAC Shallow Survey (Eisenhardt et al. 2004). Optical $B_V$ images are shown in the leftmost column, while the corresponding IRAC 3.6 $\mu$m images are shown to the immediate right. Radio 20cm contours are shown in the middle IRAC 3.6 $\mu$m planes, starting at the 3 $\sigma$ level. The fields are 20$''$ in size. Also shown are the source index from Table 2 of Hig05 and Table 1 of this paper. A linear stretch is used for both optical and infrared gray-scale images.
where $O_j$ and $T_{(1+z)}$ are the observed and template flux densities, $N_{\text{deg}}$ are the degrees of freedom, and $\alpha_2$ is a scaling constant calculated at each value of $z$. The optical and far-infrared upper limits were included in the $\chi^2$ calculation only when they were exceeded by the template flux density [i.e., when $\alpha_2T_{(1+z)} > O_j$]. When this occurred $O_j$ was set to the respective limit and $\chi^2$ was calculated as above. Formal uncertainties in $z_{\text{spec}}$ were estimated by numerically evaluating

$$\sigma^2 = \frac{2.0}{\partial^2 \chi^2 / \partial z^2}.$$  \hspace{1cm} (2)

Additional extinction corresponding to $A_V = 1–2$ (assuming a screen geometry and the Galactic reddening law in Mathis 1990) was typically required to satisfy the optical constraints.\footnote{Estimates of the intrinsic extinction in the template galaxies can vary considerably depending on angular resolution, precise location in the source, and method used. Typical values of $A_V$ are 80 mag for Arp 220 (Devriendt et al. 1999), 10 for the central region of I Zw 1 (Eckart et al. 1994), to 5 for M82 (Lester et al. 1990; Telesco et al. 1991). The elliptical models of Silva et al. have essentially zero extinction.} This was applied to the model in template (1) prior to redshifting.

As a test, we determined photometric redshifts for the four OIMSs that Hou05 fit with either an Arp 220 or NGC 7714 spectral template (OIMS 2, 7, 12, and 14 in Table 2). The minimum-$\chi^2$ fits are shown in Figure 4, along with the corresponding photometric redshifts. We find good agreement between the photometric and spectroscopic redshifts of all four, with $|z_{\text{phot}} - z_{\text{spec}}| = 0.1, 0.1, 0.1$ and 0.3, respectively. The Arp 220 template with an additional $\approx 1.5$ mag of visual extinction provided the best fits for all four, including OIMS 2, whose IRS spectrum was classified as a starburst (NGC 7714) by Hou05. Starburst templates gave similar $z_{\text{phot}}$ for this source, but produced too little emission at 8.0 and 24 $\mu$m, implying the presence of an additional dust component in the rest-frame mid-IR. The fact that OIMS 12 and 14 are significantly brighter than the Arp 220 template in the 24 $\mu$m band may reflect stronger PAH emission in these sources. Again, similar photometric redshifts were obtained using the M82 template and down-weighting the 24 $\mu$m measurements; however, only the Arp 220 template could match the observed $F_{24 \mu m}/F_{8.0 \mu m}$. The remaining OIMSs in Table 2 either lacked a sufficient number of data points for template fitting (e.g., OIMS 5, 10, and 17) or possessed power-law SEDs, for which unambiguous redshift determinations were not possible.

Photometric redshifts were derived for six OIRSs: 97, 176, 208, 245, 349, and 363. Each was detected in at least three IRAC and MIPS bands to $\geq 3\sigma$. The minimum-$\chi^2$ fits are shown in Figure 5, along with the best-matching template and derived $z_{\text{phot}}$. The results are summarized in Table 3. In each case we are fitting the inflection point in the spectrum where the dominant emission source changes from evolved stars to warm dust. For OIRS 363 the inflection point is implied by the upper limits in the IRAC 5.8 and 8.0 $\mu$m bands, which effectively rule out a power law between 3.6 and 24 $\mu$m. The derived redshifts range from 1.0 to 4.5 with a mean of 2.2. The formal redshift uncertainty is $\approx 0.2–0.6$, although a comparable contribution to the error budget may arise from our ignorance of the source’s true SED. For example, OIRS 97 and 245 would have been detected at 160 $\mu$m to $> 3\sigma$ had the Arp 220 template accurately represented their far-infrared SEDs. (A more in-depth analysis employing a larger set of templates and extinction laws is not warranted at this point given the paucity of data points.) The six OIRSs are best represented by either the starburst M82 (OIRS 176, 208, and 349) or the starburst/AGN composite Arp 220 (OIRS 97, 245, and 363) templates. In each case the best-fitting template was unambiguous. In particular, the AGN-dominated galaxy templates make poor matches to the SEDs in Figure 5. Likewise, elliptical galaxy templates are ruled out by the detection of emission at 24 $\mu$m. This subsample of OIRSs detected both with IRAC and with MIPS at 24 $\mu$m represents a population of sources with a significant starburst component with a redshift range similar to the OIMSs.

Two other OIRSs, 79 and 346, permitted rough photo-z estimates. Minimum-$\chi^2$ fits are shown in Figure 6. For OIRS 79, the flat IRAC spectrum could reasonably be interpreted as the rest-frame $\approx 1–3$ $\mu$m region, consistent with redshifts between 1.5–2.5. In fact, the smallest $\chi^2$ is achieved with a starburst (M82) template at $z_{\text{phot}} = 1.6$ with 1 mag of additional extinction. An Arp 220–like SED appears to be ruled out unless the 9.7 $\mu$m silicate absorption feature in these sources is much deeper than the template. We emphasize that these redshifts are approximate, as $z_{\text{phot}} = 2.5$ also yields a small $\chi^2$. The second OIRS in Figure 6, OIRS 346, shows a fairly steep power-law shape ($\alpha = -2.1$, for $F_\nu \propto \nu^{\alpha}$) in the IRAC data that does not extend to the MIPS 24 $\mu$m band. If this spectral break occurs at rest-frame wavelengths of 1–2 $\mu$m, then redshifts exceeding 3 are implied, and a reasonable fit using the M82 and Arp 220 template at $z_{\text{phot}} = 3.0–4.6$ are possible, as is shown in Figure 6. Note that good fits also result using the elliptical template for both, since the 24 $\mu$m upper limit provides no constraint to the shape of the SED. In both cases, the derived $z_{\text{phot}}$ is close to that derived using M82 or Arp 220. Because these redshifts are only estimates, we do not include them in Table 3.
Fig. 3.—OIMMs from Hou05. Optical $B_{V}$ images are shown in the leftmost column, along with redshifts derived from IRS spectra. Opposite these are matching IRAC 3.6 μm images from the IRAC Shallow Survey (Eisenhardt et al. 2004). Each field is 20' wide, which corresponds to ≈175 kpc for $z = 1$. The source index refers to Table 1 of Hou05 and Table 2 of this paper. A linear stretch is used for both optical and infrared gray-scale images. [See the electronic edition of the Journal for a color version of this figure.]
Overall, no starburst, AGN, or composite template could be found that would permit a fitted $z_{\text{phot}}$ of less than one for the above eight OIRSs. At the very least, a significant fraction of OIRSs are at high redshift. While galaxy templates with a sizable young stellar component (i.e., Arp 220 or M82) are consistent with the data, early-type galaxies cannot be ruled out in the two cases where there are no 24 $\mu$m detections (Fig. 6).

There are insufficient data to determine photometric redshifts for the remaining OIRSs in Table 1. It is important to keep in mind that we have derived reasonably confident $z_{\text{phot}}$ for only 1/3 of the IRAC-detected OIRSs. This represents only 17% of the total OIRS sample from Hig05. We address the issue of how likely these six are to be representative of the entire OIRS population below.

3.2. Spectral Energy Distributions and Emission Mechanisms

Hou05 found that the mid-IR spectra of the OIMs could be fit using only four templates, all derived from local galaxies (see Table 4). The same templates also fit the wider spectral energy distributions examined here. They are: (1) a heavily obscured...
Seyfert 2 nucleus, represented by IRAS F00183−7111 and noted obsSy2; (2) an obscured Seyfert 1 nucleus, represented by Mrk 231 and denoted obsSy1; (3) a starburst nucleus, represented by NGC 7714 and denoted sb; and (4) a combination of an obscured AGN and a starburst, represented by Arp 220 and denoted comb. The first four panels of Figure 7 show average rest-frame SEDs for the sources in each category. The SEDs were found by shifting each source’s flux densities (or limits) to the rest frame, then normalizing at \( \lambda_{\text{rest}} = 1.4 \) μm. The individual scaled SEDs were then co-added and binned.

The averaged SEDs for the obsSy1 and obsSy2 OIMSs both show steep power laws extending from \( \lambda_{\text{rest}} \approx 1 \) to 10 μm. This is consistent with a luminous and heavily obscured active nucleus. Assuming this emission arises from dust, which is reasonable given the high extinction deduced by Hou05, emission at \( \lambda \sim 1 \) μm implies that some of the dust approaches the sublimation temperature of refractory dust. For the obsSy2 SED, the power-law exponent \( \alpha \approx -4.0 \) (\( F_{\nu} \propto \nu^{\alpha} \)) over the range 1 μm \( \lesssim \lambda_{\text{rest}} \lesssim 4 \) μm, and there is a break in the power law at \( \lambda_{\text{rest}} \sim 5-8 \) μm. For the obsSy1 OIMSs, the slope is shallower (\( \alpha \approx -2.3 \)), but the power-law component extends over a wider range, 1 μm \( \lesssim \lambda_{\text{rest}} \lesssim 10 \) μm, with no break. The slope is still steep compared to SEDs of unobscured AGNs (e.g., Elvis et al. 1994) and even compared to the lensed z = 3.91 quasar APM 08279+5255 (Soifer et al. 2004), for which \( \alpha = -2.0 \) over 1 μm \( \lesssim \lambda_{\text{rest}} \lesssim 4 \) μm. The steep SEDs suggest a distribution of dust mass that rises rapidly with distance from the central heating source, and the break in the obsSy2 SED suggests that the rapid rise ends at a distance corresponding to \( T_{\text{dust}} \approx 400 \) K. The absence of PAH emission in the IRS spectra of these objects is consistent with the AGN interpretation of the emission.

The sb SED rises about as steeply (\( \alpha \approx -2.3 \)) as the obsSy1 SED in the rest-frame 1–8 μm spectral range, although with only one object the slope is poorly determined. A 1.6 μm bump can be seen in the IRAC data, indicating that the rest-frame 1–3 μm emission arises primarily from evolved stars. The steep rise at longer wavelengths is characteristic of dust in star formation regions. In contrast, the average SED for comb objects is much shallower for \( \lambda_{\text{rest}} \) between 1 and 3 μm, \( \alpha \approx -1.1 \), with a steeper rise from rest of 3–8 μm. The lack of a prominent 1.6 μm bump suggests a power-law AGN component contributes much of the rest-frame 1–3 μm flux, and the steepening suggests the presence of dust associated with the starburst, consistent with the dual starburst/AGN nature of these objects.

The average SED for the six IRAC-detected OIRSs with photometric redshifts is also shown in Figure 7. This SED resembles the sb class by virtue of the clear 1.6 μm bump. However, the steep rise for \( \lambda_{\text{rest}} \) between 3 and 10 μm may reflect a combination of star formation plus a weak active nucleus. In any event, there is no evidence of a dominant obscured active nucleus, which suggests that a significant fraction of the luminosity is provided by star formation. This is in marked contrast with the OIMSs, which are powered in most cases by dusty AGNs. We again wish to stress that the averaged OIRS SED was created using only the six sources with photometric redshifts and may not be representative of the remaining 13 IRAC-detected OIRSs in Table 1, much less the parent population of OIRSs in Hig05.

Additional insight into the dominant power source for OIMSs and IRAC-detected OIRSs can be gathered from their positions in an IRAC two-color diagram. Figure 8 shows that OIMSs and OIRSs tend to occupy distinct regions. Most OIMSs define a fairly narrow distribution extending from relatively flat observer-frame SEDs (\( F_{8.0 \mu m}/F_{4.5 \mu m} = F_{5.8 \mu m}/F_{3.6 \mu m} \approx 1 \)) in the lower left to steep power-law SEDs (\( F_{8.0 \mu m}/F_{4.5 \mu m} = F_{5.8 \mu m}/F_{3.6 \mu m} \approx 10 \)) in the upper right. Nearly all of the obsSy1 and obsSy2 OIMSs lie above \( F_{8.0 \mu m}/F_{4.5 \mu m} = 3 \), in the portion of the diagram...
dominated by quasars and obscured AGNs (Lacy et al. 2004). This is consistent with both their IRS spectra (which show deep 9.7 μm silicate absorption and no PAHs) and their steep power-law SEDs in Figure 7. The \textit{comb} and \textit{sb} OIMSs are situated at $F_{8.0 \, \mu m}/F_{4.5 \, \mu m} \leq 3$ and $F_{5.8 \, \mu m}/F_{3.6 \, \mu m} \leq 2$, where starburst systems dominate, also in agreement with their IRS spectra.

The IRAC-detected OIRSs are shown in Figure 8 (bottom). The six OIRSs with photometric redshifts have positions that are for the most part consistent with the dusty M82 track for $z \approx 1$–3, in agreement with their $z_{\text{phot}}$ and fitted spectral templates. The remainder of this population are also clustered in the lower left of the figure, i.e., $F_{8.0 \, \mu m}/F_{4.5 \, \mu m} < 3$ and $F_{5.8 \, \mu m}/F_{3.6 \, \mu m} < 4$. Given the uncertainties, their IRAC colors are equally consistent with elliptical galaxies at $z > 2$ or moderately obscured ($A_V \approx 2.5 \, \mu m$) $z > 1$ starbursts. However, all possess radio-loud AGN by virtue of their negative $q$-values and so cannot be pure starbursts.

Figure 8 highlights the fact that the IRAC-detected OIRSs as a group have much flatter mid-IR SEDs than the OIMSs. The latter possess mean $F_{24 \, \mu m}/F_{3.6 \, \mu m}$ ratios of 170, 65, 52, and 44 for the \textit{obsSy2}, \textit{obsSy1}, \textit{sb}, and \textit{comb} classes respectively. By contrast, the 13 IRAC-detected OIRSs without $z_{\text{phot}}$ (i.e., Fig. 8, filled circles) possess a mean $F_{24 \, \mu m}/F_{3.6 \, \mu m} < 11$. Given their 3.6 μm flux densities, all 13 should have been detected at 24 μm had their SEDs been steep power laws like the \textit{obsSy1} and \textit{obsSy2} OIMSs. Even if their SEDs resembled the \textit{sb} or \textit{comb} classes, they would have been detected by the MIPS survey.

15 For example, OIRS 232, with the smallest $F_{3.6 \, \mu m} = 8.1 \pm 1.7 \, \mu Jy$, would have yielded 24 μm flux densities between 0.5 and 1.4 mJy, easily detectable by the MIPS survey.
the estimated fits using an elliptical template are depicted using a red dashed line. For either tem-

axis. [45x55]shown in the observer’s frame on the bottom axis and in the rest frame on the top

axis. [45x69]The derived $z$ and $L$, the source rest-frame monochromatic luminosity at $5$

d The source rest-frame Johnson $K$-band luminosity, defined as $L_K = 4\pi D_L^2(1 + z)^{-1}F_K\Delta\nu_{K}$; in units of the Sun’s $K$-band luminosity, $L_{\odot,K} = 8.7 \times 10^{23}$ W (Bessell 1979). Here $D_L$ is the luminosity distance, $\Delta\nu_{K}$ in the Johnson $K$-band filter FWHM (2.1 x $10^{13}$ Hz; Tokunaga et al. 2002), and $F_K$ is the source flux density at $\lambda_{obs} = (1 + z)\lambda_{5 \mu m}$ estimated from the source’s SED template.

d The source rest-frame monochromatic luminosity at 5 $\mu m$ in watts, defined as $\nu L_{\nu}(5 \mu m)$, where $L_{\nu}(5 \mu m) = 4\pi D_L^2(1 + z)^{-1}F_{\nu}$. Here $D_L$ is again the luminosity distance and $F_{\nu}$ is the source flux density at $\lambda_{obs} = (1 + z)\lambda_{5 \mu m}$ estimated from the source’s SED template.

d Stellar mass derived by multiplying $L_K$ by $M_*/L_K = 0.3$, which is appropriate for a starburst galaxy (Bell & de Jong 2001).

$^e$ The OIRS number from Table 2 in Hig05, where source positions are given. These objects are designated in SIMBAD as [HHW2005] No. (e.g., [HHW2005] 97).

$^b$ The best-fitting galaxy template; see § 3.1 for descriptions.

$^c$ Additional visual extinction in magnitudes to satisfy optical constraints.

$^d$ The best-fitting galaxy template; see

$^f$ The three OIRSs that were best fit with a $comb$ template have a mean $L_K$ of $5 \times 10^{12} L_{\odot,K}$. This is within a factor of 2 of the average for the three $comb$ OIMSs (OIMS 7, 12 and 14). Accurate 8–1000 $\mu m$ luminosities ($L_{8-1000}$) for the OIMSs and OIRSs are not possible since none were detected at 70 or 160 $\mu m$. However, the fact that median $L_K$ for the OIRSs and $comb$ OIMSs are similar suggests that they have comparable total

### Rest-Frame Wavelength ( $\mu m$ )

| OIRS$^a$ ([HHW2005] No.) | $z_{phot}$ | Template$^b$ | $A_r$$^c$ | $L_K$$^d$ | $L_{5, \mu m}$$^e$ | $M_*/L_K$ | $L_{24, \mu m}$$^f$ |
|---------------------------|-----------|-------------|-----------|-----------|-----------|-----------|-----------|
| 97                        | 1.5 ± 0.3 | Arp 220     | 2         | 3.7 ± 1.6 | 0.3 ± 0.2 | 1.4 ± 0.5 | 0.4 ± 0.2 |
| 176                       | 4.5 ± 0.2 | M82         | 1         | 278 ± 26  | 11.6 ± 1.3| 116 ± 11  | 2.9 ± 0.3 |
| 208                       | 2.0 ± 0.3 | M82         | 1         | 9.9 ± 3.4 | 0.7 ± 0.2 | 3.4 ± 1.1 | 0.4 ± 0.1 |
| 245                       | 2.0 ± 0.3 | Arp 220     | 2         | 7.4 ± 2.7 | 1.2 ± 0.3 | 3.3 ± 1.1 | 0.5 ± 0.2 |
| 349                       | 1.0 ± 0.2 | M82         | 1         | 1.8 ± 0.6 | 0.09 ± 0.03| 0.8 ± 0.3 | 0.2 ± 0.1 |
| 363                       | 2.2 ± 0.6 | Arp 220     | 1         | 4.5 ± 2.4 | 1.1 ± 0.6 | 2.3 ± 1.4 | 0.4 ± 0.2 |

$^a$ OIRS number from Table 2 in Hig05, where source positions are given. These objects are designated in SIMBAD as [HHW2005] No. (e.g., [HHW2005] 97).

$^b$ The best-fitting galaxy template; see § 3.1 for descriptions.

$^c$ Additional visual extinction in magnitudes to satisfy optical constraints.

$^d$ The best-fitting galaxy template; see

$^e$ The source rest-frame Johnson $K$-band luminosity, defined as $L_K = 4\pi D_L^2(1 + z)^{-1}F_K\Delta\nu_{K}$; in units of the Sun’s $K$-band luminosity, $L_{\odot,K} = 8.7 \times 10^{23}$ W (Bessell 1979). Here $D_L$ is the luminosity distance, $\Delta\nu_{K}$ in the Johnson $K$-band filter FWHM (2.1 x $10^{13}$ Hz; Tokunaga et al. 2002), and $F_K$ is the source flux density at $\lambda_{obs} = (1 + z)\lambda_{5 \mu m}$ estimated from the source’s SED template.

$^f$ Stellar mass derived by multiplying $L_K$ by $M_*/L_K = 0.3$, which is appropriate for a starburst galaxy (Bell & de Jong 2001).

The rest-frame $K$-band luminosities, defined as $L_K = \Delta\nu L_{\nu}(2.2 \mu m)$, with $\Delta\nu$ corresponding to the Johnson $K$-band filter FWHM (2.1 x $10^{13}$ Hz; Tokunaga et al. 2002), were calculated for the OIMSs and the six OIRSs with photometric redshifts. These are listed in Tables 3 and 4 in units of the Sun’s $K$-band luminosity ($L_{\odot,K} = 8.7 \times 10^{23}$ W; Bessell 1979). With this definition, Arp 220 and IRAS F00183–7111 would have Johnson $K$-band luminosities of $1.3 \times 10^{11}$ and $9.1 \times 10^{11} L_{\odot,K}$, respectively. Monochromatic rest-frame luminosities at 5 $\mu m$, defined as $L_5 = \nu L_{\nu}(5 \mu m)$, were also calculated for these sources. This quantity provides a measure of the emission from hot (400–1500 K) dust free of any contribution from evolved stars and which avoids the (rest frame) 9.7 $\mu m$ silicate feature. These are also given in Tables 3 and 4. Uncertainties in redshift constitute the dominant source of error in the derived luminosities.

The OIMSs are highly luminous in the rest-frame $K$-band, with a median $L_K$ of $1.6 \times 10^{12} L_{\odot,K}$ and more than an order of magnitude spread. The $obsSy2$ OIMSs are the most luminous, with $L_K \approx 10^{12} L_{\odot,K}$ on average. These are followed by the $obsSy1$ and $comb$ OIMSs, both with average $L_K \approx 10^{12} L_{\odot,K}$. The $obsSy2$ and $comb$ OIMSs are both on average an order of magnitude more luminous than their local templates, IRAS F00183–7111 and Arp 220. Their rest-frame monochromatic 5 $\mu m$ luminosities are also extremely large, with median $L_5 \approx 1.0 \times 10^{39}$ and $1.2 \times 10^{38}$ W for the $obsSy2$ and $obsSy1$ OIMSs, respectively.

The six IRAC-detected OIRSs with photometric redshifts show a very wide range in $L_K$, led by OIRS 176 with $2.8 \times 10^{13} L_{\odot,K}$. This is roughly 50 times more luminous than the five other OIRSs and nearly twice as large as the most luminous OIMS. The three OIRSs that were best fit with a $comb$ template have a mean $L_K$ of $5 \times 10^{12} L_{\odot,K}$. This is within a factor of 2 of the average for the three $comb$ OIMSs (OIMS 7, 12 and 14). Accurate 8–1000 $\mu m$ luminosities ($L_{8-1000}$) for the OIMSs and OIRSs are not possible since none were detected at 70 or 160 $\mu m$. However, the fact that median $L_K$ for the OIRSs and $comb$ OIMSs are similar suggests that they have comparable total
Table 4
Derived OIMS Luminosities

| OIMS [(HSW2005) No.] | z_{spec} | Template | L_{K}^{c} (10^{11} L_{\odot}) | L_{\lambda_{3.6} μm}^{d} (10^{33} W) | M_{*}^{e} (10^{11} M_{\odot}) | L_{20 \text{ cm}} (10^{25} W Hz^{-1}) | log L_{\text{IR}}^{f} |
|-----------------------|----------|----------|-----------------|-------------------|-----------------|-----------------|----------------|
| 1………………… | 2.64 ± 0.25 | obsYs2 | 8.3 ± 1.8 | 8.3 ± 1.8 | <25 | <0.8 | 13.3 |
| 2………………… | 1.86 ± 0.07 | sb | 0.7 ± 0.1 | 1.0 ± 0.1 | 1.9 ± 0.2 | <0.4 | 13.0 |
| 3………………… | 1.78 ± 0.30 | obsYs1 | 0.9 ± 0.3 | 0.9 ± 0.3 | <2.7 | 0.5 ± 0.2 | 13.0 |
| 4………………… | 2.59 ± 0.34 | obsYs2 | 9.4 ± 2.9 | 9.4 ± 2.4 | <28.0 | 0.9 ± 0.3 | 13.2 |
| 5………………… | 2.34 ± 0.28 | obsYs2 | … | … | … | … | … |
| 6………………… | 1.96 ± 0.34 | obsYs1 | 1.2 ± 0.5 | 1.7 ± 0.6 | <3.7 | <0.4 | 12.8 |
| 7………………… | 1.78 ± 0.14 | comb | 1.6 ± 0.3 | 1.4 ± 0.3 | 4.8 ± 0.9 | <0.3 | 13.4 |
| 8………………… | 2.62 ± 0.26 | obsYs2 | 9.1 ± 2.1 | 10.2 ± 2.2 | <27.0 | <0.8 | 13.6 |
| 9………………… | 2.46 ± 0.20 | obsYs2 | 16.3 ± 3.2 | 21.0 ± 4.1 | <49.0 | 1.4 ± 0.3 | 13.7 |
| 10……………… | 2.08 ± 0.21 | obsYs1 | 0.9 ± 0.2 | 0.8 ± 0.2 | <2.8 | <0.5 | 13.0 |
| 12……………… | 2.13 ± 0.09 | comb | 0.7 ± 0.1 | 0.4 ± 0.1 | 2.1 ± 0.2 | 0.5 ± 0.1 | 13.8 |
| 13……………… | 1.95 ± 0.17 | obsYs2 | 10.2 ± 2.1 | 10.9 ± 2.2 | <31.0 | 10.2 ± 2.1 | 13.3 |
| 14……………… | 2.26 ± 0.11 | comb | 0.8 ± 0.8 | 3.0 ± 0.4 | 2.4 ± 0.3 | <0.6 | 13.7 |
| 15……………… | 1.75 ± 0.21 | obsYs1 | 1.8 ± 0.5 | 1.6 ± 0.4 | <5.0 | <0.3 | 12.7 |
| 16……………… | 2.73 ± 0.19 | obsYs2 | 2.7 ± 0.4 | 2.9 ± 0.5 | <8.0 | <0.8 | 13.2 |
| 17……………… | 2.13 ± 0.17 | obsYs1 | … | … | … | <0.5 | 13.0 |

* Source number from Table 1 of Hou05 where coordinates can be found. The OIMSs can also be referenced by their SIMBAD designation HSW2005 No. (e.g., [HSW2005] 13).

b Best-fitting template spectrum type; see § 3.2 for descriptions.

c Rest-frame Johnson K-band luminosity in units of the Sun’s K-band luminosity, L_{K} = 8.7 \times 10^{24} W (Bessel 1979).

d Monochromatic luminosity at rest-frame 3.6 μm in watts, defined as \nu L_{\lambda}(5 μm).

e Stellar mass derived by multiplying L_{K} by M_{K}/L_{K} = 0.3, which is appropriate for a starburst (Bell & de Jong 2001).

f Estimated 8–1000 μm luminosity from Hou05.

The 1.6 μm bump apparent in the averaged OIRS SED in Figure 7 points to a significant evolved stellar component. For these objects we estimated stellar masses by multiplying their L_{K} by near-infrared mass to light ratios derived from burst models in Bell & de Jong (2001). From their Figure 1, we adopted M_{K}/L_{K} = 0.3, which corresponds to their bluest models (B – R = 0.6). The mass-to-light ratio increases fairly slowly with color, as can be seen from the fact that M_{K}/L_{K} = 0.5 at B – R = 1.0. We find a wide range in derived stellar masses, again led by OIRSs 176 and 17 with M_{*} ≈ 10^{13} M_{\odot}. The other OIRSs have masses in the range (0.8–3.4) \times 10^{11} M_{\odot}, with a mean of ≈2 \times 10^{11} M_{\odot}. Very massive galaxies are indicated even if warm dust makes a 50% contribution to the rest-frame 2.2 μm emission.

Despite the lack of redshifts for the remaining IRAC-detected OIRSs, we can set useful limits to their stellar masses if we assume they lie at z ≥ 1 and that the (putative) AGNs makes an insignificant contribution to the IRAC 3.6 and 4.5 μm bands. The first assumption is reasonable given their faint optical limits. The second follows from the data in Table 1, where only OIRSs 49, 79, 232, and 410 have mid-IR–to–radio SEDs that might allow significant synchrotron emission in the mid-IR. For z = 1, where the IRAC 4.5 μm band measures rest-frame 2.2 μm emission, the average F_{A,5 μm} (18.0 μJy) implies a K-band luminosity of 1.5 \times 10^{11} L_{\odot}. For an early-type M_{*}/L_{K} ratio, we derive a typical stellar mass of ≈5 \times 10^{10} M_{\odot} for this subpopulation. So long as there is minimal contribution from an AGN to the 4.5 μm emission, the IRAC-detected OIRSs without redshifts also appear to be massive galaxies.

For the majority of OIMSs, the rest-frame near-infrared is dominated by nonstellar emission, and the upper limits to their stellar masses are not very informative. However, the four OIMSs with comb or sb IRS spectra (OIMS 2, 7, 12, and 14) show evidence of a weak 1.6 μm bump in Figures 1 and 4. Using the same starburst M_{*}/L_{K} of 0.3, their rest-frame L_{K} imply maximum M_{*} in the range (2–4) \times 10^{11} M_{\odot}. These objects also appear to be very massive even if the stellar component makes only a ~20% contribution to the rest-frame near-infrared.

Rest-frame 20 cm luminosity densities were estimated for the OIMSs and the six IRAC-detected OIRSs with z_{phot} using

\[ L_{20 \text{ cm}} = 1.2 \times 10^{20} D_{L}^{2}(1 + z)^{α-1} F_{\nu}(20 \text{ cm}) \text{ W Hz}^{-1}, \]

where D_{L} is the luminosity distance in Mpc, α is the radio spectral index (F_{\nu} \propto \nu^{-α}), taken to be 0.65, and F_{\nu}(20 \text{ cm}) is the observed 20 cm flux density (or 5 σ upper limit) in Jy. The latter are taken from Hig05 and de Vries et al. (2002). Seventy percent of the OIMSs were not detected in the radio, implying \L_{20 \text{ cm}} upper limits of \approx 5 \times 10^{24} \text{ W Hz}^{-1} (5 σ). Of the remainder, OIMS 13 in Table 4 is noteworthy for possessing the largest radio luminosity density among both OIRSs and OIMSs, with L_{20 \text{ cm}} = 1.0 \times 10^{26} \text{ W Hz}^{-1}. It represents the sole OIMS that is squarely in the “powerful” radio galaxy class (i.e., \L_{20 \text{ cm}} ≥ 10^{25} \text{ W Hz}^{-1}), McCarthy (1993). A wide range of values is found for the OIRSs with photometric redshifts, with \L_{20 \text{ cm}} in the range (0.2–2.9) \times 10^{25} \text{ W Hz}^{-1} and a median of 4 \times 10^{24} \text{ W Hz}^{-1}.

The six IRAC-detected OIRSs show signs of large evolved stellar populations by virtue of the 1.6 μm bump apparent in Figure 7. If we assume that their radio emission arises primarily from supernova remnants, we can estimate their current star formation rates with their L_{20 \text{ cm}}. Excluding the radio-loud OIRS 97 (q = −0.24), we derive a median SFR of 2200 M_{\odot} yr^{-1} after Bell (2003). For the single sb-like OIMS the \L_{20 \text{ cm}} upper limit implies SFR ≤ 2000 M_{\odot} yr^{-1}. Assuming a minimal contribution to L_{20 \text{ cm}} from an active nucleus, we find these objects to possess SFRs comparable to the highest values derived for local ultraluminous infrared galaxies (ULIRGs) using both X-ray and far-infrared luminosities (e.g., Persic et al. 2004).
3.4. The Near Environments of OIMSs and OIRSs

Most of the IRAC-detected OIRSs appear to possess nearby companion candidates, whereas few of the OIMSs do. Figure 3 shows that the OIMSs are typically unresolved by IRAC at 3.6 μm, with only OIMS 3 and 6 showing hints of structure. By contrast, 12 of the 19 IRAC-detected OIRSs (63% ± 18%) in Figure 1 are clearly not simple point sources. Examples include OIRS 79, 97, and 363. While gravitational lensing by foreground clusters cannot be ruled out, the most straightforward interpretation is that IRAC is detecting several closely spaced galaxies. This is consistent with the majority of the IRAC-detected OIRSs having companions within ≈ 50 kpc.

The clustering properties of these systems are beyond the scope of this paper. It is worth noting, however, that neither OIMSs nor OIRSs appear to inhabit particularly crowded environments like the cores of rich clusters. For example, using the 16 IRAC subimages of OIMSs in Figure 3 we find an average of 1.31 ± 0.29 sources per 20'' wide field (not including the OIMSs). The average number of sources in the fields centered on OIRSs is 1.74 ± 0.30, again not including the OIRSs. As a baseline figure, we would have expected 1.34 ± 0.01 sources in a random 20'' sized region given the total number of sources (≈ 370,000 at 3.6 μm) detected within the 8.5 deg² IRAC Shallow Survey (Eisenhardt et al. 2004).16

This is not to suggest that OIMSs and the IRAC-detected OIRSs do not inhabit clusters. Recent work indicates that radio

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16 We used Student's t-test to evaluate the likelihood that the IRAC-detected OIRSs have a significantly higher number of companion candidates within the 20'' wide fields relative to the OIMSs. For the sources visible in the two sets of IRAC subimages, we calculated $t = 1.43$. For 32 degrees of freedom and a 95% confidence level, $t$ would have had to exceed 2.04 for a significant difference between the OIMSs and OIRSs near environments to be real. We thus find no measurable difference in the apparent density on this scale.
4. DISCUSSION

4.1. OIMSs as Buried QSOs

Hou05 concluded that both the obsSy1 and obsSy2 OIMSs are heavily obscured and hyperluminous, with $L_{IR}$ estimated to be $\approx 10^{13} L_{\odot}$. Their IRS spectral shapes and, in particular, the absence of PAHs implied that their primary energy source was an active nucleus rather than star formation. We have shown that the obsSy1 and obsSy2 OIMSs also possess steep power-law SEDs over the rest-frame 1–10 μm region and extremely high rest-frame monochromatic 5 μm luminosities ($L_{5 \mu m} = 10^{38}$–$10^{39.2}$ W). The latter originates in the hottest dust component and necessarily implies a powerful active nucleus. To place these luminosities in context, we calculated rest-frame ν$L_ν$(5 μm) for the sample of 42 3C RR radio galaxies and quasars observed with Spitzer by Ogle et al. (2006). For the sources classified as mid-IR luminous, which consist of quasars and narrow-line radio galaxies (NLRGs), $L_{5 \mu m} = 10^{37.4}$–$10^{39.3}$ W. The quasar-like $L_{5 \mu m}$ of the obsSy1 and obsSy2 OIMSs, together with their steep power-law SEDs and IRS spectra, provide compelling evidence that they are driven by powerful AGNs accreting near the Eddington limit. These sources may be considered to be obscured or “buried” quasi-stellar objects (QSOs).

Final proof that the obsSy1 and obsSy2 OIMSs host heavily obscured QSOs would be the detection of luminous hard (i.e., >2 keV) X-ray emission. These photons originate very near the supermassive black hole and are a reliable indicator of powerful AGN activity. They are also fairly insensitive to obscuration, at least up to $N_H = 1.5 \times 10^{24}$ cm$^{-2}$, where the optical depth for Compton scattering reaches unity. Of the OIMSs discussed in this paper, only 13 (not coincidently, the most radio-loud OIMSs) was detected above the 99% confidence level in the “hard” $F_{2-7 \text{ keV}} = (1.6 \pm 0.8) \times 10^{-14}$ erg s$^{-1}$ cm$^{-2}$ and “full” $F_{0.5-7 \text{ keV}} = (2.3 \pm 1.4) \times 10^{-14}$ erg s$^{-1}$ cm$^{-2}$ bands in the 5 ks Chandra survey of the Boötes field by Kenter et al. (2005). This corresponds to a hard X-ray luminosity $L_{2-7 \text{ keV}} = (5 \pm 2) \times 10^{37}$ W, with no correction for intrinsic extinction. For the other eight obsSy1 and obsSy2 OIMSs we obtain upper limits of $L_{2-7 \text{ keV}} \lesssim 10^{37.5}$ W, again with no extinction correction. Powerful AGNs in the local universe typically possess $L_{2-7 \text{ keV}} \approx 10^{39}$–$10^{40}$ W. So while only OIMS 13 can be conclusively shown to be a “buried” QSO based on its hard X-ray emission, the other obsSy1 and obsSy2 OIMSs are still consistent with this interpretation. Deeper observations or a stacking analysis to detect hard X-rays with Chandra could be carried out, as well as searches for high-ionization infrared lines such as [S IV] 10.51 μm and [Ne v] 24.31 μm. These were not evident in the IRS spectra shown in Hou05, although this can be attributed to the low spectral resolution coupled with the relative faintness ($F_{24 \mu m} \approx 1$ mJy) of the sources.

4.2. The OIRSs Detected by IRAC

The IRAC-detected OIRSs fall into two groups depending on whether or not they were also detected with MIPS at 24 μm. Those that are detected at 24 μm appear to be massive and dusty $z \approx 2$ galaxies that are primarily driven by star formation. Those not detected at 24 μm (by far the majority) possess radio-loud AGNs, as evidenced by their negative $q$ upper limits. They also

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17 Rest-frame $\nu L_\nu$(5 μm) were extrapolated for the quasars and radio galaxies in Table 1 of Ogle et al. using the listed rest-frame $\nu L_\nu$(15 μm) and the 7–15 μm spectral indices.

18 X-ray luminosities were calculated from $L_{2-7 \text{ keV}} = 4\pi D_L^{-2} F_{2-7 \text{ keV}}(1+z)^{-2}$, where $D_L$ is the luminosity distance and $\Gamma$ is the power-law index, taken to be 1.8.
appear to be massive, with \( M_\star \approx 10^{11} \, M_\odot \) if they are at \( z > 1 \) as their faint optical limits imply. Their individual \( F_{24 \mu m}/F_{3.6 \mu m} \) limits are consistent with mid-IR SEDs in which stellar emission is at least comparable to that from dust close to the central engine.

Figure 9 shows the ratio \( F_{24 \mu m}/F_{3.6 \mu m} \) as a function of redshift for five representative objects known to contain powerful AGNs: the composite obsSy2 OIMS from Figure 7, the NLRG 3C 459, the quasar 3C 273, the low-excitation radio galaxy (LERG) 3C 293, and the “red and dead” radio galaxy LBDS 53W091 (Stern et al. 2006). Except for the OIMS and LBDS 53W091 the SEDs were constructed using data from NED. This figure also illustrates the extremely steep \( \lambda_{\text{rest}} = 1-10 \, \mu \text{m} \) SED of the obsSy2 OIMS relative to a fairly typical NLRG and quasar. The thick horizontal line in the figure represents the mean \( F_{24 \mu m}/F_{3.6 \mu m} \) upper limit for the IRAC-detected OIRSs (\( F_{24 \mu m}/F_{3.6 \mu m} < 3.9 \)). This was determined by dividing the stack-averaged \( 24 \mu m \) upper limit (67 \( \mu Jy, 3 \sigma \) by the mean \( F_{3.6 \mu m} \) for the 12 OIRSs not detected at \( 24 \mu m \). The upper/lower bounds to these limits, defined by dividing the stack-averaged \( 24 \mu m \) limit by the minimum/maximum \( F_{3.6 \mu m} \) values are also shown as two thin horizontal lines. Taken as a group, these OIRSs have spectral shapes that are inconsistent with obsSy2 OIMSs, typical NLRGs, and quasars at essentially all redshifts. They are, however, consistent with LERGs and the “red and dead” radio source LBDS 53W091 for \( z > 1 \).

Of the two, LERGs are currently the best studied at infrared wavelengths. LERGs are identified by their nuclear spectra which display a wide range of radio luminosities, with \( L_{20 \text{ cm}} \approx 10^{23} \) to \( >10^{25} \, \text{W Hz}^{-1} \), showing that LERGs can be “powerful” radio galaxies. Their flat redshift near- to mid-IR SEDs have been attributed to the absence of massive obscuring tori like those inferred in NLRGs and BLRGs. More direct evidence comes from X-ray spectra of LERG nuclei, which (with few exceptions) lack an absorbed soft component (Evans et al. 2006), and radio VLBI observations showing polarized emission on parsec scales (Kharb et al. 2005). Siebenmorgen et al. (2005) used simple dust models to fit the optical/infrared SEDs of a number of LERGs in the 3CR (Laing et al. 1983). They concluded that compared with NLRGs and BLRGs, LERGs possess lower AGN luminosities, more extensive dust distributions (i.e., much less dust at small radii), and lower overall obscuration (\( A_V \approx 2 \)).

The small \( F_{24 \mu m}/F_{3.6 \mu m} \) limits for the OIRSs not detected at \( 24 \mu m \) are consistent with a population of high-\( z \) LERGs, i.e., massive elliptical galaxies hosting radio-loud AGNs with relatively small amounts of dust close to the central engine. However, the data are also consistent with a population of radio-loud \( z > 1 \) ellipticals with active nuclei weak enough to be “drowned out” by stellar emission, even if only temporarily, due to a drop in the mass accretion rate.

Whether the OIRSs discussed in this section are LERGs or not, their radio luminosities will be substantially less than \( 10^{25} \, \text{W Hz}^{-1} \) if their typical redshifts are \( \approx 1 \). Only if \( z > 2 \) will most of these objects be classified as “powerful” radio galaxies. Future observations to better constrain their rest-frame infrared SEDs and determine accurate redshifts will be required to help resolve this issue.

It may at first seem puzzling that so many of the IRAC-detected OIRSs resemble LERGs and red and dead radio galaxies. One may ask where are the optically invisible mid-IR luminous NLRGs? Part of the answer must lie in the way the OIRS sample was originally defined, namely, by requiring a compact or unresolved radio morphology in the A-configuration 20 cm images. The original intent of the VLA survey was to detect optically obscured \( z > 1 \) starburst galaxies through their radio emission. Such sources were expected to be pointlike in the 20 cm A-configuration images. As a result, extended radio structures (i.e., jets and lobes) were excluded from consideration from the outset since they (1) would identify AGN-dominated sources, and (2) would have also proven difficult to confidently associate with an optical counterpart given the high source density in the NDWFS B, V, R, and I bands. As a consequence, it is possible that we preferentially selected beamed radio sources, i.e., sources resembling BL Lac objects. It has been suggested that FR I type radio galaxies are the parent population for BL Lac objects. The fact that LERGs comprise most of the local FR I type galaxies allows a simple explanation, namely, that most of the IRAC-selected OIRSs are in fact a population of high-\( z \) BL Lac objects.

4.3. The OIRSs Not Detected by IRAC

The fact that nearly half (16/35) of the OIRSs appear to lack IRAC counterparts (see Fig. 2) is a significant result, especially in light of the small number of spurious radio sources expected in Hig05.20 By contrast, all of the OIMSs were detected by IRAC, 19 This has led to suggestions that the accretion process in LERGs is fundamentally different from NLRGs and BLRGs (e.g., Hardcastle et al. 2006). Accordingly, supermassive black holes in NLRGs and BLRGs accrete material from a dusty molecular torus, while those in LERGs accrete hot gas directly from the intergalactic medium through Bondi accretion (Allen et al. 2006). For our purposes, this is less important in understanding their infrared SEDs than the apparent lack of a massive obscuring torus extending close to the central engine.

20 There are 392 radio sources in the final catalog. The number of false radio sources was estimated by repeating the SExtractor runs on the final VLA images multiplied by \( -1 \). The number of \( <5 \sigma \) negative “sources” provides a robust estimate of the number of false positives. Only three such sources were found in the radio images, a number that is also consistent with random fluctuations given the number of independent synthesized beams in the radio images. Minimal contamination of the source catalog is indicated. We also considered the possibility that some of the OIRSs might be hot spots in large radio doubles “resolved out” by the interferometer array. However, given their wide separation (few OIRSs are within 2–3 minutes of each other) these would have to be gigantic radio sources, and therefore unlikely.
which suggests that the two groups have very different SEDs and/or redshifts. We can constrain the average $L_k$ of the non-IRAC-detected OIRSs (and indirectly, their likely redshift range) with the stack-averaged 3 $\sigma$ upper limits at 3.6, 4.5, 5.8, and 8.0 $\mu$m listed in $\S$ 2.

If the OIRSs not detected by IRAC are primarily a $z < 1$ population, they must be sub-$L^*$ galaxies. For an object at $z = 0.64$, where rest-frame 2.2 $\mu$m shifts to the center of the IRAC 3.6 $\mu$m band, the 1.5 $\mu$Jy upper limit would correspond to $L_k < 1.2 \times 10^{10}$ $L_{\odot}/K$. This is substantially smaller than the $K$-band luminosities of $L^*$ galaxies determined by Kochanek et al. (2001), who found $L_K = (0.7-1.2) \times 10^{11}$ $L_{\odot}/K$ for early to late types. This in turn limits the stellar mass of the non-IRAC-detected OIRS hosts. For an early-type galaxy $M_*/L_k \approx 0.7$ (Bell & de Jong 2001), and the resulting $M_*$ is less than $8 \times 10^9$ $M_{\odot}$. Stellar masses result for later host types since $M_*/L_k$ will only decrease for these galaxies. Galaxies of this mass are unlikely to host radio-loud AGNs as powerful as $\approx 10^{24}$ W Hz$^{-1}$, which is the inferred average $L_{20 \text{ cm}}$ for the non-IRAC-detected OIRSs over 0.5 $< z < 1.0$.

On the other hand, if the host galaxies of these OIRSs are $z \approx 1-2$ ellipticals as suggested by Gruppioni et al. (2001), we would have expected to detect most with IRAC. A spinning supermassive black hole is generally held to be a requirement for a radio-loud active nucleus (Rees 1984). Since the black hole mass correlates with the mass of the host galaxy’s stellar bulge (e.g., Magorrian et al. 1998), radio-loud AGN hosts are known to be quite massive, and considerably more luminous than $L^*$. Using the above stack-averaged limits, we find the redshift where a massive elliptical host galaxy with $L_K = 3L_{\odot}$ would escape detection to be $z \approx 2$, with a corresponding average $L_{20 \text{ cm}}$ of $\approx 10^{25}$ W Hz$^{-1}$. The OIRSs not detected by IRAC appear to represent a population of powerful radio galaxies at $z \approx 2$.

This may not be the entire story, of course. The OIRSs lacking IRAC counterparts show a substantially wider dispersion in $F_{20 \text{ cm}}$ compared with the OIRRs detected by IRAC. Of the four OIRRs with $F_{20 \text{ cm}} > 1$ mJy, three lack IRAC counterparts. At the same time, eight of the 13 OIRSs fainter than 0.25 mJy at 20 cm lack IRAC counterparts. It may well be that the non-IRAC-detected OIRSs consist of two distinct populations: one characterized by $L_{20 \text{ cm}} < 10^{25}$ W Hz$^{-1}$ and $z \approx 1-2$ (corresponding to the $F_{20 \text{ cm}} < 0.25$ mJy objects) and a much more powerful and distant subgroup of radio galaxies (i.e., those with $F_{20 \text{ cm}} > 1$ mJy). Further progress in understanding the nature of these objects will require photometric redshifts derived either with deeper Spitzer IRAC and MIPS observations, or through ground-based spectroscopy using the next generation of large optical telescopes.

### 4.4. Comparison with Submillimeter Galaxies

It is worth comparing properties of the OIMs and OIRSs with other luminous objects at $z \approx 1-4$, in particular, the galaxies discovered at submillimeter wavelengths using instruments like SCUBA (Smail et al. 1997). Submillimeter galaxies (SMGs) are extremely luminous ($L_{IR} \approx 10^{13} L_{\odot}$) and dusty systems, with a redshift distribution that peaks near $z = 2.5$ (Chapman et al. 2003). Most appear to be powered primarily by star formation. Indeed, a significant fraction of star formation in the early universe may take place in them. SMGs also tend to be extremely faint or invisible at optical wavelengths (e.g., Hughes et al. 1998). To ensure meaningful comparisons with the OIMs and OIRSs, we selected a sample of 10 SMGs detected at 850 $\mu$m with SCUBA in the Lockman Hole East region that were observed with both IRAC and MIPS by Egami et al. (2004). Four of the SMGs were also detected at 1.2 mm with MAMBO (Eales et al. 2003) by Ivison et al. (2004), and nine were detected at 20 cm using the VLA’s A configuration (Ivison et al. 2002). The redshift range for the SMG sample ($z \approx 1-3$) is similar to that of the OIMs and the IRAC-detected OIRSs with a $z_{\text{pot}}$. Rest-frame radio and infrared luminosities as defined in $\S$ 3.3 were calculated for the SMGs and are listed in Table 5. Likewise, averaged rest-frame 1–10 $\mu$m SEDs were calculated as in $\S$ 3.2, and are shown in Figure 7 for the “cold” SMGs.

Two of the 10 SMGs possess power-law SEDs in the IRAC and MIPS data, suggesting a significant AGN contribution ("warm"
sources in the terminology of Egami et al. 2004). Their power-law exponents ($\alpha = -1.9$) are similar to those of the $\text{obsSy1}$ OIMSs. The largest $K$-band luminosity belongs to the warm SMG LK850.8b ($L_K = 5.3 \times 10^{12} L_{\odot,K}$), which is within a factor of $\approx2$ of the median $L_K$ for the hyperluminous $\text{obsSy2}$ OIMSs ($\approx 10^{13} L_{\odot,K}$). The remaining eight SMGs have SEDs consistent with obscured star formation providing the bulk of their luminosity (i.e., “cold” sources in the terminology of Egami et al.).

There is considerable overlap between the emission properties of the cold SMGs and the $\text{sb/comb}$ OIMSs and IRAC-detected OIRSs with $z_{\text{phot}}$. For all three groups we derive comparable luminosities at rest-frame $K$-band (average $L_K = 8 \times 10^{11} L_{\odot,K}$ for the cold SMGs) and 5 $\mu$m (average $\nu L_{\nu}(5 \mu m) \approx 10^{38} \text{W}$), both over an order of magnitude smaller than the $\text{obsSy1}$ and $\text{obsSy2}$ OIMSs. The similarity between the cold SMGs and the $\text{sb/comb}$ and IRAC-detected OIRSs with $z_{\text{phot}}$ extends to their averaged rest-frame 1–10 $\mu$m SEDs as well, as Figure 7 shows. In particular, both the cold SMGs and IRAC-detected OIRSs with $z_{\text{phot}}$ show a prominent 1.6 $\mu$m bump, implying substantial evolved stellar components. This is followed by a gradual rise to $L_{\text{irr}} \approx 10$ $\mu$m, as expected for dusty starbursts. Adopting a starburst $M_*/L_K$ of 0.3, we estimate a median stellar mass of $M_* = 2 \times 10^{11} M_\odot$ for the cold SMGs, which is comparable with the starburst-dominated OIMSs and OIRSs. Similarly, assuming that the radio continuum from the cold SMGs originates in supernova remnants, star formation rates between 500 and 1700 $M_\odot$ yr$^{-1}$ (median SFR = 1100 $M_\odot$ yr$^{-1}$) are implied by their $L_{20}$ cm. The similar luminosities, implied star formation rates and stellar masses, faint optical magnitudes, and SED shapes are evidence that at least a fraction of the OIMSs and IRAC-detected OIRSs are members of the same parent population as the cold (i.e., starburst-dominated) SMGs.

Figure 8 (top) includes the 10 warm and cold SMGs in the IRAC two-color diagram, along with the OIMSs. As expected, the two warm SMGs are positioned in the region occupied by the AGN-powered $\text{obsSy1}$ OIMSs. Neither have mid-IR SEDs that rise as fast as the $\text{obsSy2}$ OIMSs, although with only two warm submillimeter sources it is impossible to draw any definite conclusions. The eight cold sources are situated close to the dusty M82 track at $z \sim 1–3$, consistent both with their redshifts and with obscured star formation providing the bulk of their luminosities. There is a clear separation between the cold SMGs on one hand and the AGN-dominated $\text{obsSy1}$ and $\text{obsSy2}$ OIMSs on the other.

Figure 10 shows the relative positions of the OIMSs, OIRSs, and the 10 Lockman Hole East SMGs in a radio/infrared two-color diagram. Systematic trends can be seen: (1) $\text{obsSy1}$ and $\text{obsSy2}$ OIMSs extend to the right of center ($F_{8.0 \mu m}/F_{3.6 \mu m} > 3.5$) due to their steep power-law SEDs; (2) $\text{comb}$ and $\text{sb}$ OIMSs are situated primarily to the left of this, with $F_{8.0 \mu m}/F_{3.6 \mu m} < 3$; (3) cold SMGs are left of center ($F_{8.0 \mu m}/F_{3.6 \mu m} < 3$); (4) warm SMGs are to the right of the cold ones ($F_{8.0 \mu m}/F_{3.6 \mu m} > 4$); (5) the IRAC-detected OIRSs primarily occupy the lower left portion of the diagram. A few of the latter overlap the region occupied by the cold SMGs. However, the majority of IRAC-detected OIRSs are radio-loud (13/19 have $q < 0$) and are well separated from five of the six OIRSs with $z_{\text{phot}}$. It is also apparent that with two exceptions, the OIMSs and the warm and cold SMGs obey the radio-infrared correlation within the uncertainties. OIMSs, OIRSs, and SMGs thus occupy distinct regions in a radio/infrared two-color diagram, although there is also considerable overlap, particularly between the OIMSs and SMGs.

This overlap is further illustrated in Figure 11, where $L_K$ is plotted against $F_{8.0 \mu m}/F_{3.6 \mu m}$. A clear progression is seen, with luminous and flat-spectrum cold SMGs (i.e., $L_K \approx 10^{11–10^{12}} L_{\odot,K}$ and $F_{8.0 \mu m}/F_{3.6 \mu m} \sim 1–2$) giving way to $\text{obsSy1}$ OIMSs and warm SMGs ($L_K \approx 10^{12} L_{\odot,K}$ and $F_{8.0 \mu m}/F_{3.6 \mu m} \sim 5–10$), and finally to the steep power-law $\text{obsSy2}$ OIMSs ($L_K \approx 10^{13} L_{\odot,K}$ and $F_{8.0 \mu m}/F_{3.6 \mu m} > 10$). This suggests that the OIMSs, a subset of the IRAC-detected OIRSs, and the SMGs are all taken from the same population of dusty hyperluminous high-$z$ objects. The chief difference between them is the dominant emission mechanism: $\text{obsSy1}$ and $\text{obsSy2}$ OIMSs, in particular, can be thought of as analogs of SMG sources whose luminosities in the rest-frame near- and mid-IR are dominated by powerful and heavily obscured active nuclei accreting near the Eddington limit.

Figure 10 also illustrates a dichotomy between the IRAC-detected OIRSs with and without redshifts (i.e., those with and without 24 $\mu$m detections). With one exception, all of the former are characterized by $q > 0$, which is consistent with systems dominated by star formation, a radio-quiet AGN, or a combination of the two. By contrast, the remaining IRAC-detected OIRSs all have negative $q$-values, indicating an increasingly dominant radio-loud active nucleus. The parent OIRS population is similarly dominated by radio-loud active nuclei, for excluding the six OIRSs with $z_{\text{phot}}$. 72% of the sources in Table 1 of Hig05 have negative $q$. This suggests that the 24 $\mu$m-detected OIRSs in Figure 5 are not representative of the larger OIRSs population, but rather form a starburst dominated subgroup.

4.5. Do OIMSs and SMGs Form an Evolutionary Sequence?

Results from the previous sections suggest that the $\text{obsSy1}/\text{obsSy2}$ OIMSs and cold SMGs are members of the same parent population of heavily obscured hyperluminous galaxies, with the fundamental difference being their dominant power source, i.e., either accretion near the Eddington limit or star formation. The
obsSy1 and obsSy2 OIMSs in particular can be thought of as heavily obscured QSOs. While it is true that very few SMGs contain "buried" QSOs (≈5%; Almaini et al. 2003), recent ultra-deep X-ray observations argue persuasively that many SMGs contain massive central black holes and luminous, although not yet dominant, active nuclei. For example, 75% of the SMGs with radio counterparts and known redshifts in the Chandra Deep Field North were detected in hard X-rays by Alexander et al. (2005). Their X-ray luminosities (L(0.5–8 keV) ≈ 10^{36}–10^{37} W), levels of obscuration (80% show N_H ≈ 10^{20}–10^{24} cm^{-2}), and spectral power-law exponents (Γ ≈ 1.8) are similar to nearby powerful AGNs. However, their X-ray–to–infrared luminosity ratios (L_X/L_IR ≈ 0.4%) are typically an order of magnitude smaller than QSOs, consistent with intense star formation (SFR ∼ 1000 M☉ yr^{-1}) providing the bulk of their luminosity. This may be simply saying that that the X-ray-detected SMGs are currently accreting at substantially sub-Eddington rates, which would imply that the only real difference between the obsSy1/obsSy2 OIMSs and cold SMGs is the rate at which material is transferred to the central engine. On the other hand, near-IR spectra of SMGs typically show that when broad rest-frame optical lines are present they are typically only ∼1000–3000 km s^{-1} wide (cf. Swinbank et al., 2004), which is consistent with only modest black hole masses, i.e., ≤10^6 M☉. It is thus possible (although admittedly speculative) that what distinguishes the AGN-powered OIMSs and cold SMGs is primarily the central black hole mass rather than simply the accretion rate.

Given the well-established correlation between the masses of the spheroid and central black hole in local galaxies (e.g., Kormendy & Richstone 1995; Magorrian et al. 1998) and the evidence linking the SMG population with current-epoch massive ellipticals (e.g., Smail et al. 1997; Burger et al. 1998, 1999), it is intriguing to consider the possibility that the obsSy1 and obsSy2 OIMSs represent SMGs that have made the transition from a starburst-dominated cold phase to an accretion-dominated buried QSO phase. A plausible mechanism for this transition would be the growth of a sufficiently massive black hole (in parallel with the stellar bulge) during the high-SFR cold phase, with the subsequent transfer of material to the central regions through tidal interactions or mergers. The energy released during this relatively brief phase would act to expell the obscuring gas and dust from the central regions, effectively halting the growth of the bulge and supermassive black hole and “unveiling” a QSO in the manner envisioned by Sanders et al. (1988).

SMGs and OIMSs appear to have very different mean space densities. If so, this would have important implications for the envisioned SMG-QSO transition. For example, the number of SMGs per square degree with F_{8.5 μm} ≥ 5 mJy (which we take to represent the hyperluminous sources) is ≈400 using the cumulative 8.5 μm source count formulation in Sanders (2000). Assuming they all lie between z ≈ 1–3, their average space density becomes ρ_{SMG} = 2 × 10^{-5} Mpc^{-3}. There are 70 sources in the NDWFS Boötes field satisfying F_{24 μm} > 0.75 mJy and R > 24.5, i.e., OIMSs by our definition, of which 58 have been observed by Spitzer. Forty-five of these OIMSs can be confidently classified as obsSy1 or obsSy2 on the basis of their IRS spectra and/or steep power-law infrared SEDs (S. J. U. Higdon et al., in preparation). Over half of these sources have z_{spec} = 0.8–3.1 on the basis of IRS observations, and the remainder have IRAC/MIPS SEDs consistent with this redshift range. 23 There are thus ≈50 obsSy1 and obsSy2 OIMSs in the 8.5 deg^2 NDWFS. Assuming that the OIMSs with no redshift measurements are within z ≈ 1–3, we estimate a mean space density of ρ_{OIMS} ≈ 3 × 10^{-7} Mpc^{-3} for this population, or nearly 2 orders of magnitude smaller than ρ_{SMG}. This could be simply explained if the duration of the buried QSO phase is short compared with the SMG’s cold phase, i.e., the time spent growing a sufficiently massive black hole and bulge.

One caveat to the above analysis is the sensitivity of ρ_{SMG} to the adopted 850 μm flux density cutoff. For example, if only the F_{850 μm} ≥ 10 mJy SMGs pass through a obsSy1 or obsSy2 phase, then ρ_{SMG} ≈ 5 × 10^{-6} Mpc^{-3}, and ρ_{OIMS}/ρ_{SMG} ≈ 17. The sub-millimeter properties of the OIMS population are largely unknown, and it is not certain whether OIMSs with F_{24 μm} > 0.75 mJy map onto SMGs with F_{850 μm} ≥ 10 mJy, or for that matter, SMGs with F_{850 μm} ≥ 2 mJy.24 Despite these uncertainties, it appears likely that ρ_{OIMS}/ρ_{SMG} ≈ 20–70. This suggests that if indeed the obsSy1 and obsSy2 OIMSs represent a transition from SMGs to QSOs, and eventually to current-epoch massive elliptical galaxies, it is a relatively rapid one.

4.6. Do Interactions Trigger the Activity in OIMSs/OIRSs?

Evidence that the near environment of galaxies plays a role in triggering active nuclei has been known for some time. Heckman et al. (1984, 1986), for example, found that a large fraction of low-redshift quasars have companion galaxies within ≈50 kpc that typically differ in radial velocity from the quasar by ≤1000 km s^{-1}. In addition, roughly one-third of radio galaxies show highly peculiar morphologies (i.e., tails, bridges, and shells) indicative of tidal interactions. More recent work supports these results (e.g., Canalizo & Stockton 2001). The 3.6 μm images in Figure 1 suggest that most IRAC-detected OIRSs possess close companions, and may therefore be tidally interacting. If so, this implies that like low-redshift radio galaxies, the central activity in the majority of the IRAC-detected OIRSs may be induced through collisions.

23 It was noted in § 3.2 that the obsSy2 OIMSs show a pronounced break in their power-law SEDs near λ_{break} ≈ 5–8 μm. For the obsSy2-like OIMSs in the larger sample with featureless IRS spectra, the observed wavelength of this SED break was found to be consistent with z ∼ 1–3.

24 For example, none of the OIMSs in Hou05 and in the larger sample of OIMSs were detected by MIPS at 70 or 160 μm. Conversely, it had been previously noted that SMGs are fainter than expected at 24 μm given their inferred L_{15} (e.g., Jivon et al. 2004; Egami et al. 2004). This difference may simply reflect the presence of a strong contribution from AGN-heated dust in the OIMSs that is lacking in the cold SMGs.
The fact that most OIMSs appear pointlike with IRAC might at first suggest that they are relatively isolated. However, the mid-IR images shown in Figure 3 cannot exclude the possibility that OIMSs possess faint or lower mass companions capable of inducing tidal perturbations large enough to fuel an active nucleus. Nor can the IRAC images rule out the possibility that OIMSs are a population of late-state mergers. Local examples, such as NGC 7252, typically show luminous asymmetric cores with extended low surface brightness tails (Schweizer 1982). Neither would be detectable with IRAC given the OIMS’s redshifts. It thus remains an interesting possibility that interactions have triggered the nuclear activity in both OIRSs and OIMSs. Deep and high angular resolution near-infrared imaging studies will be needed to test this hypothesis.

5. CONCLUSIONS

OIMSs can be split into two populations based on their rest-frame infrared colors and IRAC colors in accordance with their IRS spectra: most (12/16) are dominated by a heavily obscured radio-quiet active nucleus, while the remainder are powered by either a starburst or a composite starburst/active nucleus. The AGN-dominated obsSy1 and obsSy2 OIMSs in particular are extremely luminous in the rest-frame near- and mid-IR, with $vL_\nu(5\,\mu m)$ comparable to the most luminous local NLRGs and quasars. They can be regarded as “buried” QSOs and likely represent the predecesors of current-epoch massive elliptical galaxies. OIMSs are also distinct from other high-z source populations routinely selected using UV/optical or optical/near-infrared criteria such as LBGs and BzKs in their dominant power source, levels of obscuration, and mid-IR luminosity. Compared with other optically faint mid-IR-selected populations (e.g., Yan et al. 2007), OIMSs represent extremes in both obscuration and AGN luminosity. This follows from their respective selection criteria, which for OIMSs favor steeper mid-IR continua and higher levels of extinction. There appears to be significant overlap between OIMSs and SMGs, with the sb/comb OIMSs appearing largely indistinguishable from SMGs in their optical, mid-infrared, and radio properties. Moreover, the obsSy1 and obsSy2 OIMSs may represent a brief obscured phase in the transition of a “cold” SMG to a QSO, and eventually to a massive current epoch elliptical galaxy.

The OIRSs do not represent a single-source population. The minority (6/35) that are detectable by both I/R AC and MIPS at 24 $\mu m$ have SEDs, mid-IR colors, and q-values indicative of either starburst or composite starburst/AGN-powered systems. For these sources we find $z_{\text{phot}}$ in between 1.0 and 4.5, implying rest-frame K-band luminosities, maximum star formation rates, and stellar masses virtually identical to the cold (i.e., starburst dominated) SMGs in the Lockman Hole East region.

The remaining OIRSs—which comprise 83% of the parent population in Hig05—fall into two classes depending on whether or not they are detected by IRAC. Those that are detected have flat mid-IR SEDs implying comparable luminosities from stellar photospheres and hot AGN illuminated dust. As a group, their average $L_{24\,\mu m}/L_{3.6\,\mu m}$ ratio is most consistent with either low excitation radio galaxies or objects like the “red and dead” radio galaxy LBDS 53W091. Those that are not detected by IRAC must be at $z \geq 2$ if they are as massive as the hosts of local radio sources. Both of these groups are characterized by negative values of $q$ and thus may represent a population of relatively unobscured radio galaxies at high redshift. Both represent populations that are highly distinct from the obsSy1 and obsSy2 OIMSs.

Differences between the optically invisible populations detected through observations at submillimeter, mid-IR, and radio wavelengths can be understood in terms of selection effects: (1) extreme optical/mid-IR luminosity ratios appears to ensure highly obscured AGN-dominated sources (obsSy1 and obsSy2 OIMSs), (2) extreme optical/submillimeter luminosity ratios will select highly obscured sources primarily powered by star formation (SCUBA/MAMBO sources), and (3) compact sub-mJy radio sources lacking optical counterparts appears to preferentially choose distant BL Lac–like objects (OIRSs).

We find no evidence that OIMSs or OIRSs inhabit the cores of rich clusters. Nor do we find significant differences in local galaxy density between the two on $\leq 100$ kpc scales. However, unlike the OIMSs, a large fraction of the IRAC-detected OIRSs appear to possess close and massive companions, although higher angular resolution studies will be needed to reach firm conclusions. This suggests that the luminosity of OIRSs (and conceivably OIMSs) may be triggered by tidal interactions, as appears to be the case for low-z radio galaxies and quasars. The IRAC-detected OIRSs may thus represent the formation of very massive galaxies at high redshift through major mergers.

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