SPITZER MID-INFRARED SPECTROSCOPY OF INFRARED LUMINOUS GALAXIES AT $z \sim 2$. II. DIAGNOSTICS

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ABSTRACT

We present mid-IR spectral decomposition of a sample of 48 *Spitzer*-selected ULIRGs spanning $z \sim 1$ –3 and likely $L_{\text{IR}} \sim 10^{12}$ – $10^{13} L_{\odot}$. Our study aims at quantifying the star formation and active galactic nucleus (AGN) processes in these sources that recent results suggest have evolved strongly between the observed epoch and today. To do this, we study the mid-IR contribution of PAH emission, continuum, and extinction. About $\frac{3}{4}$ of our sample are continuum (i.e., AGN) dominated sources, but $\sim 60\%$ of these show PAH emission, suggesting the presence of star formation activity. These sources have redder mid-IR colors than typical optically selected quasars. About 25% of our sample have strong PAH emission, but none are likely to be pure starbursts as reflected in their relatively high $5 \mu\text{m}$ hot dust continua. However, their steep 30 – $14 \mu\text{m}$ slopes suggest that star formation might dominate the total infrared luminosity. Six of our $z \sim 2$ sources have $\text{EW}_{6.2} \gtrsim 0.3 \mu\text{m}$ and $L_{14 \mu\text{m}} \gtrsim 10^{12} L_{\odot}$ (implying $L_{\text{IR}} \gtrsim 10^{13} L_{\odot}$). At these luminosities, such high $\text{EW}_{6.2}$ ULIRGs do not exist in the local universe. We find a median optical depth at $9.7 \mu\text{m}$ of $\langle \tau_{9.7 \mu\text{m}} \rangle = 1.4$. This is consistent with local *IRAS*-selected ULIRGs but differs from early results on SCUBA-selected $z \sim 2$ ULIRGs. Similar to local ULIRGs, about 25% of our sample shows extreme obscuration ($\tau_{9.7 \mu\text{m}} \gtrsim 3$), suggesting buried nuclei. In general, we find that our sources are similar to local ULIRGs but are an order of magnitude more luminous. It is not clear whether our $z \sim 2$ ULIRGs are simply scaled-up versions of local ULIRGs or subject to fundamentally different physical processes.

Subject headings: galaxies: active — galaxies: high-redshift — infrared: galaxies

Online material: color figures

1. INTRODUCTION

The pioneering work from the *Infrared Space Observatory* (*ISO*; for a review see Genzel & Cesarsky 2000) has already shown the power of mid-IR spectroscopy to reveal the dominant power sources among local infrared luminous galaxies. Diagnostic diagrams separating starburst- from AGN-dominated sources have been developed from several studies (Lutz et al. 1996, 1998; Genzel et al. 1998; Rigopoulou et al. 1999; Laurent et al. 2000; Tran et al. 2001; Peeters et al. 2004). Today, this work is being extended using the powerful Infrared Spectrograph (IRS; Houck et al. 2005) on the *Spitzer Space Telescope* (Werner et al. 2004). Its unprecedented sensitivity and efficiency have made it possible to expand the *ISO* work to much larger samples covering wider ranges of physical properties with better signal-to-noise ratio (S/N) and higher spectral resolution (e.g., Smith et al. 2007; Brandl et al. 2006; Schweitzer et al. 2006; Wu et al. 2006). High-S/N IRS spectra from all these local samples have enabled various teams to explore new parameter space and create new diagnostic tools characterizing different galaxy populations (e.g., Dale et al. 2006; Armus et al. 2006, 2007; Sturm et al. 2006; Spoon et al. 2007).

More importantly, IRS has enabled for the first time the mid-IR spectroscopy of IR luminous galaxies at cosmologically significant distances. Although limited to primarily low-resolution data, the IRS spectra of high- z samples allow us for the first time to apply the spectral diagnostic power of the mid-IR regime to galaxies at $z \sim 1$ –3, the epoch when luminous infrared galaxies (LIRGs)

and ultraluminous infrared galaxies (ULIRGs; for a review see Sanders & Mirabel 1996) make a significant contribution to the global averaged luminosity density and to the cosmic infrared background (Le Floc’h et al. 2005; Dole et al. 2006; Caputi et al. 2007). Recent studies (Houck et al. 2005; Yan et al. 2005, 2007, hereafter Paper I) have produced such low-resolution, mid-IR spectral samples of *Spitzer*-selected $z \sim 2$ ULIRGs. Other IRS samples include near-IR-selected starbursts, X-ray-selected AGNs (Weedman et al. 2006), and submillimeter galaxies (SMGs; Menéndez-Delmestre et al. 2007; Pope et al. 2007). Physical properties derived from these low-resolution, mid-IR spectra will allow us to put various disparate high- z ULIRG samples in context and test our understanding of IR luminous populations and their evolution.

This paper is part two of a series of papers that present the results from a *Spitzer* spectroscopy survey of *Spitzer*-selected high-redshift galaxies (Yan et al. 2005). Paper I (Yan et al. 2007) describes the survey sample, data reduction, observed mid-IR spectra, and the basic properties of the galaxies in the sample, including redshift distribution, mid-IR luminosities, and spectral types. This paper presents spectral decomposition, provides diagnostic tools, establishes the physical properties of our $z \sim 2$ *Spitzer*-selected ULIRGs, and discusses related limitations of current IRS spectra. The far-IR and radio properties of our sample are presented in A. Sajina et al. (2007, in preparation).

Throughout this paper we adopt the cosmological model with $\Omega_M = 0.3$, $\Omega_{\Lambda} = 0.7$, and $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

2. DATA

2.1. IRS Spectral Sample

Paper I gives the detailed description of the sample selection and presents the observed spectra and redshift measurements.

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TABLE 1
BROADBAND DATA AND BEST-FIT CONTINUUM PARAMETERS WITH 1σ UNCERTAINTIES

Source	z	$S_{3.6}$ (μJy)	$S_{4.5}$ (μJy)	$S_{5.8}$ (μJy)	S_8 (μJy)	S_{70} (mJy)	α	$\tau_{9.7}$
MIPS 42.....	1.95	8 ± 3	30 ± 1	103 ± 15	680 ± 15	12.8 ± 1.0	1.5 ± 0.1	0.7 ± 0.1
MIPS 78.....	2.65	6 ± 3	39 ± 4	57 ± 24	268 ± 19	1.5 ± 1.3	1.3 ± 0.1	3.4 ± 0.5
MIPS 110.....	1.00	44 ± 3	43 ± 1	72 ± 18	200 ± 15	9.1 ± 3.0	2.1 ± 0.2	0.5 ± 0.5
MIPS 133.....	1.00	57 ± 6	54 ± 4	55 ± 21	155 ± 17	13.1 ± 1.5	2.3 ± 0.1	0.9 ± 0.8
MIPS 180.....	2.47	23 ± 3	16 ± 4	14 ± 8	13 ± 17	5.8 ± 1.5	1.8 ± 0.4	2.2 ± 0.5
MIPS 227.....	1.87	72 ± 3	82 ± 3	111 ± 10	113 ± 19	10.0 ± 2.4	2.9 ± 0.2	0.2 ± 0.1
MIPS 279.....	1.23	51 ± 8	52 ± 7	84 ± 15	127 ± 16	9.8 ± 1.4	2.0 ± 0.2	0.0 ± 0.1
MIPS 283.....	0.94	117 ± 2	111 ± 3	147 ± 23	131 ± 10	10.2 ± 2.1	1.4 ± 0.1	1.5 ± 0.9
MIPS 289.....	1.86	66 ± 3	70 ± 4	106 ± 15	93 ± 20	8.1 ± 1.9	1.9 ± 0.3	0.7 ± 0.9
MIPS 429.....	2.15	18 ± 6	6 ± 4	4 ± 24	0 ± 20	3.5 ± 1.5	2.7 ± 0.2	>7.3
MIPS 464.....	1.85	15 ± 6	19 ± 4	38 ± 16	57 ± 22	8.9 ± 1.5	2.5 ± 0.3	4.9 ± 1.6
MIPS 506.....	2.52	18 ± 3	16 ± 1	26 ± 18	13 ± 19	7.5 ± 1.2	3.6 ± 0.2	>6.7
MIPS 8034.....	0.95	56 ± 5	64 ± 7	130 ± 23	216 ± 13	6.5 ± 1.7	2.3 ± 0.4	0.3 ± 0.3
MIPS 8184.....	0.99	104 ± 2	82 ± 4	82 ± 21	140 ± 21	19.7 ± 1.4	2.0 ± 0.2	0.6 ± 0.4
MIPS 8196.....	2.60	81 ± 6	61 ± 6	74 ± 19	149 ± 27	5.7 ± 1.2	1.2 ± 0.1	1.3 ± 0.4
MIPS 8207.....	0.84	117 ± 5	81 ± 9	94 ± 29	91 ± 18	17.9 ± 1.6	1.9 ± 0.2	0.9 ± 0.5
MIPS 8242.....	2.45	50 ± 3	43 ± 3	48 ± 8	88 ± 17	5.0 ± 1.5	2.8 ± 0.4	0.9 ± 0.5
MIPS 8245.....	2.70	0 ± 3	9 ± 4	5 ± 15	0 ± 14	1.3 ± 1.6	1.9 ± 0.1	2.8 ± 0.7
MIPS 8268.....	0.80	95 ± 2	87 ± 3	94 ± 7	218 ± 14	3.9 ± 1.8	1.6 ± 0.1	0.8 ± 0.4
MIPS 8327.....	2.48	12 ± 3	7 ± 4	0 ± 21	46 ± 25	5.5 ± 1.9	1.9 ± 0.1	2.4 ± 0.7
MIPS 8342.....	1.57	39 ± 6	57 ± 4	53 ± 12	119 ± 19	10.3 ± 1.8	2.1 ± 0.2	0.2 ± 0.4
MIPS 8493.....	1.80	39 ± 6	48 ± 4	62 ± 15	24 ± 14	4.8 ± 1.4	1.4 ± 0.7	>4.7
MIPS 15840.....	2.30	18 ± 2	25 ± 1	62 ± 18	197 ± 13	2.0 ± 1.6	1.6 ± 0.2	0.1 ± 0.2
MIPS 15880.....	1.64	63 ± 5	64 ± 4	58 ± 16	118 ± 22	19.5 ± 2.1	2.6 ± 0.1	3.9 ± 0.4
MIPS 15928.....	1.52	39 ± 3	51 ± 4	58 ± 21	125 ± 26	12.9 ± 2.5	2.6 ± 0.2	0.0 ± 0.1
MIPS 15949.....	2.15	27 ± 3	30 ± 3	33 ± 9	89 ± 11	7.6 ± 1.6	2.3 ± 0.2	0.0 ± 0.1
MIPS 15958.....	1.97	21 ± 3	43 ± 3	81 ± 24	181 ± 17	8.0 ± 2.8	1.6 ± 0.3	0.5 ± 0.4
MIPS 15977.....	1.85	57 ± 3	61 ± 4	69 ± 16	130 ± 22	15.0 ± 1.0	2.2 ± 0.2	0.1 ± 0.1
MIPS 16030.....	0.98	84 ± 3	72 ± 1	94 ± 16	132 ± 20	2.3 ± 1.6	1.8 ± 0.2	0.4 ± 0.4
MIPS 16059.....	2.43	17 ± 3	19 ± 4	33 ± 14	66 ± 15	6.2 ± 2.4	2.1 ± 0.1	2.7 ± 0.8
MIPS 16080.....	2.04	27 ± 3	31 ± 7	38 ± 24	71 ± 24	5.5 ± 1.7	1.7 ± 0.1	2.1 ± 0.5
MIPS 16095.....	1.81	21 ± 2	21 ± 4	24 ± 24	84 ± 14	11.1 ± 2.2	2.2 ± 0.2	0.3 ± 0.1
MIPS 16113.....	1.90	23 ± 3	16 ± 3	55 ± 15	35 ± 12	0.9 ± 1.5	1.4 ± 0.4	3.3 ± 1.3
MIPS 16122.....	1.97	17 ± 3	34 ± 9	31 ± 15	101 ± 15	3.1 ± 1.2	1.9 ± 0.4	1.8 ± 0.6
MIPS 16144.....	2.13	68 ± 3	84 ± 3	108 ± 24	105 ± 19	2.2 ± 1.2	2.1 ± 0.4	2.0 ± 1.4
MIPS 22204.....	2.08	20 ± 9	39 ± 6	132 ± 15	478 ± 8	13.2 ± 1.1	1.4 ± 0.1	1.6 ± 0.2
MIPS 22277.....	1.77	69 ± 3	67 ± 4	142 ± 15	254 ± 9	17.5 ± 1.3	1.9 ± 0.2	1.4 ± 0.3
MIPS 22303.....	2.34	9 ± 3	10 ± 4	0 ± 18	103 ± 13	7.2 ± 2.2	1.7 ± 0.1	2.9 ± 0.6
MIPS 22404.....	0.61	126 ± 5	93 ± 3	128 ± 16	117 ± 22	44.3 ± 3.0	2.2 ± 0.1	1.5 ± 1.4
MIPS 22467.....	0.80	59 ± 9	40 ± 4	31 ± 15	142 ± 25	9.0 ± 1.8	1.8 ± 0.1	0.9 ± 0.5
MIPS 22482.....	1.84	39 ± 2	48 ± 3	55 ± 18	93 ± 26	12.1 ± 1.1	1.9 ± 0.2	1.2 ± 0.4
MIPS 22530.....	1.96	42 ± 5	52 ± 4	43 ± 10	81 ± 12	3.4 ± 1.9	2.7 ± 0.8	>5.2
MIPS 22554.....	0.82	99 ± 0	79 ± 3	67 ± 13	62 ± 15	11.3 ± 1.5	1.6 ± 0.2	>4.2
MIPS 22558.....	3.20	15 ± 3	13 ± 7	0 ± 16	60 ± 16	4.7 ± 1.1	2.2 ± 0.2	>5.6
MIPS 22600.....	0.86	93 ± 2	58 ± 7	46 ± 13	88 ± 20	10.1 ± 1.4	1.7 ± 0.2	2.2 ± 3.3
MIPS 22651.....	1.73	92 ± 3	109 ± 4	94 ± 15	99 ± 10	7.0 ± 1.0	2.0 ± 0.3	0.7 ± 0.5
MIPS 22661.....	1.75	36 ± 2	30 ± 1	12 ± 8	76 ± 19	2.3 ± 2.4	2.3 ± 0.2	0.0 ± 0.1
MIPS 22699.....	2.59	9 ± 5	18 ± 4	17 ± 19	105 ± 13	2.5 ± 2.3	1.2 ± 0.2	1.2 ± 0.7

The full sample has 52 sources selected to have $24\text{ }\mu\text{m}$ flux density brighter than 0.9 mJy and very red $24\text{ }\mu\text{m}$ –to– $8\text{ }\mu\text{m}$ and $24\text{ }\mu\text{m}$ –to– R colors.⁵ The IRS low-resolution data revealed that 47 of the targets have measurable redshift from the features detected in their mid-IR spectra, with the majority ($33/47 = 72\%$) at $1.5 < z < 2.7$ and a smaller fraction ($12/47 = 28\%$) at $0.65 < z < 1.5$. An additional source (MIPS 279) has a Keck redshift ($z = 1.23$), bringing our sample to 48.

⁵ (1) $R(24, 8) \equiv \log_{10}[\nu f_{\nu}(24\text{ }\mu\text{m})/\nu f_{\nu}(8\text{ }\mu\text{m})] \gtrsim 0.5$; (2) $R(24, 0.7) \equiv \log_{10}[\nu f_{\nu}(24\text{ }\mu\text{m})/\nu f_{\nu}(0.7\text{ }\mu\text{m})] \gtrsim 1.0$.

2.2. Broadband Data

We supplement the IRS spectra with Infrared Array Camera (IRAC; Fazio et al. 2004) and Multiband Photometer for *Spitzer* (MIPS; Rieke et al. 2004) $70\text{ }\mu\text{m}$ broadband photometry.

The IRAC observations were obtained as part of the *Spitzer* Extragalactic First Look Survey⁶ (XFLS; Lacy et al. 2005). The rms noise within a $6''$ diameter aperture is 2.8, 3.2, 15, and $14.4\text{ }\mu\text{Jy}$ at 3.6, 4.5, 5.8, and $8.0\text{ }\mu\text{m}$, respectively. We measured the aperture fluxes of our 48 sources through apertures with a diameter of

⁶ See <http://ssc.spitzer.caltech.edu/fls/>.

FIG. 1.—*Left*: The solid line is the IRS spectrum of NGC 7714. The dashed line is the $\alpha = 3$ power law that best fits the $\sim 5\text{--}15\ \mu\text{m}$ continuum without extinction. The PAH template used is the residual (*dotted line*). *Right*: Milky Way average (i.e., disk) extinction curve and the GC extinction curve (Chiar & Tielens 2006). Here we normalized both to the K band to highlight their differences in the $\sim 5\text{--}15\ \mu\text{m}$ regime of interest.

$7.3''$ (6 pixels) using the IRAC mosaicked images from Lacy et al. (2005). We applied aperture corrections of 1.112, 1.113, 1.125, and 1.218 for the 3.6, 4.5, 5.8, and $8.0\ \mu\text{m}$ fluxes, respectively. To obtain the sky variance, we used 12 sky apertures at ≥ 10 pixels away from the source. From our sample, five sources are confused by nearby stars/bright galaxies. For these cases, we subtract the contaminant from the images by PSF fitting before performing the aperture photometry on our sources. The sources affected are MIPS 289, MIPS 42, MIPS 22661, MIPS 110, and MIPS 227.

The MIPS $70\ \mu\text{m}$ fluxes of our sample come from the combined scan map data (Frayer et al. 2006) and pointed photometry data (PI: P. Choi). Most of our targets have roughly 700 s integration time per pixel. The $70\ \mu\text{m}$ fluxes are estimated using a similar method as described for the IRAC bands. The aperture fluxes are measured through 3 pixel radius apertures. The total fluxes are computed by applying an aperture correction of 2.0. We also estimate flux errors using 12 sky apertures and find typical rms flux errors of 1.3 mJy. All broad fluxes from 3.6 to $70\ \mu\text{m}$ are listed in Table 1.

3. FITTING APPROACH

3.1. Spectral Decomposition Model

The mid-IR spectra of a wide range of sources can be thought of as a superposition of a starburst-powered polycyclic aromatic hydrocarbon (PAH) component and a predominantly AGN-powered continuum component (see, e.g., Laurent et al. 2000; Sturm et al. 2000; Tran et al. 2001). This PAH-to-continuum diagnostic has been applied to ULIRG spectra as well (Genzel et al. 1998; Tran et al. 2001). However, lately the significant obscuration of mid-IR continua of the majority of ULIRGs has been highlighted as an important diagnostic parameter as it can dilute, or even erase, the power source signatures (Levenson et al. 2007; Spoon et al. 2007; Imanishi et al. 2007). With this in mind, below we describe our simple phenomenological approach aiming at

distinguishing the contributions of PAH emission, continuum emission, and mid-IR obscuration.

Our spectral fitting consists of two parts. The first is to determine continuum and opacity by fitting simultaneously three components: (1) an extinction-free PAH emission spectrum, (2) a power-law continuum, and (3) a mid-IR extinction law applied to the continuum. Because our spectra do not necessarily have the same relative PAH ratio as the assumed PAH template, the second step is to fit *all* available PAH features simultaneously using Lorentz profiles, with the predetermined continuum fit

FIG. 2.—Example of our PAH fitting procedure. The thick solid line is the best-fit continuum. The thin dashed lines are the Lorentz fits to the individual PAH features. The total is given in the thin solid line. The bottom panel shows the residual. [See the electronic edition of the *Journal* for a color version of this figure.]

FIG. 3.—*Left*: IRS spectra ($\pm 1\sigma$) with the best-fit continuum (*bottom line*) and continuum+PAH (*top line*). *Right*: Including the IRAC and MIPS data (*squares*). Overlaid is our model plus the host galaxy (*gray dashed line*) and cold dust excess. [See the electronic edition of the *Journal* for a color version of this figure.]

from the first step. The analytical formula describing the first fitting is as follows:

$$F_\nu = a_{\text{PAH}} F_{\nu, \text{PAH}} + a_c \nu^{-\alpha} e^{-\tau_\nu}, \quad (1)$$

where a_{PAH} and a_c are the amplitudes of the two components, $F_{\nu, \text{PAH}}$ is a PAH template, α is the spectral slope, and τ_ν is the extinction curve. The normalized extinction curve is fixed, with $\tau_{9.7}$ being the free parameter. We perform a simultaneous fit on the four free parameters above.

We limit the fitting to the rest-frame 5–15 μm spectral window, which is the typical rest-frame coverage of our IRS spectra. The power-law approximation is assumed to be valid in this limited re-

gion but is expected to break down at shorter and longer wavelengths due to dust sublimation and influence of colder dust components, respectively (e.g., Armus et al. 2007).

Due to the range of redshifts ($0.6 < z < 3.2$) of our sources, we see intrinsically different parts of the PAH spectrum. However, for comparisons within our sample, we need consistent continuum estimates regardless of the rest-frame spectral coverage. This requires adopting a single PAH template and ignoring PAH variability at this point (see above and § 3.2). The pure PAH spectrum⁷

⁷ This is referred to as a PAH spectrum simply because of the lack of continuum. It is more accurately thought of as a “continuum-subtracted starburst spectrum.” For simplicity, however, we refer to it as a “PAH template.”

FIG. 3—Continued

(F_{PAH}) is derived from the IRS, low-resolution spectrum of the starburst NGC 7714 (Brandl et al. 2006), where we have subtracted its continuum as shown in the left panel of Figure 1.

We tested the effect of our choice of PAH template on the fit results (see § 4.1). We looked at variations in the χ^2 when substituting the NGC 7714–based template with the M82 spectrum, which intrinsically has much less $\sim 5\text{--}15\ \mu\text{m}$ continuum emission than the average starburst (Brandl et al. 2006), and therefore we took it “as is” without subtracting a continuum. We found the variations in the χ^2 to be negligible, i.e., well within the continuum uncertainties. Therefore, for our data, the PAH-continuum decomposition is robust against different PAH template choices.

We choose the Galactic center (GC) extinction curve (Chiar & Tielens 2006) as likely closer to the extreme environments in ULIRGs than a standard interstellar medium (ISM) extinction curve. The right panel of Figure 1 shows the GC extinction curve compared with the Milky Way disk (MW) extinction curve (Chiar & Tielens 2006).

We assume screen extinction,⁸ which means that we ignore radiative transfer effects: absorption and emission along the line of sight in an optically thick medium.

⁸ Since this is the most efficient way to absorb light (compared with mixed and/or clumpy distributions), the optical depths derived in this manner are lower limits.

FIG. 3—Continued

This approach is similar to some previous studies of local ULIRGs (Tran et al. 2001; Lutz et al. 2003).

3.2. PAH Profile Fitting

To accurately measure the strength of observed PAH features, we simultaneously fit a set of Lorentz profiles of the continuum-subtracted spectrum at approximately 6.2, 7.7, 8.6, and 11.3 μm .⁹ An example is presented in Figure 2. Below we give the expressions for line flux and equivalent width, as well as their associated uncertainties. The amplitudes, widths, and exact central wavelengths of the features are all free parameters. The widths are not fixed because of intrinsic variability such as due to second-

ary features (e.g., Smith et al. 2007). The central wavelengths are allowed to vary within a limited range largely due to the redshift uncertainties of our sample (see Paper I). Denoting the flux density as F_λ and the continuum flux density as F_c , the total flux and its associated uncertainty are determined by equation (2). Note that these are the flux densities of each fitted component rather than of the original spectrum:

$$F = \sum_{\lambda_1}^{\lambda_2} (F_\lambda - F_c) d\lambda,$$

$$\sigma^2(F) = \sum_{\lambda_1}^{\lambda_2} [\sigma(F_\lambda) d\lambda]^2 + \sum_{\lambda_1}^{\lambda_2} [\sigma(F_c) d\lambda]^2, \quad (2)$$

⁹ We ignore the 12.6 μm feature since it is blended with the Ne II 12.8 μm line.

FIG. 3—Continued

where the limits, λ_1 and λ_2 , are such that they encompass 95% of the line profile.¹⁰

Assuming a constant rms and ignoring the continuum uncertainty, the above formula simplifies to the more familiar $1 \sigma = N_{\text{pix}}^{1/2} \text{rms} \Delta \lambda$. Equivalent widths (EWs) and their uncertainties are determined by equation (3):

$$\text{EW} = \sum_{\lambda_1}^{\lambda_2} \frac{F_{\lambda} - F_c}{F_c} d\lambda,$$

¹⁰ For a Lorentz profile this is 5γ , where 1γ is the half-width encompassing half the power in the line. For comparison, in a Gauss profile, this corresponds to 2σ . The Lorentz width parameter, γ , translates into the more familiar Gaussian FWHM via $\gamma \sim \text{FWHM}/1.8$.

$$\sigma^2(\text{EW}) = \sum_{\lambda_1}^{\lambda_2} \left[\frac{\sigma(F_{\lambda})}{F_c} d\lambda \right]^2 + \sum_{\lambda_1}^{\lambda_2} \left[\frac{F_{\lambda} \sigma(F_c)}{F_c^2} d\lambda \right]^2. \quad (3)$$

In cases where the spectral coverage includes a specific line but is too weak for profile fitting, we estimate 1σ upper limits by using the uncertainty equations for the flux and equivalent width, respectively. This requires adopting a minimum width, γ_{min} . For 6.2, 7.7, and 11.3 lines, respectively, this is 0.1, 0.2, and 0.1 μm . These values are consistent with the minimum widths found for the detected sources.

Both the flux density and equivalent width uncertainties are affected by not just the rms of the spectra, but the uncertainty of the continuum level as well (see eqs. [2] and [3]). As we discuss

FIG. 3—Continued

in § 4.1, we use Markov Chain Monte Carlo (MCMC) fitting, which provides us with the probability distributions of the fit parameters. These include both the uncertainty in the data and the uncertainty purely due to the continuum level. We can derive the latter by subtracting the variance of the data from the MCMC-derived variance by using $\sigma_{\text{tot}}^2 = \sigma^2(F_c) + \sigma^2(F_\lambda)$. This is necessary in order to avoid counting the data rms twice.¹¹ This is a nonnegligible effect as we find that the continuum error dominates at 7.7 and 11.3 μm , and for $\sim \frac{1}{2}$ of the sources at 6.2 μm .

¹¹ Note that this therefore is different from the uncertainty in the continuum luminosities, which we estimate from the marginalized probability distribution as is, since in that case we want to include the data rms as well (see § 4.1).

4. FITTING RESULTS

4.1. Spectral Decomposition

We fit the model described in § 3.1 using MCMC (for a description and references see Sajina et al. 2006). The left panels of Figure 3 show the 5–15 μm spectra (over which the fit was performed) overlaid with the best-fit model. For the $z > 2.5$ sources, we include the MIPS 70 μm point in the fit to help constrain the $\lambda > 13$ μm continuum. A number of typically weaker features¹² are likely to be present in our data but are unaccounted for by the model. These include the neon lines, especially at 12.8 μm ;

¹² The start and end couple of microns of the spectra frequently show apparently strong, but likely spurious, features.

FIG. 3—Continued

absorption features at 6.0, 6.9, and 7.3 μm due to water ice and hydrocarbons (see Spoon et al. 2002, 2003); and the 9.7 μm H_2 emission feature (Higdon et al. 2006). With this caveat, we find that our simple model provides reasonable fits to the spectra (the fit for MIPS 464 was forced to go through the 5.5 μm continuum due to the strong 6 μm absorption; see the Appendix). The best-fit continuum parameters are given in Table 1. The uncertainties are determined from the probability distributions sampled by the MCMC.

Our model fitting is performed on the $\sim 5\text{--}15$ μm spectra alone as stated above. However, the availability of the IRAC and MIPS 70 μm data allows us access to additional diagnostics as described in § 4.3. Therefore, in the right panels of Figure 3 we show the IRS

spectra along with the available IRAC 3.6, 4.5, 5.8, and 8.0 μm , as well as MIPS 70 μm , broadband points. We overlay the best-fit model shown in the left panels, but with one important modification. Since the power-law approximation cannot physically extend to much shorter and longer wavelengths, we truncate it below 5 μm and above 15 μm .¹³ It is expected that the IRAC points would be sensitive to host galaxy stellar light (if present), while the 70 μm points ($\lambda_{\text{rest}} \gtrsim 20$ μm) would be sensitive to cooler dust emission (if present). The data do not allow sophisticated study of either of these components, and hence we characterize each

¹³ This is done by assuming that the power law is a collection of blackbodies and setting $T_{\text{min}} = 600$ K and $T_{\text{max}} = 1000\text{--}1500$ K.

FIG. 3—Continued

with a single template (see § 4.3 for details). For each of these two components a simple linear fit is performed to find the best-fit amplitude for the corresponding template. In the right panels of Figure 3 we show the best-fit host galaxy component (*gray dashed line*) and the best-fit thermal dust component (*gray dotted line*). The dark gray solid line shows the best-fit mid-IR model with these two components added to it (see § 4.3 for a discussion).

4.2. Mid-IR Continuum Slope and Opacity

Figure 4 shows the distribution of optical depth versus continuum slope for our sample. There is a notable lack of sources with low τ and flat spectra (i.e., $\alpha \sim 1$). This is due to one of our selection cuts, $\log(S_{24}/S_8) > 0.5$ (see Paper I). The effect of this cut

as a function of optical depth is shown in Figure 4 for $z = 2$ and 2.5. The median parameter values are $\langle \alpha \rangle = 2.0$ and $\langle \tau_{9.7} \rangle = 1.4$.

Our optical depth measurements assume an extinction curve acting on a power-law continuum. Another common measure is the apparent depth of the silicate feature compared with the continuum defined by the 5 and 15 μm points (e.g., Brandl et al. 2006; Spoon et al. 2007). Given a fixed extinction curve, the two quantities have a simple scaling relation. In the case of the GC extinction curve we adopt, this relation is simply $\tau_{9.7} = 1.4\tau_{\text{Si,obs}}$.

4.3. Monochromatic Luminosities

We use the best-fit continua of our IRS spectra to derive monochromatic luminosities (νL_ν) in two pure continuum regions. We

FIG. 3—Continued

pick $5.8 \mu\text{m}$ due to its sampling of the hot dust continuum just shortward of the $6.2 \mu\text{m}$ PAH feature, and $14 \mu\text{m}$ for its sampling of the continuum between the 9.7 and $18 \mu\text{m}$ SiO absorption features (it is a minimum in the GC extinction curve; see Fig. 1). We read these luminosities from the best-fit continuum fits, not directly from the data. This is necessary because of variable rest-frame spectral coverage and noise spikes at the beginning and end of spectra. This also means that observed absorption features (e.g., MIPS 464) not present in the model do not affect these luminosities.

The IRAC and MIPS $70 \mu\text{m}$ photometric points allow us to sample the spectral energy distributions (SEDs) of our sources outside of the regions covered by the IRS spectra (see § 4.1). Here we quantify the emission shortward and longward of the

available spectra by deriving the monochromatic 1.6 and $30 \mu\text{m}$ emission wherever possible. As discussed in § 4.1, the IRAC points (rest frame $\sim 1\text{--}3 \mu\text{m}$) are likely to be sensitive to direct stellar emission from the host galaxy, which has a characteristic bump at $1.6 \mu\text{m}$. We only accept that we are likely seeing host galaxy light if (1) the source is detected in both 3.6 and $4.5 \mu\text{m}$ and (2) the spectral shape changes color from the dust continuum (e.g., yes for MIPS 15949, but no for MIPS 15958). These data do not allow us to explore the properties of the stellar populations. All we can address is the amplitude of the host galaxy emission whenever present. To do so, we subtract from the IRAC points the mid-IR continuum (truncated below $\sim 5 \mu\text{m}$ as described in § 4.1) and perform a simple linear fit using a 10 Gyr

FIG. 3—*Continued*

old stellar population template (Fiac & Rocca-Volmerange 1997). The choice of template here is irrelevant, as it merely allows us to find the amplitude of the host galaxy emission (quantified via the monochromatic $1.6 \mu\text{m}$ luminosity).

On the other hand, at $z < 1.6$, the MIPS $70 \mu\text{m}$ point samples rest frame $\sim 30 \mu\text{m}$. If it is present, this traces the colder dust emission dominating the typical star-forming galaxy's SED. We therefore fit a 50 K thermal emission to the MIPS $70 \mu\text{m}$ point, whenever it is in excess of the truncated power-law continuum. We emphasize that, as in the case of the stellar population, the current data do not allow us to determine the SED peak (and hence dust temperature). Therefore, the 50 K blackbody is used *only* as a spectral template, allowing us to derive the monochromatic $30 \mu\text{m}$ luminosity.

The broadband-derived 1.6 and $30 \mu\text{m}$ luminosities, along with the 5.8 and $14 \mu\text{m}$ luminosities derived from the IRS spectral fitting itself, are shown in Table 2.

4.4. PAH Feature Strength

To determine the PAH feature strength, we start by subtracting the best-fit continuum from the spectra. We then perform the simultaneous Lorentz profile fits to the main features as described in § 3.2.

The PAH equivalent widths and fluxes are tabulated in Table 3, where the values less than 2σ (this includes both the data and continuum uncertainties) are shown as upper limits (sources without spectral coverage have no value). We leave off the $8.6 \mu\text{m}$ feature as it is too confused with the $7.7 \mu\text{m}$ feature and affected by the continuum uncertainties (due to the Si feature). We only

FIG. 3—Continued

include it in the fitting primarily for the sake of improving the $7.7 \mu\text{m}$ feature strength estimates.

Out of a total of 48 sources, 38 have data at $6.2 \mu\text{m}$, of which 2 have the $6.2 \mu\text{m}$ PAH feature detected at $>3 \sigma$ (9 at $>2 \sigma$). Out of 46 sources with spectral coverage, 24 have their $7.7 \mu\text{m}$ feature detected at $>3 \sigma$ (36 at $>2 \sigma$). For the $11.3 \mu\text{m}$ feature, out of 37 sources with data, 12 are detected at $>3 \sigma$ (20 at $>2 \sigma$). Although the uncertainties vary within the sample, the minimum detectable equivalent widths are roughly $\text{EW}_{6.2} \gtrsim 0.2 \mu\text{m}$, $\text{EW}_{7.7} \gtrsim 0.3 \mu\text{m}$, and $\text{EW}_{11.3} \gtrsim 0.3 \mu\text{m}$. Care must be taken when comparing our EW measurements with those obtained using different approaches. The differences in $6.2 \mu\text{m}$ feature equivalent width measurements are well within $\sim 50\%$ between different fitting

approaches; however, our $7.7 \mu\text{m}$ equivalent widths are about a factor of 4 larger than those obtained by using a cubic spline continuum (e.g., Brandl et al. 2006; Armus et al. 2007).

The luminosity of the strongest PAH feature, $L_{7.7}$, is given in Table 2, along with the key monochromatic luminosities tracing the SEDs discussed in § 4.3.

4.4.1. Stacking Weak-PAH Spectra

In Figure 5 we show the stacked spectra of the weakest PAH sources (i.e., $\text{EW}_{7.7} < 0.7 \mu\text{m}$), separated into optically thin ($\tau_{9.7} < 1$) and optically thick ($\tau_{9.7} > 1$) sources. Individual spectra were first scaled to have the same total power (i.e., $\sum \nu F_\nu$), which is less biased than normalizing at a particular wavelength.

FIG. 3—*Continued*

The stacked spectra are the weighted means of these scaled spectra. These stacked spectra clearly show that the PAH+continuum interpretation is valid even if this is not always obvious in individual spectra. As discussed in § 4.1, other features are likely to be present in the spectra, which could lead to misidentification of features and therefore wrong redshifts. Figure 5 suggests that this is unlikely for the vast majority of the sample.

The stacked spectra of the high- τ , weak-PAH sources highlight that the distorted hump at $\sim 8 \mu\text{m}$ is easily explained by a standard PAH emission spectrum superimposed on a deeply obscured continuum. The presence of the $6.2 \mu\text{m}$ feature confirms this. However, we have excluded MIPS 429 and MIPS 464 due to their exceptionally strong $\sim 6 \mu\text{m}$ absorption features likely due to water ice and/or hydrocarbons (see the Appendix). The average

of the remaining obscured weak-PAH sources still shows a weaker $6.2 \mu\text{m}$ feature compared with our template, which suggests that the same absorption might be present in these sources as well. On the other hand, the weak-PAH, low- τ sources also show a $6.2 \mu\text{m}$ PAH feature that is weaker relative to our PAH template. This may indicate smearing due to redshift uncertainties, PAH obscuration, or variations in the intrinsic PAH feature strength.

5. STARBURST-AGN DIAGNOSTICS

5.1. The PAH Feature Strength

5.1.1. $7.7 \mu\text{m}$ PAH Feature

We focus on the $7.7 \mu\text{m}$ feature as it is usually the strongest and this spectral region is observed for all of our sample.

FIG. 3—Continued

The downside is that it is the feature most affected by the continuum model. The $6.2 \mu\text{m}$ feature is much cleaner in that respect and therefore is usually used as proxy for the PAH strength of local LIRGs and ULIRGs (e.g., Armus et al. 2007; Desai et al. 2006). In Figure 6 we show the rest-frame $6.2 \mu\text{m}$ equivalent width ($\text{EW}_{6.2}$) versus the rest-frame $7.7 \mu\text{m}$ equivalent width ($\text{EW}_{7.7}$). We find that $\text{EW}_{6.2} \gtrsim 0.2 \mu\text{m}$ is the detectability threshold for the $6.2 \mu\text{m}$ feature, which translates into $\text{EW}_{7.7} \gtrsim 0.8 \mu\text{m}$. Armus et al. (2007) find that $\text{EW}_{6.2} \gtrsim 0.4 \mu\text{m}$ separates pure starbursts from composite systems. Although this is uncertain to $\sim 50\%$ due to the different fitting approach in Armus et al. (2007), it suggests that our borderline detected sources are likely to include a significant AGN contribution as well. Therefore, this equivalent width

cut should not automatically be translated into a starburst-AGN separation, but merely into a separation into strong-PAH (largely corresponding to a detected $6.2 \mu\text{m}$ feature when the data are available) and weak-PAH sources. From now on we refer to sources with $\text{EW}_{7.7} \gtrsim 0.8 \mu\text{m}$ as “PAH-rich” and those with $\text{EW}_{7.7} < 0.8 \mu\text{m}$ as “PAH-poor.” We emphasize that PAH-poor does not imply no PAH since 67% of the PAH-poor sources also have a detectable $7.7 \mu\text{m}$ PAH feature and likely have some star formation activity in addition to the dominant AGN. One-quarter of our sample are PAH-rich sources, and three-quarters are PAH-poor sources. In the rest of this section we attempt to attach more physical meaning to this empirical classification. In particular, we ask whether or not our strong-PAH sources are composite systems

FIG. 4.— Continuum parameters α and τ . The lines show the effect of our S_{24}/S_8 color selection for $z = 2$ and 2.5 as labeled.

with comparable AGN and starburst contribution to the mid-IR light, or some of them are clearly starburst dominated.

Lastly, for the purpose of comparison, we have applied our fitting approach on a small subsample of the local ULIRG sample from Armus et al. (2007). These are overplotted in Figure 6 and are included whenever possible in subsequent figures.

5.1.2. Trends with Redshift and Luminosity

In Paper I we presented the redshift distribution of our sample, showing a $z \sim 2.1$ peak and a smaller $z \sim 0.8$ peak. Given our $24 \mu\text{m}$ flux selection, we expect the lower z galaxies to have $10^{12} L_{\odot}$ (typical local ULIRGs) and the higher z galaxies to have up to $L_{\text{IR}} \sim 10^{13} L_{\odot}$ (potential HyLIRGs). Locally the AGN fraction in local ULIRGs rises with total infrared luminosity, dominating above $\sim 3 \times 10^{12} L_{\odot}$ (Tran et al. 2001; Desai et al. 2007). If this holds for our sample, we would expect the strong PAH sources to be among the lower z subsample and the higher z , higher L_{IR} sources to be continuum dominated.

Figure 7 shows that within a given redshift bin, there is a trend of increasing L_{14} with decreasing $\text{EW}_{7.7}$. This might be a trivial result as increasing mid-IR continuum by definition decreases the equivalent width. We need total infrared luminosities to study trends in PAH strength with luminosity as seen for local ULIRGs (Tran et al. 2001).

A more intriguing aspect of Figure 7 is that although it is true that strong PAH sources are predominantly low z , there is a population of equally strong PAH sources at $z \sim 2$. Figure 8 shows the average of strongest PAH ($\text{EW}_{7.7} \gtrsim 2 \mu\text{m}$) of these $z \sim 2$ sources (MIPS 289, MIPS 8493, MIPS 16144, and MIPS 22530), normalized at $7.7 \mu\text{m}$. These sources have $L_{14} \sim 10^{12} L_{\odot}$, implying $L_{\text{IR}} \sim 10^{13} L_{\odot}$. For comparison we overlay the average starburst template from Brandl et al. (2006), as well as the local ULIRG NGC 6240 ($L_{14} \sim 7 \times 10^{10} L_{\odot}$, from our own fit; Armus et al. 2006). Our $z \sim 2$ strong-PAH sources have spectra very similar to NGC 6240; however, our sources are about an order of magnitude more luminous. Lastly, both our average $z \sim 2$ spec-

trum and NGC 6240 show excess emission at $\lambda < 6 \mu\text{m}$ relative to the average starburst. We return to this point in § 5.2.

5.2. Mid-IR Colors: Hot and Cold Dust

The inner dust tori around AGNs can be heated to near sublimation temperatures (~ 1000 – 1500 K), which dominate the mid-IR spectra provided that these hot regions are not obscured (e.g., Pier & Krolik 1992). Such emission peaks in the ~ 3 – $6 \mu\text{m}$ region, leading to (type 1) AGNs having flatter ~ 5 – $15 \mu\text{m}$ spectral slopes ($\alpha \sim 1$, e.g., 3C 273) than the typical starburst ($\alpha \sim 3$, e.g., NGC 7714). The typical slopes of local ULIRGs (Armus et al. 2007) lie roughly between these values and are consistent with our median slope of $\alpha \sim 2$. We find no difference in the ~ 5 – $15 \mu\text{m}$ slope distribution of the PAH-rich and PAH-poor sources.

The longer wavelength SED is dominated by cold dust of $\lesssim 50$ K associated with star formation. In § 4.3 and Figure 3 we show that many of our sources show very warm spectra peaking at $\sim 30 \mu\text{m}$, while others show an excess over the mid-IR continuum, consistent with the presence of cooler dust. These were used to derive $\nu L_{\nu}(30 \mu\text{m})$ (see Table 2) for sources with $z \lesssim 1.6$ such that the MIPS $70 \mu\text{m}$ point is not too redshifted away from rest frame $30 \mu\text{m}$. Figure 9 shows that while the $\sim 5 \mu\text{m}$ –to– $15 \mu\text{m}$ colors are the same for both PAH-rich and PAH-poor sources (as is the case for the entire sample), the $\sim 15 \mu\text{m}$ –to– $30 \mu\text{m}$ colors separate the two groups very well. Our PAH-poor sources are redder than the optically selected quasars, consistent with their being dustier. Our PAH-rich sources are generally consistent with the starbursts' colors although they show slightly bluer ~ 5 – $15 \mu\text{m}$ slopes suggesting enhanced hot dust.

We expand on the last point, now using the entire sample, in Figure 10, where we show the hot dust continuum luminosity $\nu L_{\nu}(5.8)$ versus the $7.7 \mu\text{m}$ PAH luminosity. For lower luminosity star-forming sources, the two are well correlated with slope unity, suggesting that, at least at moderate luminosities, the mid-IR SEDs of purely star-forming galaxies are fairly constant. As expected, optically selected quasars have stronger $5.8 \mu\text{m}$ continuum per $7.7 \mu\text{m}$ luminosity. Our weak-PAH sources, at higher luminosities, are consistent with the local AGN trend, despite their redder slopes. However, to a lesser extent, our strong-PAH sources are also noticeably shifted with respect to the local starbursts. There are two possible explanations for this:

1. They have significant AGN contributions leading to enhanced $5.8 \mu\text{m}$ continuum.
2. The local starburst trend does not extend to the highest luminosity regime, but curves toward our strong-PAH sources, making them starburst dominated as well. In other words, extreme starbursts generate enhanced hot dust emission compared with lower luminosity ones.

The first explanation is very likely given the extreme luminosities of our sources. As discussed in § 5.1.1, our equivalent width cut is more an upper limit on the starburst-dominated sources, since especially borderline sources are likely to include a significant AGN contribution as well. Therefore, we also look individually at the $z \sim 2$ sources with strongest PAH emission ($\text{EW}_{7.7} \gtrsim 2 \mu\text{m}$, or $\text{EW}_{6.2} \gtrsim 0.3 \mu\text{m}$). Even these strongest PAH sources show excess emission at $\lambda < 6 \mu\text{m}$, relative to the typical starburst (see Fig. 8), indicating higher hot dust contribution. Figure 8 also shows that our strong-PAH sources are similar to NGC 6240 in that respect, which was already interpreted by Armus et al. (2006) as having $\sim 20\%$ AGN contribution to the bolometric luminosity ($\sim 50\%$ of the mid-IR emission; Lutz et al. 2003).

On the other hand, hot dust emission has been observed to be associated with star formation activity as well (Hunt et al. 2002;

TABLE 2
LUMINOSITIES WITH 1σ UNCERTAINTIES

Source	$\log(L_{1.6}/L_{\odot})$	$\log(L_{5.8}/L_{\odot})$	$\log(L_{14}/L_{\odot})$	$\log(L_{30}/L_{\odot})$	$\log(L_{\text{PAH},7.7}/L_{\odot})$
MIPS 42.....	...	12.51 ± 0.02	12.68 ± 0.03	...	10.60 ± 0.20
MIPS 78.....	...	12.66 ± 0.02	12.76 ± 0.04	...	<10.56
MIPS 110.....	10.81 ± 0.10	11.21 ± 0.07	11.64 ± 0.02	11.84 ± 0.52	9.73 ± 0.19
MIPS 133.....	10.81 ± 0.14	10.97 ± 0.05	11.45 ± 0.03	11.71 ± 0.27	<9.70
MIPS 180.....	11.10 ± 0.70	12.32 ± 0.03	12.57 ± 0.07	...	10.92 ± 0.10
MIPS 227.....	11.53 ± 0.10	11.68 ± 0.06	12.39 ± 0.02	...	10.26 ± 0.18
MIPS 279.....	10.89 ± 0.35	10.19 ± 0.08	11.57 ± 0.02	11.92 ± 0.34	9.65 ± 0.20
MIPS 283.....	11.12 ± 0.03	10.85 ± 0.08	11.01 ± 0.04	11.48 ± 0.72	10.38 ± 0.03
MIPS 289.....	11.47 ± 0.15	11.47 ± 0.23	11.80 ± 0.22	...	11.14 ± 0.05
MIPS 429.....	...	11.66 ± 0.09	12.22 ± 0.03	...	10.63 ± 0.09
MIPS 464.....	...	11.53 ± 0.06	12.16 ± 0.03	...	10.09 ± 0.19
MIPS 506.....	11.17 ± 0.35	11.82 ± 0.20	12.74 ± 0.01	...	11.11 ± 0.13
MIPS 8034.....	10.75 ± 0.20	11.21 ± 0.08	11.66 ± 0.02	11.58 ± 0.48	<9.59
MIPS 8184.....	10.88 ± 0.08	10.94 ± 0.06	11.32 ± 0.02	11.87 ± 0.23	10.44 ± 0.03
MIPS 8196.....	11.74 ± 0.24	12.46 ± 0.02	12.53 ± 0.02	...	11.09 ± 0.08
MIPS 8207.....	10.89 ± 0.12	10.71 ± 0.07	11.06 ± 0.04	11.59 ± 0.32	10.20 ± 0.03
MIPS 8242.....	11.51 ± 0.21	12.07 ± 0.04	12.74 ± 0.04	...	10.70 ± 0.19
MIPS 8245.....	...	12.23 ± 0.08	12.55 ± 0.03	...	10.41 ± 0.18
MIPS 8268.....	10.79 ± 0.05	10.82 ± 0.05	11.04 ± 0.02	11.19 ± 0.80	<9.05
MIPS 8327.....	...	12.07 ± 0.07	12.40 ± 0.04	...	10.62 ± 0.21
MIPS 8342.....	11.00 ± 0.35	11.50 ± 0.08	11.93 ± 0.02	12.28 ± 0.36	10.52 ± 0.10
MIPS 8493.....	11.27 ± 0.27	11.38 ± 0.23	11.49 ± 0.22	...	10.93 ± 0.06
MIPS 15840.....	11.22 ± 0.20	12.28 ± 0.03	12.50 ± 0.04	...	<10.29
MIPS 15880.....	11.28 ± 0.18	11.94 ± 0.03	12.51 ± 0.01	...	10.60 ± 0.09
MIPS 15928.....	10.95 ± 0.23	11.44 ± 0.05	12.04 ± 0.02	12.36 ± 0.37	10.69 ± 0.05
MIPS 15949.....	11.16 ± 0.35	11.94 ± 0.04	12.45 ± 0.03	...	10.71 ± 0.08
MIPS 15958.....	...	11.95 ± 0.05	12.19 ± 0.04	...	10.29 ± 0.20
MIPS 15977.....	11.36 ± 0.15	11.82 ± 0.05	12.28 ± 0.02	...	<10.24
MIPS 16030.....	10.98 ± 0.07	10.93 ± 0.07	11.22 ± 0.06	11.39 ± 0.75	9.91 ± 0.08
MIPS 16059.....	11.17 ± 0.57	12.05 ± 0.04	12.46 ± 0.02	...	10.76 ± 0.09
MIPS 16080.....	11.19 ± 0.42	11.93 ± 0.04	12.18 ± 0.02	...	10.20 ± 0.17
MIPS 16095.....	10.85 ± 0.32	11.69 ± 0.05	12.12 ± 0.02	...	<10.16
MIPS 16113.....	...	11.77 ± 0.08	11.88 ± 0.16	...	10.80 ± 0.08
MIPS 16122.....	...	11.81 ± 0.06	12.13 ± 0.09	...	10.41 ± 0.21
MIPS 16144.....	11.67 ± 0.10	11.59 ± 0.28	12.01 ± 0.14	...	11.20 ± 0.06
MIPS 22204.....	...	12.50 ± 0.02	12.63 ± 0.01	...	11.01 ± 0.10
MIPS 22277.....	11.36 ± 0.13	12.03 ± 0.08	12.36 ± 0.05	...	10.44 ± 0.19
MIPS 22303.....	...	12.32 ± 0.06	12.57 ± 0.03	...	<10.50
MIPS 22404.....	10.84 ± 0.04	10.32 ± 0.07	10.77 ± 0.04	11.52 ± 0.33	...
MIPS 22467.....	10.52 ± 0.26	10.57 ± 0.05	10.86 ± 0.02	11.31 ± 0.62	...
MIPS 22482.....	11.19 ± 0.15	11.71 ± 0.08	12.04 ± 0.14	...	10.86 ± 0.13
MIPS 22530.....	11.33 ± 0.26	11.48 ± 0.25	12.10 ± 0.15	...	11.02 ± 0.10
MIPS 22554.....	10.91 ± 0.03	10.50 ± 0.09	10.71 ± 0.08	11.29 ± 0.57	9.96 ± 0.04
MIPS 22558.....	...	12.49 ± 0.02	12.88 ± 0.01	...	10.96 ± 0.12
MIPS 22600.....	10.83 ± 0.10	10.59 ± 0.10	10.83 ± 0.08	11.34 ± 0.53	10.04 ± 0.05
MIPS 22651.....	11.50 ± 0.10	11.50 ± 0.15	11.86 ± 0.05	...	10.77 ± 0.07
MIPS 22661.....	10.94 ± 0.21	11.44 ± 0.07	11.93 ± 0.04	...	10.21 ± 0.21
MIPS 22699.....	...	12.12 ± 0.04	12.17 ± 0.08	...	<10.34

NOTE.—Upper limits are 3σ .

Lu et al. 2003). An extreme example are high SFR intensity dwarf galaxies that show continuum-dominated mid-IR spectra (Galliano et al. 2003). Therefore, the possibility of enhanced hot dust emission being associated with extreme starbursts cannot be excluded.

We conservatively adopt the first explanation above but stress that the properties of high-luminosity, pure starbursts remain unclear.

5.3. Near-IR Host Galaxy Light

It has been proposed that the presence of the $1.6 \mu\text{m}$ bump, characteristic of stellar populations older than ~ 100 Myr, is an efficient way of separating starburst- from AGN-dominated sources

(e.g., Weedman et al. 2006; Teplitz et al. 2007). The rationale is that the hot dust continuum of AGNs overwhelms their host galaxy's stellar bump.

Figure 3 shows that the IRAC points (which probe the $1.6 \mu\text{m}$ stellar bump at $z \sim 2$) often (in 73% of the sources) have excess emission over the extrapolated mid-IR continuum. This excess is most likely the $1.6 \mu\text{m}$ stellar bump of old stellar populations together with some unknown young star contribution (see § 4.3). The left panel of Figure 11 shows the $1.6 \mu\text{m}$ luminosity versus the PAH luminosity. Both our PAH-rich and PAH-poor sources (where the excess is observed) obey the relation defined by the local star-forming galaxies. This suggests that even in the continuum-dominated sources (with a few exceptions) we do not

TABLE 3
PAH STRENGTH WITH 1 σ UNCERTAINTIES

Source	EW _{6.2} (μm)	EW _{7.7} (μm)	EW _{11.3} (μm)	$F_{6.2}$ (10^{-15} ergs s $^{-1}$ cm $^{-2}$)	$F_{7.7}$ (10^{-15} ergs s $^{-1}$ cm $^{-2}$)	$F_{11.3}$ (10^{-15} ergs s $^{-1}$ cm $^{-2}$)
MIPS 42.....	<0.08	0.08 $\pm$ 0.04	<0.04	<6.8	6.2 $\pm$ 2.9	<2.2
MIPS 78.....	<0.04	<0.06	...	<2.6	<2.8	...
MIPS 110.....	<0.26	0.18 $\pm$ 0.08	<0.08	<6.0	4.4 $\pm$ 1.9	<2.0
MIPS 133.....	<0.30	<0.30	<0.26	<5.4	<5.2	<3.4
MIPS 180.....	0.08 $\pm$ 0.04	0.26 $\pm$ 0.07	...	<2.6	7.3 $\pm$ 1.6	...
MIPS 227.....	<0.22	0.17 $\pm$ 0.08	0.08 $\pm$ 0.04	<3.4	3.2 $\pm$ 1.3	<2.0
MIPS 279.....	...	0.17 $\pm$ 0.08	0.25 $\pm$ 0.08	...	2.2 $\pm$ 1.0	3.3 $\pm$ 1.1
MIPS 283.....	...	2.66 $\pm$ 0.33	1.85 $\pm$ 0.37	...	22.8 $\pm$ 1.6	9.9 $\pm$ 1.6
MIPS 289.....	0.48 $\pm$ 0.14	2.81 $\pm$ 0.23	0.82 $\pm$ 0.13	4.4 $\pm$ 1.4	24.3 $\pm$ 2.7	5.4 $\pm$ 1.7
MIPS 429.....	<0.30	0.41 $\pm$ 0.09	<2.4	<3.2	5.2 $\pm$ 1.0	<2.6
MIPS 464.....	<0.12	0.51 $\pm$ 0.10	<0.32	<1.4	6.9 $\pm$ 1.2	<1.2
MIPS 506.....	0.30 $\pm$ 0.14	0.87 $\pm$ 0.36	...	3.4 $\pm$ 1.7	10.8 $\pm$ 3.3	...
MIPS 8034.....	<0.26	<0.22	0.23 $\pm$ 0.10	<5.8	<5.4	5.8 $\pm$ 2.5
MIPS 8184.....	...	1.83 $\pm$ 0.11	1.08 $\pm$ 0.13	...	22.8 $\pm$ 1.3	11.7 $\pm$ 1.3
MIPS 8196.....	<0.06	0.31 $\pm$ 0.08	...	<2.0	9.5 $\pm$ 1.7	...
MIPS 8207.....	...	2.13 $\pm$ 0.21	0.77 $\pm$ 0.13	...	20.0 $\pm$ 1.5	6.4 $\pm$ 1.1
MIPS 8242.....	<0.12	0.21 $\pm$ 0.10	...	<2.4	4.5 $\pm$ 2.0	...
MIPS 8245.....	<0.16	0.09 $\pm$ 0.04	...	<3.4	1.8 $\pm$ 0.8	...
MIPS 8268.....	...	<0.12	<0.36	...	<1.6	<3.6
MIPS 8327.....	<0.14	<0.30	...	<2.4	<3.6	...
MIPS 8342.....	<0.16	0.58 $\pm$ 0.14	0.11 $\pm$ 0.04	<2.2	8.4 $\pm$ 2.0	1.6 $\pm$ 0.5
MIPS 8493.....	0.32 $\pm$ 0.13	2.72 $\pm$ 0.43	2.72 $\pm$ 0.52	2.4 $\pm$ 1.1	16.4 $\pm$ 2.2	4.2 $\pm$ 1.0
MIPS 15840.....	<0.10	<0.06	<0.22	<3.2	<2.0	<5.0
MIPS 15880.....	0.06 $\pm$ 0.03	0.23 $\pm$ 0.05	<0.06	<2.2	8.9 $\pm$ 1.9	<1.0
MIPS 15928.....	0.33 $\pm$ 0.07	0.89 $\pm$ 0.11	0.20 $\pm$ 0.03	4.7 $\pm$ 1.0	14.2 $\pm$ 1.7	4.0 $\pm$ 0.6
MIPS 15949.....	<0.14	0.31 $\pm$ 0.06	<0.12	<2.8	6.4 $\pm$ 1.2	<2.6
MIPS 15958.....	<0.14	0.14 $\pm$ 0.06	<0.12	<3.0	3.0 $\pm$ 1.4	<1.8
MIPS 15977.....	0.18 $\pm$ 0.07	<0.14	0.06 $\pm$ 0.03	3.7 $\pm$ 1.4	<3.0	1.3 $\pm$ 0.7
MIPS 16030.....	...	0.60 $\pm$ 0.12	0.58 $\pm$ 0.11	...	7.0 $\pm$ 1.3	5.6 $\pm$ 1.1
MIPS 16059.....	<0.14	0.29 $\pm$ 0.07	...	<2.6	5.3 $\pm$ 1.2	...
MIPS 16080.....	<0.14	0.11 $\pm$ 0.05	<0.20	<2.8	2.2 $\pm$ 0.9	<1.8
MIPS 16095.....	<0.12	<0.16	<0.06	<2.4	<3.2	<1.0
MIPS 16113.....	<0.16	0.79 $\pm$ 0.16	<0.38	<2.6	10.6 $\pm$ 2.1	<1.6
MIPS 16122.....	<0.16	0.25 $\pm$ 0.11	0.19 $\pm$ 0.09	<2.8	3.9 $\pm$ 1.9	1.7 $\pm$ 0.8
MIPS 16144.....	<0.32	2.50 $\pm$ 0.26	0.50 $\pm$ 0.24	<2.8	20.2 $\pm$ 2.8	<2.6
MIPS 22204.....	<0.08	0.22 $\pm$ 0.05	<0.10	<7.8	13.6 $\pm$ 3.1	<2.8
MIPS 22277.....	<0.12	0.15 $\pm$ 0.07	<0.08	<4.2	5.5 $\pm$ 2.4	<2.8
MIPS 22303.....	<0.12	<0.10	...	<4.6	<3.2	...
MIPS 22404.....	...	...	1.68 $\pm$ 0.16	...	...	12.7 $\pm$ 1.2
MIPS 22467.....	...	...	<0.26	...	...	<2.2
MIPS 22482.....	<0.16	0.90 $\pm$ 0.15	<0.12	<2.6	13.0 $\pm$ 3.8	<3.2
MIPS 22530.....	0.39 $\pm$ 0.15	1.85 $\pm$ 0.32	0.91 $\pm$ 0.29	3.4 $\pm$ 1.3	16.2 $\pm$ 3.8	3.4 $\pm$ 1.5
MIPS 22554.....	...	2.09 $\pm$ 0.31	4.59 $\pm$ 1.13	...	12.0 $\pm$ 1.1	9.1 $\pm$ 1.6
MIPS 22558.....	<0.04	0.16 $\pm$ 0.08	...	<1.2	4.3 $\pm$ 1.2	...
MIPS 22600.....	...	1.94 $\pm$ 0.32	2.38 $\pm$ 0.63	...	13.0 $\pm$ 1.4	8.6 $\pm$ 1.7
MIPS 22651.....	0.28 $\pm$ 0.10	1.12 $\pm$ 0.18	0.21 $\pm$ 0.06	3.2 $\pm$ 1.2	12.4 $\pm$ 2.0	2.0 $\pm$ 0.5
MIPS 22661.....	<0.28	0.32 $\pm$ 0.16	0.17 $\pm$ 0.06	<2.6	3.1 $\pm$ 1.5	1.8 $\pm$ 0.6
MIPS 22699.....	<0.12	<0.12	...	<2.0	<1.8	...

NOTE.—Upper limits are 2 σ .

see the AGN itself (accretion disk emission), but the host galaxy light alone.¹⁴ Circumstantial support is provided by optically selected quasars whose 1.6 μm luminosities (McLeod & Rieke 1994a, 1994b) lie significantly to the right of the star-forming galaxy relation. Although not shown for clarity, the AGN-subtracted H -band luminosities of the PG QSOs (McLeod & Rieke 1994a, 1994b) agree much better with the star-forming galaxy relation, suggesting that the offset is predominantly due to the effect

of AGN dominance at 1.6 μm rather than suppressed 7.7 μm emission.

The last point is supported by the right panel of Figure 11, which shows $\nu L_\nu(1.6 \mu\text{m})$ versus the 7.7 μm PAH feature luminosity, both normalized to the 5.8 μm continuum. The effect of increasing hot dust emission is now obvious, as there is a clear trend between the star-forming galaxies and our PAH-rich and PAH-poor sources. The PG QSO sample has the same 7.7 μm feature strength relative to the 5.8 μm as our PAH-poor sources, but it shows an excess of 1.6 μm emission.

Lastly, these results have implications for AGN selection methods such as the IRAC color-color diagram (see Lacy et al. 2004,

¹⁴ Upcoming NICMOS observations of the sample would be able to address this directly.

FIG. 5.—Stacked spectra of weak-PAH sources divided into optically thin ($\tau_{9.7} < 1$) and optically thick ($\tau_{9.7} > 1$). Note that a simple model with our PAH template added to a continuum is a reasonable fit to the data. The power-law slope is 2.1 for the low- τ spectrum and 1.7 for the high- τ spectrum. A $\tau_{9.7} = 2.0$ extinction is applied to the latter. [See the electronic edition of the Journal for a color version of this figure.]

2007; Stern et al. 2005; Sajina et al. 2005). These rely on the IRAC bands of AGNs being dominated by a power-law continuum, rather than PAH features and a stellar bump as in starbursts. In Sajina et al. (2005) we stressed that this might fail at $z \sim 2$ due to the unknown fraction of AGNs whose host galaxies dominate at $\lambda = 1.6 \mu\text{m}$.

Figure 12 shows the IRAC color-color plot for our sample. About 20% of the continuum-dominated sources fall outside of the AGN regime due to host galaxy emission as discussed above. This assumes that the sources undetected in more than one IRAC band and therefore not included in Figure 12 are undetected due to

FIG. 6.—Sources with $EW_{7.7} > 3 \sigma$, where data are available at $6.2 \mu\text{m}$ as well. The $6.2 \mu\text{m}$ detection limit is $EW_{6.2} \geq 0.2 \mu\text{m}$, corresponding to $EW_{7.7} > 0.8 \mu\text{m}$. Both limits are shown as dashed lines. We use the $7.7 \mu\text{m}$ equivalent widths in the rest of the paper as they are available for most of our sources. From now on, crosses denote PAH-rich sources ($EW_{7.7} \geq 0.8 \mu\text{m}$), while circles denote PAH-poor sources ($EW_{7.7} < 0.8 \mu\text{m}$). [See the electronic edition of the Journal for a color version of this figure.]

FIG. 7.—For the $z \geq 1.5$, we find a trend of decreasing $EW_{7.7}$ with increasing L_{14} . As usual, we mark the strong-PAH sources (i.e., $EW_{7.7} \geq 0.8 \mu\text{m}$) with crosses, while those below this limit are shown with open circles. All $z < 1.5$ sources (larger symbols) are significantly below the trend found for the higher z sources. For the whole sample, 25% are strong PAH sources; for the low- z ($z < 1.5$) sources this fraction is 42%, while for the high- z sources it is only 23%. [See the electronic edition of the Journal for a color version of this figure.]

FIG. 8.—Average spectra of four of our $z \sim 2$ strong-PAH sources, normalized at $7.7 \mu\text{m}$. Our sources appear very similar to the local ULIRG NGC 6240. Both are similar to the starburst template, except for the excess power at $\lambda < 6 \mu\text{m}$. [See the electronic edition of the Journal for a color version of this figure.]

steeply falling red continua and would have fallen inside the AGN wedge. Since our sample is biased toward less prominent hot dust, this is an upper limit for the AGN population as a whole. It does, however, imply that the use of this technique to search for obscured AGNs, although remarkably effective at lower z (e.g., Lacy et al. 2007), becomes less reliable at $z \gtrsim 2$.

FIG. 9.—Mid-IR color-color diagram, where only $z < 1.6$ sources are shown as reliable $30 \mu\text{m}$ luminosities cannot be obtained for the rest. For comparison we overlay local samples of starbursts and optically selected quasars. The dashed line is to guide the eye. Note that among the reddest in both color sources, the two populations are indistinguishable. [See the electronic edition of the Journal for a color version of this figure.]

FIG. 10.—The $\nu L_\nu(5.8)$ vs. $L_{\text{PAH},7.7}$. For comparison we overlay local samples of optically selected AGNs, normal star-forming galaxies, and starbursts. The exact positions of these are uncertain as we have converted the published PAH $7.7 \mu\text{m}$ feature strength values to our continuum definition. We have fitted the named sources with our method. [See the electronic edition of the Journal for a color version of this figure.]

5.4. The $9.7 \mu\text{m}$ Silicate Feature

The depth of the $9.7 \mu\text{m}$ silicate feature has recently been highlighted (Levenson et al. 2007; Spoon et al. 2007; Imanishi et al. 2007) as a tool to distinguish between sources dominated by buried nuclei and sources with more clumpy, extended dust distributions. Spoon et al. (2007) presented an intriguing diagnostic diagram of the $\text{PAH}_{6.2}$ equivalent width versus the $9.7 \mu\text{m}$ silicate feature depth. Sources with weak silicate features range from pure starbursts to pure AGNs in the manner of traditional PAH over-continuum diagnostics. A distinct secondary sequence of increasing silicate feature depth with decreasing PAH feature strength is revealed. This is interpreted as an increasingly dominant buried nucleus.

For low-S/N, high- z samples such as ours, the equivalent diagram is based on the $7.7 \mu\text{m}$ PAH feature strength and the optical depth estimate (Fig. 13). The overlaid grids are generated via equation (1), with an $\alpha = 2$ continuum and starburst fractions spanning between 3C 273 (0%) and NGC 7714 (100%). As we increase the optical depth, the observed fractions remain constant, while the intrinsic fractions curve since the unextincted $L_{5.8}$ is higher than the observed one. We mark $\tau_{9.7} = 1$ as separating optically thin from optically thick sources, which is also where extinction correction effects become strong. This largely corresponds to the separation between class 1 and class 2 sources in Spoon et al. (2007) or, in other words, between sources with clumpy dust (weak silicate feature) and buried nucleus sources (significant silicate feature).

Roughly 40% of the sample has $\tau_{9.7} < 1$, indicating that a buried nucleus is not present or significant. Of these sources, three-quarters are continuum-dominated (most likely AGN) sources. One-quarter are strong PAH sources, but none of them are likely to be pure starbursts and most likely have a significant AGN contribution as well.

FIG. 11.—*Left*: The 1.6 μm stellar bump strength vs. the 7.7 μm PAH strength. The normal star-forming galaxies are used to define the best-fit line shown. Note that both our PAH-rich and PAH-poor sources agree very well with this relation. Optically selected AGNs light to the right of this, suggesting that for the bulk of our PAH-poor sources, the 1.6 μm emission is more likely to be due to host galaxy emission rather than that of the AGN itself as in the PG QSO sample. *Right*: The 1.6 μm stellar bump strength vs. the 7.7 μm PAH strength normalized to the 5.8 μm luminosities. [See the electronic edition of the Journal for a color version of this figure.]

The bulk of our sample, $\sim 60\%$, has $\tau_{9.7} > 1$, suggesting that the buried nucleus dominates over more clumpy dust geometries. Although about 25% of these sources have significant PAH emission, after extinction correction $\sim 90\%$ of these highly obscured sources are continuum dominated. It is important to realize that since our sensitivity to weak PAH emission (even using

the 7.7 μm feature) is worse than for the local sample used by Spoon et al. (2007), our diagram is missing (or they are lost in the upper limits) the weakest PAH sources (class A in Spoon et al. 2007). The 50% line roughly corresponds to the separation between class B and class C sources in Spoon et al. (2007).

Lastly, we compared the relative distribution of our sources along the τ -direction with that of local ULIRGs (Spoon et al.

FIG. 12.—IRAC color-color plot of our sample, excluding sources with more than one band at $< 3\sigma$. The symbols as usual mean PAH-rich (crosses) and PAH-poor (circles). The dashed lines indicate the wedge used in selecting AGN-dominated sources at lower z (Lacy et al. 2004). [See the electronic edition of the Journal for a color version of this figure.]

FIG. 13.—Low- τ , x-axis starburst fraction spanning the range from pure starburst (NGC 7714) to pure type 1 AGN (3C 273). Maintaining the same observed fraction with increasing τ gives us the solid lines. Maintaining the same intrinsic fraction with increasing τ gives the dotted lines. The stars show the Brandt et al. (2006) starbursts. [See the electronic edition of the Journal for a color version of this figure.]

2007). We find that the two are roughly consistent with both populations having the bulk of their members residing in the moderate optical depth regime ($\tau_{9.7} \sim 1-3$). For both local and high- z ULIRGs (including those with only lower limits on $\tau_{9.7}$), $\sim 25\%$ of the population resides in the most obscured source regime ($\tau_{9.7} \gtrsim 3$). This corresponds to class 3 in Spoon et al. (2007), which contains the sources with evidence of extremely cold and dense media (see the Appendix). We estimate that for the local sample, the space density of these extremely obscured sources is roughly $\sim 6 \times 10^{-8} \text{ Mpc}^{-3}$ (assuming that the ULIRG sample in Spoon et al. [2006] is not biased in its τ -distribution compared with the *IRAS* 1 Jy ULIRG sample). Given that our sample of $z \sim 2$ extremely obscured sources is incomplete, we derive a lower limit density of $\sim 7 \times 10^{-7} \text{ Mpc}^{-3}$. These estimates are uncertain to within a factor of 2 but clearly suggest that the density of such objects was about an order of magnitude larger at $z \sim 2$ than today.

6. SUMMARY AND CONCLUSIONS

We presented spectral decomposition of a sample of 48 $z \sim 2$, low-resolution mid-IR IRS spectra. The detailed analysis, separating the contribution of PAH emission, continuum emission, and continuum extinction, has revealed several significant characteristics of $z \sim 2$ ULIRGs.

In Paper I we discussed that our sources have quasar-like luminosities and frequently continuum-dominated spectra, suggesting that an AGN is the primary power source. We find that 75% of our sample has continuum-dominated spectra. However, 4 sources of the original sample of 52 were not included here because of their featureless spectra and hence lack of redshifts. If we include these 4 sources, this fraction rises to nearly 80%. About 60% of these show detectable PAH emission, suggesting that these are composite sources rather than pure AGNs. At much higher S/N, Schweitzer et al. (2006) find that $\sim 40\%$ of PG QSOs have detectable PAH. We have shown that our sources have much redder mid-IR colors than the PG quasar sample. Lastly, in optically selected quasars, the AGN dominates in the near-IR, whereas for us the host galaxy, or a significantly obscured AGN, appears to dominate at $\sim 1-2 \mu\text{m}$. The greater obscuration is also seen in the fact that $\sim 60\%$ of these continuum-dominated sources have $\tau_{9.7} > 1$ (see discussion below), whereas optically selected quasars have $\tau_{9.7} \sim 0$ (and even show silicate emission). All of these suggest that the bulk of our sources are potentially related to the still elusive type 2 quasars. Follow-up observations are needed to ascertain their nature.

About 25% of our sample has strong PAH. In particular, for 38 spectra covering the rest-frame $6 \mu\text{m}$, 6 sources have detectable $6.2 \mu\text{m}$ PAH emission with $\text{EW}_{6.2}$ in the range $\sim 0.3-0.5 \mu\text{m}$. Their $14 \mu\text{m}$ monochromatic luminosities are on the order of $10^{12} L_{\odot}$. ULIRGs with such a high infrared luminosity and such a large $6.2 \mu\text{m}$ PAH equivalent width do not exist in the local universe. As shown by the IRS observations of local ULIRGs (Armus et al. 2007), a galaxy with $6.2 \mu\text{m}$ PAH equivalent width of $0.3 \mu\text{m}$ has $14 \mu\text{m}$ luminosity $\sim 10^{11} L_{\odot}$, an order of magnitude less than that of our $z \sim 2$ PAH-emitting sources. Regardless of the exact degree of AGN contribution, it is obvious that the local PAH $6.2 \mu\text{m}$ versus L_{IR} relation (Desai et al. 2007) does not hold at $z \sim 2$ (or experiences strong evolution). These $z \sim 2$ strong-PAH sources likely all have significant AGN contribution to their mid-IR emission, as evidenced by excess hot dust emission. However, their bolometric emission is likely still dominated by the starburst (by analogy with sources such as NGC 6240, and the observed hints of colder dust at longer wavelengths). Far-IR observations are needed to disentangle the star formation and AGN

contribution to their infrared luminosity (see A. Sajina et al. 2007, in preparation). If these sources are indeed starburst dominated, translating their continuum luminosities into bolometric luminosities (see Paper I) implies an SFR on the order of $1000 M_{\odot} \text{ yr}^{-1}$ (this could be lowered significantly by including an obscured AGN or top-heavy initial mass function; Baugh et al. 2005). Such extreme values have been claimed before for SMGs (see, e.g., Blain et al. 2002; Pope et al. 2006), which have comparable number density at $z \sim 2$ as our sources (Paper I).

The bulk of these luminous sources show significant obscuration with optical depths $\tau_{9.7} > 1$. We propose a new diagnostic diagram, applicable to low-S/N, high- z data, where we plot the optical depth against the traditional PAH strength indicator of relative starburst/AGN activity. Following Levenson et al. (2007) and Spoon et al. (2007), about 60% of our sample is consistent with being dominated by buried nuclei rather than the clumpy dust distribution indicating (but not exclusively) extended star formation activity. About 50% of our strong-PAH sources fall in this category. However, we find some $z \sim 2$, $L_{\text{IR}} \sim 10^{13} L_{\odot}$ strong-PAH sources that are potentially consistent with extended, clumpy star formation (e.g., MIPS 289). Recent observations suggest that this may be the case with some SMGs as well (Ivison 2007). The definitive answer to this question will have to await the greater spatial resolution in the submillimeter regime of the Atacama Large Millimeter Array (ALMA; Wooten 2006).

Among our sources, the distribution of the absorption depth at $9.7 \mu\text{m}$ is similar to that observed among local ULIRGs, with $\langle \tau_{9.7} \rangle \sim 1.5$; however, our sources on average are a factor of 5–10 more luminous ($L_{8-1000 \mu\text{m}}$) than local ULIRGs and close to the bolometric luminosity of the brightest, optically selected quasars. The relative starburst-AGN contribution to the mid-IR emission of these sources is difficult to assess, especially for the most extremely obscured sources ($\tau_{9.7} \sim 3$), which represent $\sim 25\%$ of our sample. The strong similarity between the mid-IR spectrum of the nascent starburst NGC 1377 (Roussel et al. 2006) and the deep silicate feature ULIRG IRAS 08572+3915 suggests that even in sources with weak or absent PAH, a buried nucleus can be powered by either an AGN or a young starburst (or more likely both). High-resolution mid-IR spectra with neon line ratios, deep X-ray spectra, and L -band ($3-4 \mu\text{m}$) spectroscopic diagnostics could provide useful additional information, but uncertainties due to high obscuration would remain (see, e.g., discussion on Arp 220; Spoon et al. 2004). If this deeply obscured phase is one of the ULIRG/quasar evolutionary stages, this phase is unlikely to last longer than $\sim 10^6-10^7 \text{ yr}$, or until the supernova- or AGN-driven winds punch holes through the cocoon. Establishing the frequency of such sources, compared with the clearly starburst-like and AGN-like ULIRGs, any possible evolution with redshift and luminosity would be the first steps to test whether this is a necessary evolutionary stage that all ULIRGs pass or an alternate pathway depending on the properties of the merging components. From our sample, we estimate that $z \sim 2$ extremely obscured sources have a space density of at least $\sim 7 \times 10^{-7} \text{ Mpc}^{-3} \text{ sr}^{-1}$, or about an order of magnitude greater than locally.

Our study hints at some of the specific physical processes behind the strong evolution of the infrared luminosity function between $z \sim 2$ and today (Le Flocc'h et al. 2005; Caputi et al. 2007). Although our biased selection precludes a robust comparison, we find that $z \sim 2$ ULIRGs have roughly consistent spectral properties (PAH strength, mid-IR slope, and SiO feature depth) as local ULIRGs but are an order of magnitude more luminous. Thus, the implied luminosity evolution does not follow local trends with luminosity, which would, for example, preclude the existence of strong-PAH sources with $L_{\text{IR}} \sim 10^{13} L_{\odot}$. The fraction of extremely

obscured sources remains constant, but their space density increases by about an order of magnitude, suggesting that number evolution plays a role, as well as luminosity evolution. Lastly, whether our sources are scaled-up local ULIRGs or driven by fundamentally different modes of star formation and/or black hole accretion remains an open question.

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APPENDIX

WATER ICE AND CRYSTALLINE SILICATE FEATURES IN $z \sim 2$ ULIRGs

About 25% of our sources show extreme silicate absorption ($\tau \gtrsim 3$) consistent with the deeply obscured sources in Spoon et al. (2002) or class 3A and 3B in Spoon et al. (2007). The high-resolution data available for the local sources discussed in Spoon et al. (2006) show that this class of sources frequently shows additional absorption features consistent with extremely cold, dense media. These include in particular ices and crystalline silicates. Here we discuss evidence that these might be present in the most deeply obscured of our $z \sim 2$ sources.

As mentioned in § 4.1, a number of our sources show $\sim 6\text{--}7\ \mu\text{m}$ absorption in addition to the extinction curve. Most of these are within the $1\ \sigma$ uncertainty of the data. The source in which this is most prominent is the highly obscured MIPS 464 ($\tau_{9.7} \sim 4.9$, $z = 1.85$). Figure 14 shows the optical depth profile of MIPS 464 compared with the GC extinction curve. In addition, we overlay the $5\text{--}8\ \mu\text{m}$ optical depth profile of NGC 4418 showing the broad $6.2\ \mu\text{m}$ water ice absorption feature, as well as the narrower hydrogenated amorphous carbon (HAC) absorption features at 6.9 and $7.3\ \mu\text{m}$. The NGC 4418 profile has been scaled down by 15% to match the MIPS 464 optical depth at $9.7\ \mu\text{m}$. Although the S/N of our data does not allow us the detailed feature fitting that can be done for NGC 4418, the good agreement between the two optical depth profiles suggests that MIPS 464 is consistent with having water ice absorption as well. Recent studies show that water ice absorption is observed in most local ULIRGs with high silicate feature optical depths ($\tau_{9.7} \gtrsim 3$; Imanishi et al. 2007). The inferred $6.0\ \mu\text{m}$ absorption depth of MIPS 464 (see Fig. 14) is about twice the average of the Imanishi et al. (2007) sample, meaning that this feature is likely to be at $\lesssim 1\ \sigma$ for most of our highly obscured sources.

We also examined our highest S/N spectra for the presence of crystalline substructure on the otherwise smooth $10\ \mu\text{m}$ amorphous silicate feature. In the general ISM of our Galaxy the timescale for transformation of crystalline silicates into amorphous silicates is estimated to be short compared with the timescale for injection. This is in agreement with the strict upper limit of <0.01 for the crystalline fraction of the ISM in the line of sight to our GC (Kemper et al. 2004). Recently, Spoon et al. (2006) found the first

FIG. 14.—Absorption profile of MIPS 464 after removing the best-fit continuum. We overlay the GC extinction curve. There is noticeable excess at $\sim 6\text{--}7\ \mu\text{m}$. This is most likely due to water ice and HAC absorption features. For comparison we overlay the $5\text{--}8\ \mu\text{m}$ optical depth profile of NGC 4418 scaled to the $9.7\ \mu\text{m}$ depth of MIPS 464 (which is $\sim 85\%$ that of NGC 4418). Despite the low S/N of our data, the agreement between the two suggests significant ice absorption in MIPS 464. The dip at $\lambda \sim 8$ is due to a potential weak PAH component in MIPS 464. The dip at $\lambda \sim 10\ \mu\text{m}$ is likely due to $\text{H}_2\text{S}(3)$ emission. [See the electronic edition of the *Journal* for a color version of this figure.]

FIG. 15.—Silicate feature profile of MIPS 15880 after removing the best-fit continuum. Extinction curves at best only approximate the observed profile. The IRAS 08572 spectrum has *its* best-fit continuum removed, but scaled to the MIPS 15880 optical depth. The two show very similar Si feature profiles. The discrepancy at $\lambda \lesssim 8$ is due to a weak PAH component in MIPS 15880, whereas IRAS 08572 does not require any PAH. The PAHs have not been removed from the MIPS 15880 profile in order to highlight the excess opacity at $11 \mu\text{m}$ even *before* the $11.3 \mu\text{m}$ PAH feature is removed. [See the electronic edition of the Journal for a color version of this figure.]

evidence for crystalline silicates in 12 local ULIRGs. Surprisingly, they found a crystalline fraction of ~ 0.1 , or about an order of magnitude higher than in the Milky Way disk. Figure 15 shows the silicate feature profile of MIPS 15880 ($\tau_{9.7} \sim 3.9$, $z = 1.64$), which has the highest S/N of our sample. The observed profile is remarkably similar to that of IRAS 08572+3915, including excess absorption at $11 \mu\text{m}$, which for IRAS 08572+3915 has been identified with a crystalline silicate feature. Given the error bars, this opacity bump is only $\sim 2 \sigma$. The $11.3 \mu\text{m}$ PAH feature has not been removed, in order to emphasize the significance of this potential excess opacity.

Figures 14 and 15 show that the S/N of our data does not allow detection of these weak features. However, the good agreement between their observed absorption profiles and those of two of the most obscured local sources, NGC 4418 and IRAS 08572+3915, suggests similar dust properties and source geometry.

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