MID-INFRARED SPECTROSCOPY OF OPTICALLY FAINT EXTRAGALACTIC 70 µM SOURCES

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ABSTRACT

We present mid-infrared (mid-IR) spectra of 16 optically faint sources with 70 µm fluxes in the range 19 mJy < f_70(70 µm) < 38 mJy. The sample spans a redshift range of 0.35 < z < 1.9, with most lying between 0.8 < z < 1.6, and has IR luminosities of 10^{12}-10^{13} L_⊙. 10 of the 16 objects show prominent polycyclic aromatic hydrocarbon (PAH) emission features; four of 16 show weak PAHs and strong silicate absorption, and two objects have no discernable spectral features. Compared to samples with f_70(24 µm) > 10 mJy, the 70 µm sample has steeper IR continua and higher luminosities. The PAH-dominated sources are among the brightest starbursts seen at any redshift, and reside in a redshift range where other selection methods turn up relatively few sources. The absorbed sources are at higher redshifts and have higher luminosities than the PAH-dominated sources, and may show weaker luminosity evolution. We conclude that a 70 µm selection extending to ~ 20 mJy, in combination with selections at mid-IR and far-IR wavelengths, is necessary to obtain a complete picture of the evolution of IR-luminous galaxies over 0 < z < 2.

Key words: galaxies: active – galaxies: starburst – infrared: galaxies

Online-only material: color figure

1. INTRODUCTION

Among the most important cosmological results of the last few decades was the discovery by the Cosmic Background Explorer (COBE) of a background radiation at infrared (IR) wavelengths (Puget et al. 1996; Hauser et al. 1998). This background is comparable in intensity to the integrated optical light from the galaxies in the Hubble Deep Field, implying that the star formation rate (SFR) density at z ≥ 1 was more than an order of magnitude higher than locally, and that most of this star formation was obscured. Later surveys (Aussel et al. 1999; Dole et al. 2001; Rowan-Robinson et al. 2004) resolved the bulk of this background into a population of distant IR-luminous galaxies (LIRGs, L_ird ≥ 10^{11} L_⊙), which undergo strong luminosity evolution with redshift (\( (1 + z)^{-4} \)), e.g., Pozzi et al. 2004; Le Floch et al. 2005), reaching a comoving density at least 40 times greater at z = 1 than in the local universe (Elbaz et al. 2002). Reviews of their properties can be found in Sanders & Mirabel (1996) and Lonsdale et al. (2006).

Significant effort has been devoted to understanding the mechanisms driving the evolution of LIRGs. At low redshift, they are almost invariably mergers (Surace et al. 1998; Farrah et al. 2001; Bushouse et al. 2002; Veilleux et al. 2002), powered mainly by star formation (Genzel et al. 1998; Rigopoulou et al. 1999; Imanishi et al. 2007; Vega et al. 2008), and reside in average density environments (Zauderer et al. 2007). LIRGs at high redshift appear to be mainly starburst-dominated merging systems (Farrah et al. 2002; Chapman et al. 2003a; Smail et al. 2004; Takata et al. 2006; Borys et al. 2006; Valiante et al. 2007; Berta et al. 2007; Bridge et al. 2007), though there are signs of differences compared to their low-redshift counterparts; for example, weak X-ray emission (Franceschini et al. 2003; Wilman et al. 2003; Iwasawa et al. 2005), different modes of star formation (Farrah et al. 2008), and a tendency to reside in overdense regions (Blain et al. 2004; Farrah et al. 2006; Magliocchetti et al. 2007).

Controversies remain, therefore, over how LIRGs may or may not evolve with redshift. Part of the reason for this is that an efficient census of LIRGs at z ≥ 0.5 is difficult, as surveys conducted in a single IR band can miss a significant fraction of the LIRG population. For example, submillimeter surveys find large numbers of obscured starbursts at z > 1 (Barger et al. 1999; Chapman et al. 2005; Aretxaga et al. 2007; Clements et al. 2008; Dye et al. 2008), but few sources at z < 1, and virtually no sources with “hot” dust (Blain et al. 2002). It is therefore essential that we survey for LIRGs in every IR band available to us and, having found them, systematically study them further.

The Spitzer Space Telescope (Werner et al. 2004; Soifer et al. 2008) has the capacity to revolutionize our understanding of LIRGs. The Infrared Array Camera (IRAC; Fazio et al. 2004) and the Multiband Imaging Photometer for Spitzer (MIPS; Rieke et al. 2004) imaging instruments, and the Infrared Spectrograph (IRS; Houck et al. 2004) all offer dramatic improvements in sensitivity and resolution over previously available facilities. In particular, the MIPS 70 µm channel is ideal for studying high-redshift LIRGs; at z ∼ 2 the rest-frame emission is always longward of 18 µm, giving good sensitivity to both starbursts and active galactic nuclei (AGNs). The optically faint, high-redshift 70 µm Spitzer sources may be a prime example of the sources that previous surveys in the submillimeter or in the IR have missed—in the submillimeter because the sources harbor dust that is too hot for current generation submillimeter cameras to see, and in the surveys of the Infrared Space Observatory (ISO) because of sensitivity limits at >20 µm.8

8 For example, the ELAIS ISO survey reached a limiting depth of ~100 mJy at 90 µm (Rowan-Robinson et al. 2004), compared to ~20 mJy for large area surveys with MIPS at 70 µm.)
In this paper, we use the IRS to observe a sample of 16 sources selected at 70 μm using data from the Spitzer Wide Area Infrared Extragalactic survey (SWIRE; Lonsdale et al. 2003; Oliver et al. 2004; Davoodi et al. 2006a, 2006b; Waddington et al. 2007; Berta et al. 2007; Shupe et al. 2008; Siana et al. 2008) survey. Our aim is to explore the range in redshifts, luminosities, and power sources seen in the optically faint 70 μm population. We assume Ω = 1, Λ = 0.7, and H₀ = 70 km s⁻¹ Mpc⁻¹. Luminosities are quoted in units of erg s⁻¹ or of bolometric solar luminosities, where L⊙ = 3.86 × 10³³ erg s⁻¹.

2. METHODS

2.1. Sample Selection

The sources are selected from the SWIRE Lockman Hole field, which covers 10.6 deg² and reaches 5σ depths of 4.2 μJy at 3.6 μm, 7.5 μJy at 4.5 μm, 46 μJy at 5.8 μm, 47 μJy at 8.0 μm, 209 μJy at 24 μm, 18 mJy at 70 μm, and 108 mJy at 160 μm. The primary selection criterion for our sample is a confident detection at 70 μm, so we first rejected all sources fainter than 19 mJy at 70 μm. In order to be able to obtain mid-IR IRS spectra with reasonable signal to noise, we also constrained the sources to have f_{24}(μm) > 0.9 mJy, although >90% of sources with f_{70} > 19 mJy also satisfy f_{24} > 0.9 mJy. This resulted in a parent sample of 1250 sources. From this, we selected optically faint sources by taking all sources (12 in total) with r-band magnitudes fainter than m_r = 23, and including an additional four sources with r-band magnitudes in the range 20 < m_r < 23, for a total of 16 objects.

2.2. Observations

All 16 objects were observed as part of Spitzer program 30364 with the first order of the short-low module (SL1; 7.4 μm–14.5 μm, slit size 3.7′ × 57′′ with 1′8 pixel⁻¹, R ~ 60–127), and the second order of the long-low module (LL2; 14.0 μm–21.3 μm, slit size 10.5′ × 168′′ with 5′1 pixel⁻¹, R ~ 57–126). Eight of these objects were additionally observed with long-low order 1 (LL1; 19.5 μm–38.0 μm). The targets were placed in the center of each slit using the blue peak-up array. Each target was observed with an individual ramp time of 60 s in SL1, and 120 s in LL1, with the number of ramps determined by the targets 24 μm flux density. Details are given in Table 1.

The data were processed through the Spitzer Science Center’s pipeline software (ver. 15.3), which performs standard tasks such as ramp fitting and dark current subtraction, and produces Basic Calibrated Data (BCD) frames. Starting with these frames, we removed rogue pixels using the irsclean⁹ tool and campaign-based pixel masks. The individual frames at each nod position were then combined into a single image using the SMART software package (Higdon et al. 2004). Sky background was removed from each image by subtracting the image for the same object taken with the other nod position (i.e., “nod–nod” sky subtraction). One-dimensional spectra were then extracted from the images using the SPICE software package using “optimal” extraction and default parameters. This procedure results in separate spectra for each nod and for each order. The spectra for each nod were inspected; features present in only one nod were treated as artifacts and removed. The two nod positions were then combined. The first and last four pixels on the edge of each order, corresponding to regions of decreased sensitivity on the array, were then removed, and the spectra in different orders merged, to give the final spectrum for each object.

3. RESULTS

The spectra are presented in Figures 1 and 2. Redshifts and fluxes are given in Table 2, and spectral measurements are given in Table 3.

3.1. Redshifts

We derive spectroscopic redshifts from broad emission features at 6.2 μm, 7.7 μm, 8.6 μm, 11.2 μm, and 12.7 μm, assigned to bending and stretching modes in neutral and ionized

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⁹ This tool is available from the Spitzer Science Center (SSC) Web site: http://ssc.spitzer.caltech.edu
The variations in PAH peak wavelengths seen in local galaxies and is of order $\Delta \lambda = 0.02$. In three cases (2, 10, 12), the PAHs are weak, and the redshifts are derived from a prominent silicate absorption feature. In these cases, the redshifts have a larger error, $\Delta z \simeq 0.2$, but should still be reliable. Finally, in two cases (8 and 11), no spectral features can be unambiguously...
identified; we derive tentative redshifts based on what are plausibly PAH or silicate features. In these cases, the error on the redshift is large, $\Delta z \simeq 0.4$, and the redshifts should be treated with caution.

3.2. Spectral Properties

We measure the properties of the PAH features using two methods. For the $6.2 \mu m$ and $11.2 \mu m$ PAH features, we compute fluxes and equivalent widths (EWs) by integrating the flux above a spline interpolated local continuum fit (for a description of the method see Brandl et al. 2006 and Spoon et al. 2007). The errors on the EWs are large because the continua of our sample are only weakly detected. Using this method means, however, that our EWs can be compared directly to those of local LIRGs as measured by Spitzer (Weedman et al. 2005; Brandl et al. 2006; Armus et al. 2007; Spoon et al. 2007). For the $7.7 \mu m$ PAH feature, we do not attempt to measure EWs because of the uncertainties in determining a continuum baseline underneath this broad and complex feature. Instead, we measure only the
Figure 2. Individual spectra, continued from Figure 1.

Flux density at the peak of the 7.7 \( \mu m \) feature, as in Houck et al. (2007) and Weedman and Houck (2008). Due to the low-S/N and restricted wavelength range of the spectra, we cannot correct for water ice and/or aliphatic hydrocarbon absorption, although the effect of this lack of correction is likely to be insignificant.

For the four objects with clear detections of the 6.2 \( \mu m \) and 11.2 \( \mu m \) PAH features, we derive SFRs via the formula from Farrah et al. (2007); this yields SFRs of between 100 and 300 \( M_\odot \) year\(^{-1}\). We derive SFRs in Table 3 for all sources using the formula in Houck et al. (2007):

\[
\log(\text{SFR})[M_\odot \text{ year}^{-1}] = \log(\nu L_\nu(7.7 \mu m)) - 42.57.
\]  

For the four objects for which both formulae can be used, we obtain consistent results within the uncertainties, which are of order 50%.
We measured the strengths of the silicate features, $S_{\text{sil}}$, via

$$S_{\text{sil}} = \ln \left( \frac{F_{\text{obs}}(9.7 \, \mu m)}{F_{\text{cont}}(9.7 \, \mu m)} \right),$$

where $F_{\text{obs}}$ is the observed flux density at rest-frame 9.7 $\mu m$ and $F_{\text{cont}}$ is the underlying continuum flux density at rest-frame 9.7 $\mu m$ deduced from a spline fit to the continuum on either side. A description of this method can be found in Spoon et al. (2007), Levenson et al. (2007), and Sirocky et al. (2008).

Other than the PAH and silicate features, we see weak but clear detections of the H$_2$S(3) line at 9.66 $\mu m$ in two objects (6 and 14), but no other spectral features.

### 3.3. SED Fitting

We measure the IR luminosities of the sample by fitting the IR photometry simultaneously with the library of model spectral energy distributions (SEDs) for the emission from a starburst (Efstathiou et al. 2000) and an AGN (Rowan-Robinson 1995), following the methods in Farrah et al. (2003). The fits were good, with $\chi^2 < 2$ in all cases, and the observed-frame 70 $\mu m$ flux gave good constraints on the IR luminosities (see also discussion in Rowan-Robinson et al. 2005). The photometry is too limited, however, to provide meaningful constraints on the starburst and AGN fractions, so we only present the derived total IR luminosities, and not the SED fits. The luminosities are presented in Table 3. All objects have IR luminosities exceeding $\sim 10^{11.5} L_\odot$, with most lying in the range $10^{12} - 10^{13} L_\odot$, making them ultra luminous infrared galaxies (ULIRGs).

### 4. DISCUSSION

#### 4.1. Redshifts and Luminosities

The redshift distribution for our sample is shown in the left panel of Figure 3. All objects lie in the range $0.35 < z < 1.8$. There is a peak at $z \simeq 0.9$, a long tail up to $z \simeq 2$, and a shorter tail down to $z \simeq 0.4$.

The redshift range $0.5 \lesssim z \lesssim 1.5$ has been a difficult one in which to select ULIRGs because their distances make them faint at observed-frame 10–100 $\mu m$, and the $k$-correction that makes ULIRGs bright at observed-frame 200–1000 $\mu m$ does not become strong enough for current submillimeter cameras until $z \gtrsim 1.5$. Moreover, this is the redshift range where the evolution in the ULIRG luminosity function is thought to be strongest. Therefore, our simple selection method, consisting of little more than a minimum 70 $\mu m$ flux and an optical cut, should prove invaluable in studying the cosmological evolution of ULIRGs from future wide-area surveys. It seems likely that it is the optical cut that is resulting in our sources mostly lying in the $0.5 \lesssim z \lesssim 1.5$ range, as other spectroscopic surveys of purely 70 $\mu m$ selected sources find a lower median redshift. For example, Huyhn et al. (2007) present redshifts for 143 sources selected solely on the basis of 70 $\mu m$ flux but to a much fainter limit of $f_{70} > 2$ mJy, and find a median redshift of 0.64, with 79% of the sources lying at $z < 1$ and about half the sources at $z < 0.5$.

Given the difficulties in obtaining spectroscopic redshifts for distant ULIRGs, it is useful to assess the accuracy of photometric redshifts for this type of source. In the right panel of Figure 3, we compare the spectroscopic redshifts to the photometric redshifts derived by Rowan-Robinson et al. (2008) for those eight objects where the photometric redshift code produced a formally acceptable fit ($\chi^2 < 10$, see discussion in Rowan-Robinson et al. 2008). The photometric redshifts are reasonably good, given the faintness and high redshifts of the sample. Seven of the eight objects lie within or close to the “catastrophic failure” boundary of $\log(1 + z_{\text{phot}}) = \log(1 + z_{\text{spec}}) \pm 0.06$. Only in one case there is a clear mismatch between $z_{\text{phot}}$ and $z_{\text{spec}}$, and the photometric redshift for this object is unreliable, as it is based on limited data.

#### 4.2. Comparisons to Other Samples

##### 4.2.1. Local ULIRGs

We first compare our mid-IR spectra to those of local ULIRGs. Our sample is faint at 24 $\mu m$, so detailed spectral diagnostics are not possible. We therefore employ a simple comparison using the “Fork” diagram of Spoon et al. (2007), as shown in Figure 4. Our 70 $\mu m$ sample has similar PAH and silicate absorption properties to the 1B/1C/2B/2C classes from Spoon et al. (2007). This identifies our sample with moderately obscured star-forming sources, but not with the most heavily absorbed sources or those that contain an unabsorbed or silicate-emitting AGN without PAH emission.

##### 4.2.2. 70 $\mu m$ Selected Samples

The 70 $\mu m$ population has been studied relatively little with the IRS. The only other published study is that of Brand et al.
who select 11 sources with \( f_{70} > 32 \) mJy and an \( r \)-band magnitude fainter than \( m_r = 20 \). Thus, the two samples make for interesting comparisons; our sample is 1–2 mag fainter in the optical and \( \sim 1.6 \) times fainter at 70 \( \mu m \).

The IR luminosities of both samples are comparable, with both lying mostly in the \( 10^{12}–10^{13} L_\odot \) range. The fraction of sources with prominent PAHs is also similar with seven of the 11 PAH-dominated sources in Brand et al. (2008) and 10 of the 16 in ours. There are, however, two areas where there are differences, albeit with the caveat of small sample sizes. The first is redshift distribution. The redshift distribution for the Brand et al. sample is overplotted in the left panel of Figure 3. The Brand et al. sample has a less pronounced peak, a broader distribution with more sources over 0.5 < \( z \) < 1 and fewer sources at \( z > 1.2 \), than does our sample. The second difference is the distribution of spectral types with redshift. The Brand et al. sample shows no discernible separation of spectral type with redshift whereas our sample shows that all of the sources with strong PAHs, irrespective of the presence of silicate absorption, lie toward the lower end of the redshift range, while the strongly absorbed sources with negligible PAHs are all at the upper end.10

Both differences probably arise due to our sample reaching fainter 70 \( \mu m \) fluxes than the sample of Brand et al. In principle, surveys to fainter 70 \( \mu m \) fluxes should include higher redshift, more luminous sources (see Section 4.2.3). Moreover, a 70 \( \mu m \) selection should result in sensitivity to different effective dust temperatures at different redshifts; at \( z \approx 0.7 \) the 70 \( \mu m \) observations sample rest-frame 40 \( \mu m \), while at \( z \approx 1.5 \) they sample rest-frame 28 \( \mu m \), so at \( z \approx 1.5 \) we are sensitive to sources with \( \sim 30 \) K hotter dust than at \( z \approx 0.7 \). Therefore, higher redshift sources in a 70 \( \mu m \) selected sample are more likely to be absorbed, AGN-like sources with weak PAH features, which is what we see in our sample. The absence of this trend in the Brand et al. sample suggests that optically faint sources with \( f_{70} \gtrsim 30 \) mJy are mainly ULIRGs at moderate redshift, but that at 70 \( \mu m \) fluxes below 30 mJy we start to see significant numbers of heavily absorbed sources, with large masses of hot dust, at \( z > 1 \). Interestingly, a similar situation is seen at longer wavelengths; submillimeter surveys are adept at picking up sources with large masses of cold dust, but radio surveys in the same fields have shown that there exist populations of “hot” dust sources at comparable redshifts but with different IR spectral shapes (Chapman et al. 2003b, see also Khan et al. 2005). Our higher redshift sources could be the lower-\( z \)-tall of this radio-selected, “hot dust” population.

4.2.3. 24 \( \mu m \) Selected Samples

Most previous samples selected from Spitzer surveys for IRS follow-up use a mid-IR selection based on 24 \( \mu m \) flux. It is important, therefore, to understand whether our 70 \( \mu m \) sample differs from samples selected at 24 \( \mu m \). To make these comparisons, we combine our sample with that of Brand et al. (2008) for a total of 27 70 \( \mu m \) selected sources, as the sample selections are complementary; our sample reaches fainter 70 \( \mu m \) fluxes, but the optical cut is similar.

**Bright Samples.** We first compare the mid-IR continuum properties of the combined 70 \( \mu m \) sample to sources with high 24 \( \mu m \) fluxes via the flux limited, \( f_{24} > 10 \) mJy sample in Weedman and Houck (2009). To perform this comparison we use the rest-frame 15 \( \mu m \) continuum luminosity and the \( f_{24} / f_{15} \) continuum slope. If both these rest-frame wavelengths are seen in the IRS spectra then we measured these quantities directly; otherwise, we estimated fluxes at one or both wavelengths via interpolation from a power law with a slope determined from comparison of observed \( f_{24} (24 \mu m) \) and \( f_{15} (70 \mu m) \). These interpolations should be regarded with caution, as they are sensitive to PAH and silicate contamination of the (observed-frame) 24 \( \mu m \) band, which are difficult to compute for our sample as we either lack long-low data, or it is of relatively low signal to noise. The \( \sim 20\% \) uncertainty assigned in Table 3 to these interpolated values for the continuum slope reflects the possibility that the observed 24 \( \mu m \) flux density may not be purely a measure of dust continuum emission.

The comparison is shown in Figure 5. The continuum luminosities for the 70 \( \mu m \) sample are much greater than for the 24 \( \mu m \) sample. The median \( \log \left( \nu L_\nu (15 \mu m) \right) \) (erg s\(^{-1}\)) for the 70 \( \mu m \) sample is 44.8 compared to 43.3 for the 24 \( \mu m \) sample.
This is straightforward to understand. The fainter optical and 24 μm fluxes used for the 70 μm selection allow the discovery of IR-luminous sources to much higher redshifts so we may reasonably expect to see more luminous sources.

Interestingly, however, the luminosity differences between the samples may not be as large for the sources with weak PAH features. For these sources, the median log(νLν(15 μm)) (erg s⁻¹) for the 70 μm sample is 45.4 compared to 45.0 for the 24 μm sample, and the most luminous sources in both samples are similar, log(νLν(15 μm)) ≈ 46.2. This comparison is not robust, given that the weak PAH sources in the 70 μm sample only have the silicate feature in absorption, whereas the 24 μm sample contains sources with the silicate feature in both absorption and emission. Nevertheless, it seems that the fainter optical and 24 μm fluxes used for the 70 μm selection do not result in discovering more luminous absorbed sources, even though the sources are systematically at higher redshift. We therefore suggest, with some reserve, that sources with weak PAHs and strong silicate absorption show weaker luminosity evolution with redshift than do PAH-dominated sources.

Considering the continuum slopes, we see results that would be expected from the 70 μm selection; selecting sources at the longer wavelength favors sources with steeper spectra. For PAH sources, the median rest-frame ratio f24/f15 for the 70 μm sample is 4.5 compared to 3.5 for the 24 μm sample. For absorbed sources, the median rest-frame ratio f24/f15 for the 70 μm sample is 2.7, compared to 1.7 for the 12 sources in the 24 μm sample at sufficiently low redshifts to have a measurement. For both PAH-dominated sources and absorbed sources, the most extreme ratios are within the 70 μm sample.

These results demonstrate a systematic difference in effective dust temperatures for the 70 μm sample compared to the 24 μm sample. For the 70 μm sample, the steeper spectrum at rest frame ~ 24 μm implies a larger dust fraction at intermediate temperatures of ~100 K. It is also notable that the PAH-dominated spectra are consistently steeper than the absorbed spectra in both samples. In the 70 μm sample, the ratio f24/f15 is 4.5 and 2.7, respectively, and in the 24 μm sample they are 3.5 and 1.7. This implies that the intermediate dust temperature component is more prominent in PAH-dominated sources than in absorbed sources. For absorbed sources, if they contain a luminous AGN, the spectra can be flattened by having a more significant hot dust component to increase continuum emissivity at shorter wavelengths.

Faint Samples. Finally, we compare our combined sample to those sources that are faint at observed-frame 24 μm (f24 ≤ 2 mJy). This is a difficult comparison to make as the IRS spectra of these sources are usually of low signal to noise, making detailed comparisons difficult. We therefore make two adjustments. First, as most of our sample show PAH features, we restrict the comparison to those 24 μm sources that also show PAH features by using the compilation in Weedman and Houck (2008). This compilation includes new spectral measurements of faint sources, and published data from various IRS observing programs (Houck et al. 2007; Brand et al. 2008; Weedman et al. 2006b; Farrah et al. 2008; Houck et al. 2005; Weedman et al. 2006a; Yan et al. 2007; Pope et al. 2008). Second, we use a simple diagnostic that can be used for faint sources at a variety of redshifts—the peak luminosity of the 7.7 μm PAH feature¹¹— and study how this peak luminosity evolves with redshift. The flux densities fν(7.7 μm) and luminosities νLν(7.7 μm) for our sample are in Table 3, or in Brand et al. (2008), while those for the faint 24 μm samples are in Weedman and Houck (2008).

We plot these 7.7 μm PAH luminosities against redshift in Figure 6. We also include the 24 μm bright sources from Weedman and Houck (2008), and low-redshift ULIRGs from Spoon et al. (2007). Two important results can be seen. First, the 70 μm selected starbursts are among the most luminous known from any IR-selected samples. They are more luminous, on average, than both low-redshift ULIRGs or the Yan et al. (2007) sources at comparable redshifts, and approach the luminosities of the 24 μm and submillimeter selected sources at z > 1.5. This is expected—the high redshifts of our sample mean we are probing a greater volume and hence can find more luminous sources than local examples, and the additional demand of a 70 μm detection means our sources will be more luminous, on average, than sources with just a 24 μm detection at similar redshifts.

Second, they reside in a redshift range, 0.5 ≤ z ≤ 1.5, where other selection methods turn up relatively few sources. The faint 24 μm samples, which have comparable 24 μm fluxes to our sample but are not detected at 70 μm, span a significantly broader redshift range of 0.5 ≤ z ≤ 3, with the majority lying at z > 1.5. It seems therefore that a 70 μm selection of ~20 mJy, together with a faint optical and 24 μm flux cut, serves to select sources almost entirely in the crucial redshift range 0.5 ≤ z ≤ 1.5. This is the redshift range, for example, in which the results of Le Floc’h et al. (2005) show steeper evolution of the IR-luminous galaxy population than is shown in Figure 6. We conclude that a 70 μm selection, in combination with selections at mid-IR and far-IR/submillimeter wavelengths, is vital to measure adequately the luminosity evolution of luminous starburst galaxies over 0 < z < 2.5.

¹¹ As we are using the peak luminosity of this feature, rather than its integrated flux, our luminosities differ from those quoted in Yan et al. (2007) and Pope et al. (2008).
5. SUMMARY

Sixteen spectra have been obtained with the Spitzer IRS of extragalactic sources in the SWIRE Lockman Hole field having $f_{\nu}(70 \, \mu m) > 19$ mJy, including 12 sources with optical magnitudes $m_r > 23$. Results are combined with the sample of 11 sources with $f_{\nu}(70 \, \mu m) > 30$ mJy from the NOAO Deep Wide-Field Survey region in Bootes (Brand et al. 2008) to consider the nature of the 70 $\mu$m population.

The 70 $\mu$m sources are characterized either by strong PAH features or by strong silicate absorption features with weak or absent PAHs. 10 of the 16 objects show prominent PAHs; four show strong silicate absorption, and two have no discernable spectral features. The continuum luminosities (measured by $\nu L_{\nu}(15 \, \mu m)$ in erg s$^{-1}$) span 43.8 < log $\nu L_{\nu}(15 \, \mu m)$ < 46.3 with the absorbed sources having higher luminosities than the PAH-dominated sources. Compared to sources that are bright at 24 $\mu$m ($f_{\nu}(24 \, \mu m) > 10$ mJy), the 70 $\mu$m sources have steeper rest-frame mid-IR continua and higher luminosities.

The 70 $\mu$m sources with strong PAH features are among the most luminous starbursts seen at any redshift. Furthermore, these sources effectively fill the redshift range 0.5 < z < 1.5 where previous selection methods using a 24 $\mu$m flux of ~1 mJy but without a 70 $\mu$m detection have found few sources. This result demonstrates that selection of sources at 70 $\mu$m to fainter flux limits will provide crucial samples for determining the evolution of star formation with redshift.

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