

## INFRARED LUMINOSITIES AND AROMATIC FEATURES IN THE 24 $\mu\text{m}$ FLUX-LIMITED SAMPLE OF 5MUSES

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### ABSTRACT

We study a 24  $\mu\text{m}$  selected sample of 330 galaxies observed with the infrared spectrograph for the 5 mJy Unbiased *Spitzer* Extragalactic Survey. We estimate accurate total infrared luminosities by combining mid-IR spectroscopy and mid-to-far infrared photometry, and by utilizing new empirical spectral templates from *Spitzer* data. The infrared luminosities of this sample range mostly from  $10^9 L_{\odot}$  to  $10^{13.5} L_{\odot}$ , with 83% in the range  $10^{10} L_{\odot} < L_{\text{IR}} < 10^{12} L_{\odot}$ . The redshifts range from 0.008 to 4.27, with a median of 0.144. The equivalent widths of the 6.2  $\mu\text{m}$  aromatic feature have a bimodal distribution, probably related to selection effects. We use the 6.2  $\mu\text{m}$  polycyclic aromatic hydrocarbon equivalent width (PAH EW) to classify our objects as starburst (SB)-dominated (44%), SB-AGN composite (22%), and active galactic nucleus (AGN)-dominated (34%). The high EW objects (SB-dominated) tend to have steeper mid-IR to far-IR spectral slopes and lower  $L_{\text{IR}}$  and redshifts. The low EW objects (AGN-dominated) tend to have less steep spectral slopes and higher  $L_{\text{IR}}$  and redshifts. This dichotomy leads to a gross correlation between EW and slope, which does not hold within either group. AGN-dominated sources tend to have lower  $\log(L_{\text{PAH}7.7 \mu\text{m}}/L_{\text{PAH}11.3 \mu\text{m}})$  ratios than star-forming galaxies, possibly due to preferential destruction of the smaller aromatics by the AGN. The  $\log(L_{\text{PAH}7.7 \mu\text{m}}/L_{\text{PAH}11.3 \mu\text{m}})$  ratios for star-forming galaxies are lower in our sample than the ratios measured from the nuclear spectra of nearby normal galaxies, most probably indicating a difference in the ionization state or grain size distribution between the nuclear regions and the entire galaxy. Finally, we provide a calibration relating the monochromatic continuum or aromatic feature luminosity to  $L_{\text{IR}}$  for different types of objects.

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

*Online-only material:* color figures, machine-readable table

### 1. INTRODUCTION

Infrared bright galaxies play critical roles in galaxy formation and evolution. The *InfraRed Astronomical Satellite* (IRAS) facilitated the study of an important group of objects, the Ultra-Luminous InfraRed Galaxies (ULIRGs; Soifer et al. 1989; Sanders & Mirabel 1996), which were first hinted at by ground observations of Rieke & Low (1972). Studies from the *Infrared Space Observatory* (ISO; Elbaz et al. 1999) and the *Spitzer Space Telescope* (Houck et al. 2005; Yan et al. 2007) later revealed that LIRGs and ULIRGs are much more common at high redshift than in the local universe. The number density of IR luminous galaxies evolves strongly with redshift to at least  $z \sim 1$  (Le Floch et al. 2005). The fraction of galaxies powered by star formation versus active galactic nucleus (AGN) is still controversial, but is crucial for determining unbiased luminosity functions for various categories of objects and understanding the evolution process.

The superb sensitivity of the *Spitzer Space Telescope* (Werner et al. 2004) has led to the discovery of new populations of faint, high-redshift galaxies with extreme IR/optical colors (Dickinson et al. 2004; Houck et al. 2005; Weedman et al. 2006; Yan et al. 2007; Caputi et al. 2007; Dey et al. 2008; Dasyra et al. 2009; Murphy et al. 2009). However, these studies often have at least one other constraint than the mid-IR flux limit, usually a minimum *R*-band magnitude or an IRAC-based color selection, designed to favor sources in specific redshift ranges, or with high luminosity. The 5 Millijankys Unbiased *Spitzer* Extragalactic Survey (5MUSES) is an infrared selected sample. A major advantage of 5MUSES is its simple selection:  $f_{\nu}(24 \mu\text{m}) > 5 \text{ mJy}$ . This relatively bright flux limit allows for a more detailed study of the infrared properties, filling in the gap between local galaxies and high redshift samples, and helping to improve the modeling of galaxy populations and their evolution.

In order to advance our understanding of the properties and evolution of galaxies, it is crucial to obtain accurate estimates

of their bolometric luminosities. Several studies have shown that monochromatic luminosities in the mid-IR can be used to estimate  $L_{\text{IR}}$  (Sajina et al. 2007; Bavouzet et al. 2008; Rieke et al. 2009; Calzetti et al. 2010), and the uncertainties on these estimates decrease significantly when far-infrared (FIR) fluxes are available (Kartaltepe et al. 2010). However, the spectral energy distribution (SED) of star-forming galaxies, AGNs and ULIRGs display a wide range of shapes (Weedman et al. 2005; Brandl et al. 2006; Smith et al. 2007; Armus et al. 2007; Hao et al. 2007; Wu et al. 2009; Veilleux et al. 2009). Applying these methods without knowing a source's spectral type could cause significant biases in luminosity estimates between types of objects and seriously mislead the interpretations. The 5–36  $\mu\text{m}$  spectra obtained by the Infrared Spectrograph (IRS; Houck et al. 2004) for the 5MUSES sample allows for aromatic feature identification, excitation line analysis, and decomposition into star formation and AGN components, thus providing essential information for classifying the origin of the luminosity.

The mid-IR is home to a set of broad emission line features, which are thought to originate from Polycyclic Aromatic Hydrocarbons (PAHs; Puget et al. 1985; Allamandola et al. 1989). PAHs are organic molecules that are ubiquitous in our own Galaxy (Peeters et al. 2002) and nearby star-forming galaxies (Helou et al. 2001; Smith et al. 2007). In total, they can contribute a significant fraction (10% or more) of the total infrared luminosity in star-forming galaxies. PAHs are weak in low-metallicity galaxies (Madden et al. 2006; Wu et al. 2006; Engelbracht et al. 2008), or in galaxies with powerful (Roche et al. 1991; Weedman et al. 2005; Armus et al. 2007; Desai et al. 2007; Wu et al. 2009) or even weak AGNs (Smith et al. 2007; Dale et al. 2009). The PAH features, including their profiles, central wavelengths, and band-to-band intensity ratios, have been studied in detail by Peeters et al. (2002), Smith et al. (2007), and most recently reviewed by Tielens (2008). The 6.2  $\mu\text{m}$  feature and the 7.7  $\mu\text{m}$  complex are attributed to vibrational modes of the carbon skeleton. The 8.6  $\mu\text{m}$  feature is attributed to in-plane C–H bending, while the features at 11.3  $\mu\text{m}$  and 12.7  $\mu\text{m}$  are identified as out-of-plane C–H bending modes. It is generally thought that charged PAHs radiate more strongly in the C–C vibrational modes, while neutral PAHs radiate strongly in the out-of-plane C–H bending modes at 11.3  $\mu\text{m}$  and 12.7  $\mu\text{m}$ . The fraction of the power radiated by PAH in the different bands following single-photon heating depends on both the PAH ionization and on the size of the PAH (Draine & Li 2007). Thus, the observed variations in the PAH band-to-band ratios can reflect variations in physical conditions (Smith et al. 2007; Galliano et al. 2008; Gordon et al. 2008; O'Dowd et al. 2009).

Because PAH emission can be very prominent in star-forming systems, it has often been used as a relatively extinction-free diagnostic tool to constrain star formation. Detailed studies on the properties of PAH features locally (Spoon et al. 2007; Desai et al. 2007) and at higher redshift (Yan et al. 2005; Houck et al. 2005; Huang et al. 2009) reveal differences in the PAH equivalent widths (EWs) and  $L_{\text{PAH}}/L_{\text{IR}}$  ratios. This might indicate that some evolution in the PAH properties occurs with redshift, or that sample selection effects make for large variations in the aromatic feature properties. However, one cannot simply apply our knowledge from the local universe to high redshift galaxies, or make fair comparisons between the two unless truly equivalent samples have been studied. Current analysis on the PAH properties are based on *ISO* or *Spitzer* observations of relatively bright objects, which have been selected because of previously known optical or *IRAS*

criteria. Thus, it is crucial to have a complete or at least unbiased census of galaxies in order to understand the galaxy evolution process and its relation to the aromatic feature emission.

In this paper, we study the properties of PAH emission and IR luminosities. This is the first of a series of papers to study the IR selected representative sample of 5MUSES. G. Helou et al. (2010, in preparation) will address the general properties of the sample and how it bridges the gap between local and high- $z$  galaxies. Y. Shi et al. (2010, in preparation) will present the correlations between old stars and current star formation. Detailed population modeling will also be performed to address the bimodal distribution of the PAH EWs discovered in this study. In Section 2, we briefly describe the sample selection, data reduction, and measurements of spectral features. We introduce our library of empirical IR SED templates built upon *Spitzer* observations in Section 3, and derive the total infrared luminosities for 5MUSES galaxies. We also discuss how well one can constrain the IR SED if only mid-IR data are available. In Section 4, we study the properties of PAH emission from our flux-limited sample. Finally, we present our conclusions in Section 5. Using the IR luminosities we derived in Section 3 and the PAH luminosities from Section 4, we discuss estimation of  $L_{\text{IR}}$  from PAH luminosity or monochromatic continuum luminosity in the Appendix. Throughout this work, we assume a  $\Lambda$ CDM cosmology with  $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ,  $\Omega_m = 0.27$  and  $\Omega_\lambda = 0.73$ .

## 2. OBSERVATIONS AND DATA ANALYSIS

### 2.1. The Sample

5MUSES is a mid-IR spectroscopic survey of a 24  $\mu\text{m}$  flux-limited ( $f_{24 \mu\text{m}} > 5 \text{ mJy}$ ) representative sample of 330 galaxies. The galaxies are selected from the SWIRE fields (Lonsdale et al. 2003), including Elais-N1 (9.5 deg<sup>2</sup>), Elais-N2 (5.3 deg<sup>2</sup>), Lockman Hole (11.6 deg<sup>2</sup>), and XMM (9.2 deg<sup>2</sup>), in addition to the *Spitzer* Extragalactic First Look Survey (XFLS; 5.0 deg<sup>2</sup>) field (Fadda et al. 2006). It provides a representative sample at intermediate redshift ( $\langle z \rangle \sim 0.144$ ) which bridges the gap between the bright, nearby star-forming galaxies (Kennicutt et al. 2003; Smith et al. 2007; Dale et al. 2009), local ULIRGs (Armus et al. 2007; Desai et al. 2007; Veilleux et al. 2009), and the much fainter and more distant sources pursued in most  $z \sim 2$  IRS follow-up work to date (Houck et al. 2005; Yan et al. 2007). The full details of the sample, including selection criteria and observation strategy are covered in G. Helou et al. (2010, in preparation).

### 2.2. Observation and Data Reduction

Because of its selection in the SWIRE and XFLS fields, IRAC 3.6–8.0  $\mu\text{m}$  photometry is available for the entire 5MUSES sample. In addition to the Multiband Imaging Photometer for *Spitzer* (MIPS; Rieke et al. 2004) 24  $\mu\text{m}$  photometry used to select this sample, 90% of our sources have also been detected at 70  $\mu\text{m}$  and 54% have been detected at 160  $\mu\text{m}$ . Low-resolution spectra ( $R = 64\text{--}128$ ) of all 330 galaxies in 5MUSES have been obtained with the short-low (SL: 5.5–14.5  $\mu\text{m}$  and long-low (LL: 14–35  $\mu\text{m}$ ) modules of the IRS using the staring mode observations. The integration time on each object was estimated based on its 24  $\mu\text{m}$  flux densities and typically ranges from 300 to 960 s (see Table 1). A subset of the 5MUSES sample has also been observed with the high-resolution modules of the IRS, which will be covered in a future paper.

**Table 1**  
On-source Integration Time of the Sample

$f_{24\ \mu\text{m}}$ (mJy)	SL2 (s)	SL1 (s)	LL2 (s)	LL1 (s)
5–7	480	480	480	480
7–10	480	240	240	240
10–15	480	480	180	180
15–25	240	120	120	120
>25	120	120	60	60

The low-resolution IRS data were processed by the Spitzer Science Center data reduction pipeline version S17. The two-dimensional image data were converted to slopes after linearization correction, subtraction of darks, cosmic-ray removal, stray light, and flat-field correction. The post-pipeline reduction of the spectral data started from the pipeline products basic calibrated data files. We took the median of all images from the off-source part of the slit (off-order and off-nod) and then subtracted it from the image on the source. Then, we combined all the background-subtracted images at one nod position and took the mean. The resulting images were then cleaned with the IRSCLEAN package<sup>13</sup> to remove bad pixels and apply rogue pixel correction.

We used the *Spitzer* IRS Custom Extractor (SPICE)<sup>14</sup> software to extract the spectra. With a flux limit of 5 mJy at 24  $\mu\text{m}$ , we chose to use the optimal extraction with point-source calibration because it significantly improved the signal-to-noise ratios (S/Ns) for our sources. When using the optimal method, each pixel was weighted by its position, based on the spatial profile of a bright calibration star. The outputs from SPICE produced one spectrum per order at each nod position, which were then combined. We also trimmed the ends of each order where the noise rose quickly. Finally, the flux-calibrated spectra of each order (including the first, second, and third orders) and module were merged without applying any scaling factor between SL and LL, and yielded a single spectrum per source. This spectrum was used to estimate aromatic feature fluxes, continuum flux densities at various wavelengths and line fluxes.

### 2.3. Data Analysis

#### 2.3.1. The PAH Fluxes and Equivalent Widths

To study the properties of PAH emission in our sample, we have used two methods to estimate the feature strength. The first method defines a local continuum or “plateau” under the emission features at 6.2 and 11.3  $\mu\text{m}$  by fitting a spline function to selected points, and measures the features above the continuum. The wavelength limits for the integration of the features are approximately 5.95–6.55  $\mu\text{m}$  for the 6.2  $\mu\text{m}$  PAH and 10.80–11.80  $\mu\text{m}$  for the 11.3  $\mu\text{m}$  PAH. We have not taken into account the possibility of water ice or hydroaromatic carbon (HAC) absorption in our measurement of the 6.2  $\mu\text{m}$  PAH EW because these features are known to be important mainly in strongly obscured local ULIRGs (Spoon et al. 2004); thus, neglecting this component does not significantly change the 6.2  $\mu\text{m}$  PAH EW. Although the 9.7  $\mu\text{m}$  silicate feature could affect the measurement on the 11.3  $\mu\text{m}$  PAH, our sample has very few deeply obscured sources. The PAH EWs are derived by dividing the integrated flux over the average continuum flux

in each feature range. This PAH EW measured from the spline fitting method is defined as the “apparent PAH EW” and is directly comparable to the studies in the literature such as Peeters et al. (2002), Spoon et al. (2007), Armus et al. (2007), Desai et al. (2007), Pope et al. (2008), and Dale et al. (2009). In the second method, we use the PAHFIT software (Smith et al. 2007) to measure the PAHs in our sample (see Figure 1 for examples). In PAHFIT, the PAH features are fit with Drude profiles, which have extended wings that account for a significant fraction of the underlying plateau (Smith et al. 2007). As has been shown in Smith et al. (2007) and Galliano et al. (2008), although the PAHFIT method gives higher values of PAH integrated fluxes or EWs due to the lower continuum adopted than the “apparent PAH EW” method, the two methods yield consistent results on trends, such as the variations of band-to-band PAH luminosity ratios. Throughout this paper, when we refer to PAH EWs, we mean the apparent PAH EWs measured from the spline fitting method and they are used to classify object types. When we refer to PAH flux or luminosity, we mean the values derived from PAHFIT.

#### 2.3.2. The Fine-structure Line Fluxes

The mid-IR has a rich suite of fine-structure lines. [S IV]10.51  $\mu\text{m}$ , [Ne II]12.81  $\mu\text{m}$ , [Ne III]15.55  $\mu\text{m}$ , [S III]18.71/33.48  $\mu\text{m}$ , and [Si II]34.82  $\mu\text{m}$  are the most frequently detected fine-structure lines in the spectral range covered by the IRS. The high-excitation line of [O IV]25.89  $\mu\text{m}$  has often been detected in low-metallicity galaxies, starburst galaxies or AGNs, excited by the shocks associated with intense star formation or nuclear activity, while the [Ne V]14.32/24.32  $\mu\text{m}$  lines are frequently detected in AGN-dominated sources and serve as unambiguous indicators of an AGN.

We use the ISAP package in SMART (Higdon et al. 2004) to measure the strength of the fine-structure lines. A Gaussian profile is adopted to fit the lines above a local continuum. The continuum is derived by linear fitting except for the [Ne II]12.81  $\mu\text{m}$  line, which is blended with the 12.7  $\mu\text{m}$  PAH feature. The continuum underlying the [Ne II] line is fit with a second-order polynomial. The integrated fitted flux above the continuum is taken as the total flux of the line. Upper limits are derived by measuring the flux with a height of three times the local rms and a width equal to the instrument resolution. In this paper, we only use the flux ratio of [Ne III]/[Ne II] to compare with the PAH strength, while the tabulated line fluxes will be presented and discussed in a future paper.

## 3. THE INFRARED LUMINOSITIES OF THE 5MUSES SAMPLE

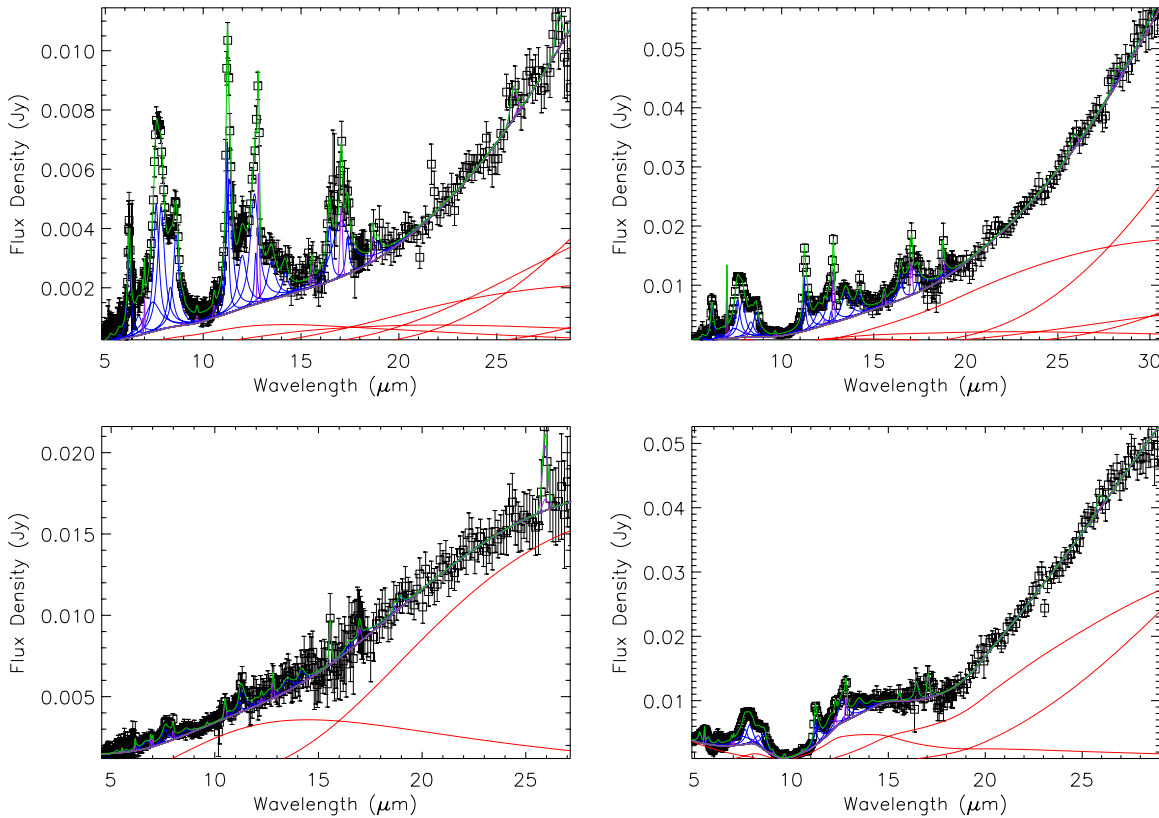
Several SED libraries have been built to capture the variation in the shape of IR SEDs and to estimate  $L_{\text{IR}}$  (Dale & Helou 2002; Chary & Elbaz 2001; Draine & Li 2007; Rieke et al. 2009). In the absence of multi-wavelength data, monochromatic luminosities have also been widely used to estimate  $L_{\text{IR}}$  (Sajina et al. 2007; Bavouzet et al. 2008; Rieke et al. 2009; Kartaltepe et al. 2010). The 5MUSES sample has mid-IR spectra, in addition to the IRAC and MIPS photometry, which allows us to account properly for variations in the SED shape and obtain more accurate estimates of  $L_{\text{IR}}$ .

### 3.1. Constructing an SED Template Library

In order to cover a wide range of SED shapes to fit the 5MUSES sources, we have built an IR template library based

<sup>13</sup> For more details, see <http://ssc.spitzer.caltech.edu/dataanalysis/tools/irsclean/>.

<sup>14</sup> For more details, see <http://ssc.spitzer.caltech.edu/dataanalysis/tools/spice/>.



**Figure 1.** Examples of PAHFIT decomposition of 5MUSES spectra (black squares) with strong, moderate, weak PAH emission and with silicate absorption. The best-fit SED (green) is composed of thermal dust continua (red), PAH features (blue), stellar light (magenta), and emission lines (purple).

(A color version of this figure is available in the online journal.)

on the recent observations obtained from *Spitzer*. The library encompasses 83 ULIRGs observed by the IRS Guaranteed Observation (GTO) sample (Armus et al. 2007); 75 normal star-forming galaxies from *Spitzer* Infrared Nearby Galaxies Survey (SINGS; Kennicutt et al. (2003)); and 136 Palomar-Green (PG) and 2MASS quasars (Shi et al. 2007). The templates in the library consist of SEDs derived from IRS spectra and/or IRAC and MIPS photometry. For both the ULIRG and PG/2MASS sources, full 1–1000  $\mu\text{m}$  SEDs have been obtained by J. A. Marshall et al. (2010, in preparation) and Y. Shi et al. (2010, in preparation) from IRS, MIPS, and *IRAS* observations. For the SINGS galaxies, Dale et al. (2007) have provided SED fits to the MIPS 24, 70, and 160  $\mu\text{m}$  photometry using the Dale & Helou (2002) templates. However, these templates do not sample the full variation of the strength of PAH features in the 5–15  $\mu\text{m}$  regime, due to the limited mid-IR spectra available when the templates were created. As a result, when we use SINGS galaxies as templates, we use their FIR SED from the fits of Dale et al. (2007), while in the mid-IR, we use the observed IRAC photometry integrated from the whole galaxy. This extensive template library provides a good coverage on the variations of IR SEDs. 33% of our sources are best-fit with SINGS-type templates and 38% are best-fit with quasar-type templates. The remaining sources are best-fit by ULIRG-type templates. The type of the best-fit template also correlates well with the 6.2  $\mu\text{m}$  PAH EWs. Starburst (SB)-dominated sources are normally best fit by SINGS-type templates and AGN-dominated sources are best-fit with quasar-type templates. For SB-AGN composite sources, the best-fit templates are divided among ULIRG, SINGS, and quasar-type templates (48%, 37%, and 15%, respectively).

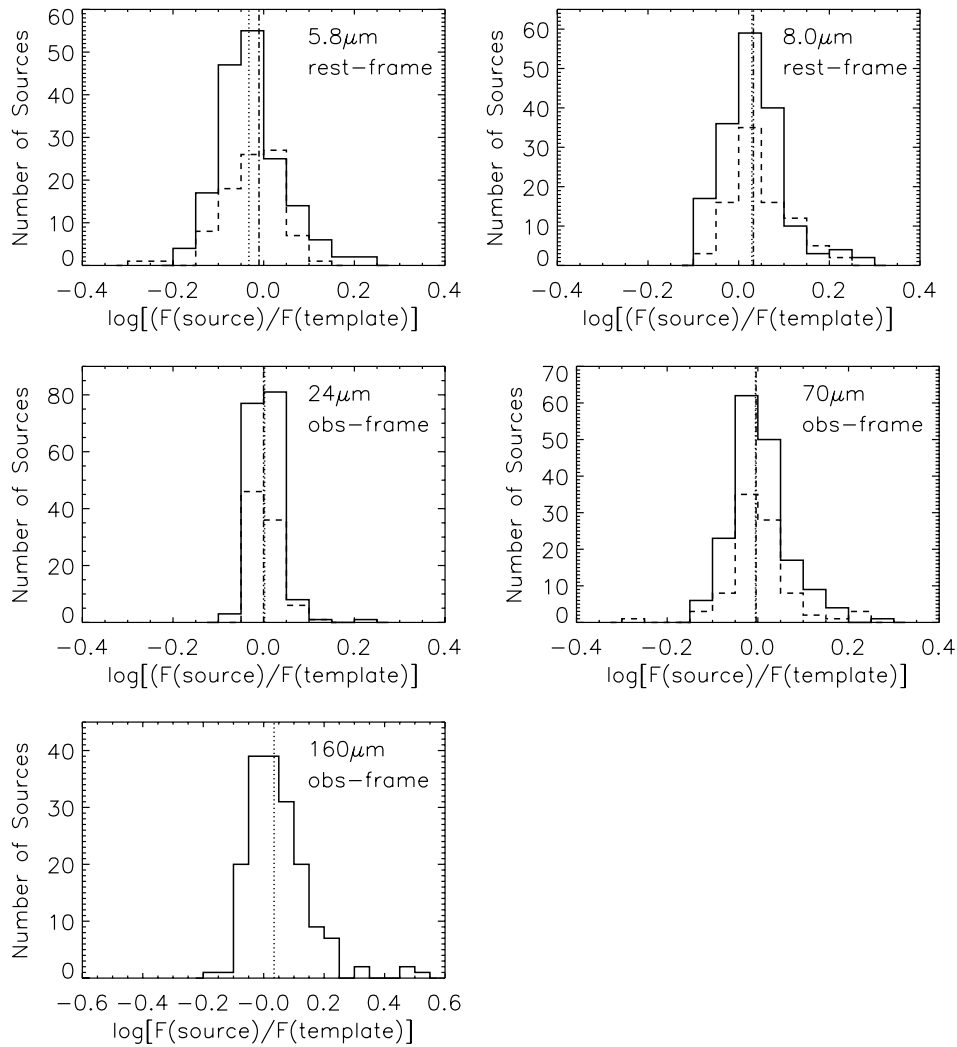
### 3.2. Estimating $L_{\text{IR}}$ Using *Spitzer* Data

Out of the 330 sources in 5MUSES, 280 galaxies have redshifts from optical or mid-IR spectroscopy. We are in the process of obtaining spec- $z$  for the remaining 50 sources. We have estimated redshifts for 11 out of these 50 objects from silicate features or very weak PAH features, but do not include them in the discussion of this paper because of the large associated uncertainties. For the 280 objects, we use a combination of synthetic IRAC photometry obtained from the rest-frame IRS spectra, as well as the observed MIPS photometry to compare with the corresponding synthetic photometry from the SED templates and estimate total  $L_{\text{IR}}$ . We select the best-fit template by minimizing  $\chi^2$  and we use progressively more detailed and accurate  $L_{\text{IR}}$  estimation methods for 5MUSES source with more photometry available. The final SED is composed of the IRS spectrum in the mid-IR and the best-fit template SED in the FIR. In the remainder of this section, we describe our method for estimating  $L_{\text{IR}}$  and the associated uncertainties.

#### 3.2.1. Sources with MIPS FIR Photometry

For sources with FIR detection at MIPS 70 and 160  $\mu\text{m}$ , we use five data points to fit their SEDs. The first two data points are rest-frame IRAC 5.8 and 8.0  $\mu\text{m}$ <sup>15</sup> derived by convolving the rest-frame 5MUSES spectrum with the filter response curves of IRAC 5.8 and 8.0  $\mu\text{m}$ . The other three data points are the observed MIPS 24, 70, and 160  $\mu\text{m}$  photometry for

<sup>15</sup> 5MUSES-312 has a redshift of 4.27 and for this source, we only use its MIPS 70 and 160  $\mu\text{m}$  fluxes during the SED fitting.



**Figure 2.** Histogram of the flux ratios between the source and the best-fit template, for galaxies with MIPS 70 and 160  $\mu\text{m}$  detections (solid line) and for galaxies only with MIPS 70  $\mu\text{m}$  detections (dashed line). The dotted and dash-dotted lines indicate the medians of the flux ratios for sources with 70 and 160  $\mu\text{m}$  detections and sources with only 70  $\mu\text{m}$  detections. All five bands appear to peak around a  $\log[F(\text{source})/F(\text{template})]$  ratio of 0 with rather narrow distributions. The  $1\sigma$  deviations in  $F(\text{source})/F(\text{template})$  for the 5.8, 8.0, 24, and 70, 160  $\mu\text{m}$  bands are 0.07, 0.07, 0.03, 0.06 and 0.10 dex, respectively, for sources with 70 and 160  $\mu\text{m}$  detections and 0.07, 0.07, 0.03 and 0.07 dex for sources with only 70  $\mu\text{m}$  detections.

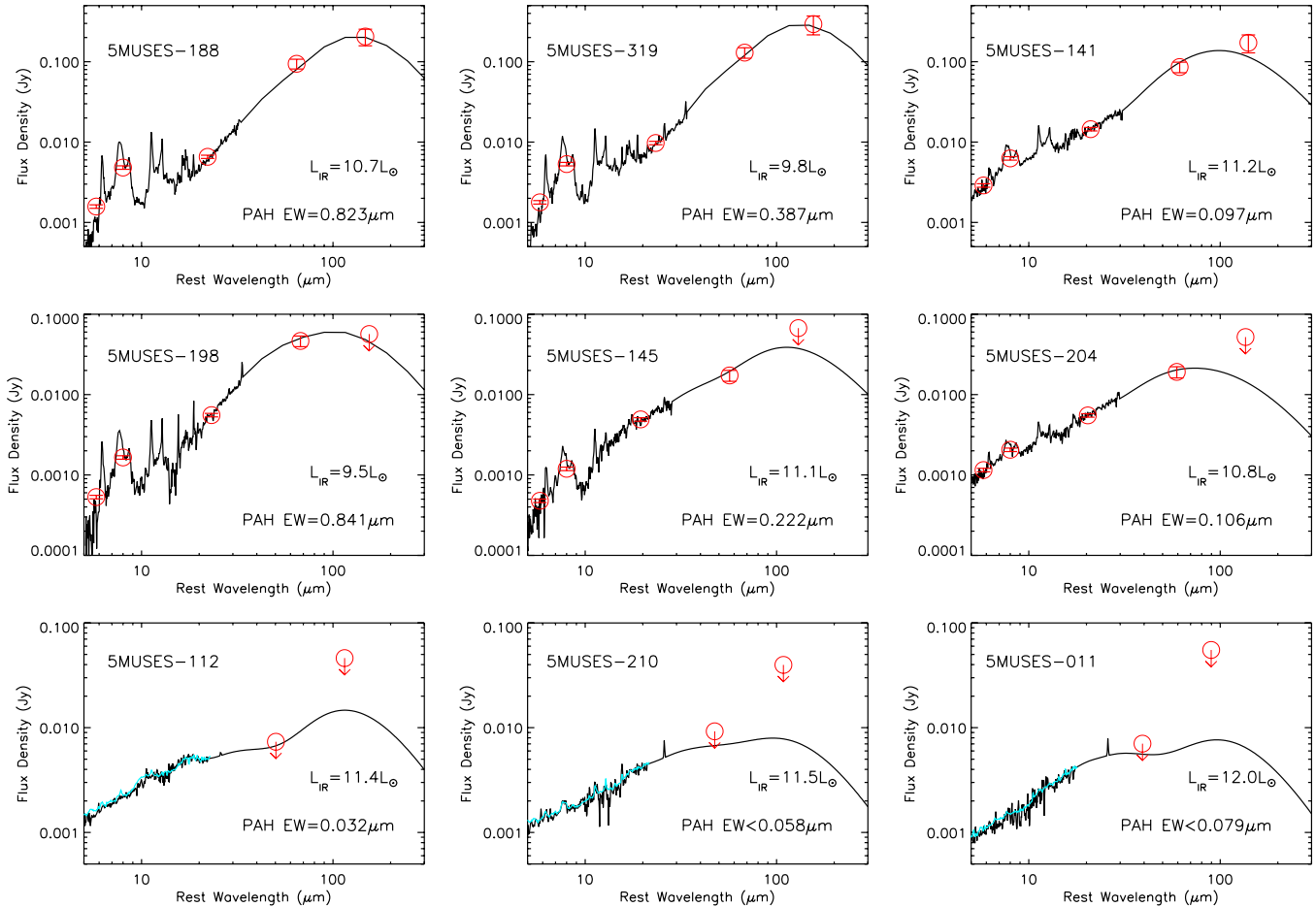
each 5MUSES source. The corresponding data points from the templates are derived in the following way: for ULIRG and PG/2MASS templates, the 5.8 and 8.0  $\mu\text{m}$  fluxes are derived in the same manner as 5MUSES sources. The 24, 70, and 160  $\mu\text{m}$  data points are derived by convolving the template SED at matching redshift with the MIPS 24, 70, and 160  $\mu\text{m}$  filter response curves. For SINGS templates, we use directly the observed IRAC 5.8 and 8.0  $\mu\text{m}$  photometry as the first two data points, which are essentially at rest frame for all SINGS objects. Then, we move the SINGS SEDs given by Dale et al. (2007) to the redshift of the 5MUSES source and derive the corresponding observed-frame MIPS 24, 70, and 160  $\mu\text{m}$  photometry. During the SED fitting, we weight the data points by their wavelength since the majority of the energy is emitted at FIR for IR selected sources, and look for the template that fits each 5MUSES source best by minimizing the  $\chi^2$ . A comparison of the ratio of flux densities at rest frame 5.8, 8.0  $\mu\text{m}$  and the observed MIPS 24, 70, and 160  $\mu\text{m}$  photometry from the source and the best-fit template can be found in Figure 2 (solid line). The dispersion in the ratio of the observed photometry over the photometry from the best-fit template ( $F_{\text{source}}/F_{\text{template}}$ ) in each band is 0.07, 0.07, 0.03, 0.06, and 0.10 dex, respectively.

For sources with FIR detection only at MIPS 70  $\mu\text{m}$ , we apply the same technique to fit the SED. We use the rest-frame IRAC 5.8 and 8.0  $\mu\text{m}$  photometry and the observed MIPS 24 and 70  $\mu\text{m}$  data in our fitting. The upper limit at 160  $\mu\text{m}$  is used to exclude templates for which the synthetic photometry exceeds the  $2\sigma$  upper limit of the source. A comparison of the ratio of flux densities at rest frame 5.8, 8.0  $\mu\text{m}$  and the observed MIPS 24 and 70  $\mu\text{m}$  photometry from the source and the best-fit template can be found in Figure 2 (dashed line). The dispersion in the ratio of  $F_{\text{source}}/F_{\text{template}}$  in each band is 0.07, 0.07, 0.03, and 0.07 dex, respectively.

Once the best-fit template is identified, we derive  $L_{\text{IR}}$  as explained in the last paragraph of the next section.

### 3.2.2. Sources without MIPS FIR Photometry

Nineteen objects do not have FIR detection even at 70  $\mu\text{m}$ . For these sources, we select the IR SED based on the mid-IR spectra. Our method is to fit the IRS spectrum of the 5MUSES source with the mid-IR spectra of the templates in the corresponding wavelength regime and adopt the SED of the best-fit template. The templates of which the synthetic photometry exceeded the  $2\sigma$  upper limits at MIPS 70 and 160  $\mu\text{m}$  bands are excluded.



**Figure 3.** SEDs of a sample of nine 5MUSES sources. The final SED (black) is composed of the IRS spectrum in the mid-IR and the best-fit template in the FIR. The observed data are shown as red circles. The three sources in the top panel are fit with five data points (IRAC 5.8, 8.0  $\mu\text{m}$  and MIPS 24, 70, and 160  $\mu\text{m}$ ). The three sources in the middle panel are fit with four data points (IRAC 5.8, 8.0  $\mu\text{m}$  and MIPS 24 and 70  $\mu\text{m}$ ). The three sources in the bottom panel are fit with only the IRS spectra. The blue line is the mid-IR SED of the best-fit template for the sources fit with the IRS spectra.

(A color version of this figure is available in the online journal.)

As will be shown in Section 3.2.3, this IRS-only method might underestimate the  $L_{\text{IR}}$  for cold sources by  $\sim 20\%$ , while it shows no significant offset for warm sources.<sup>16</sup> All of the 19 objects in this category show SEDs with high  $(f_{24\mu\text{m}}/f_{70\mu\text{m}})_{\text{obs}}$  ratios<sup>17</sup>; thus, they are more likely to be warm sources. This suggests that our approach of using the IRS spectrum to find the best-fit SED is unlikely to result in significant biases on  $L_{\text{IR}}$ .

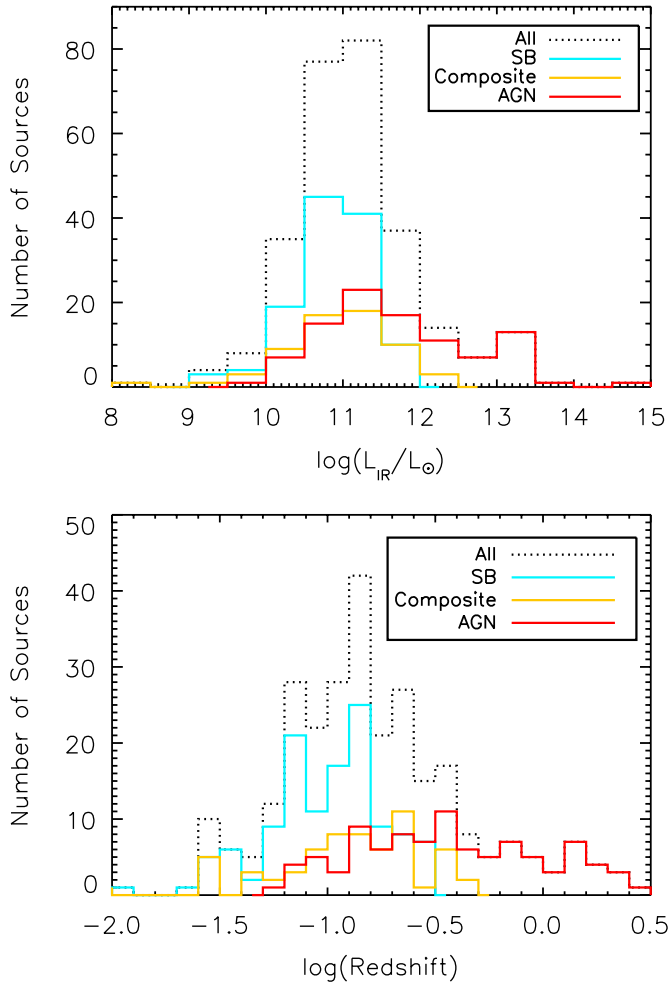
Finally, for each source, we visually inspect the fitting results. We find that a range of templates could fit the SED well. We construct the final 5–1000  $\mu\text{m}$  SED of a galaxy by combining its IRS spectrum in the mid-IR with the best-fit template SED at FIR. The total IR luminosity is derived by integrating under this SED curve. The uncertainty is derived from the standard deviation among the six best fits. We show examples of our SED fitting results in Figure 3 and the distribution of  $L_{\text{IR}}$  is shown Figure 4(a). We also show the distribution of  $L_{\text{IR}}$  for each type of objects, e.g., starburst, AGN, and composite (defined in detail in Section 4.1) in this figure. The derived  $L_{\text{IR}}$  for each source and its uncertainty is tabulated in Table 2. The distribution for the redshifts of 5MUSES objects is shown in Figure 4(b).

<sup>16</sup> Warm sources are defined to have  $f_{24\mu\text{m}}/f_{70\mu\text{m}} > 0.2$ , derived from the definition of  $f_{25\mu\text{m}}/f_{60\mu\text{m}} > 0.2$  by Sanders et al. (1988).

<sup>17</sup> The 70  $\mu\text{m}$  flux densities are upper limits.

### 3.2.3. How Well Can we Constrain IR SED from Mid-IR?

As has been shown above as well as in Kartaltepe et al. (2010), the availability of longer wavelength data greatly reduces the uncertainty in the estimate of  $L_{\text{IR}}$ . We need to quantify how well one can constrain the SED of a galaxy if only the continuum shape up to  $\sim 30\mu\text{m}$  is available. In Figure 5, we show the comparison of the IRS predicted  $L_{\text{IR}}^{\text{IRS}}$  and the  $L_{\text{IR}}^{\text{phot}}$  estimated from photometric data points (IRAC 5.8, 8.0  $\mu\text{m}$  and MIPS 24, 70, and 160  $\mu\text{m}$ ). For the IRS-only method, we use only the IRS spectrum and do not employ any longer wavelength information (70 and 160  $\mu\text{m}$  fluxes or upper limits) in our SED fitting, with the goal of testing solely the power of using mid-IR SED to predict FIR SED. We find that  $L_{\text{IR}}$  estimated from mid-to-FIR photometry are on average 10% higher than  $L_{\text{IR}}$  estimated from the IRS-only method, with a considerable scatter of 0.14 dex. It is worth noting that  $L_{\text{IR}}^{\text{IRS}}$  deviates from  $L_{\text{IR}}^{\text{phot}}$  by more than 0.2 dex for 20% of the sources while 5% of the sources deviate by more than 0.3 dex. We further divide the sources into two groups: cold sources and warm sources, based on the ratio of  $f_{24\mu\text{m}}/f_{70\mu\text{m}}$ . Cold sources ( $f_{24\mu\text{m}}/f_{70\mu\text{m}} < 0.2$ ) show an average underestimate of 17% when using the IRS-only method and the  $1\sigma$  scatter is 0.16 dex, while warm sources ( $f_{24\mu\text{m}}/f_{70\mu\text{m}} > 0.2$ ) do not show systematic offset in the estimated  $L_{\text{IR}}$  from the two methods, with a scatter of 0.18 dex.



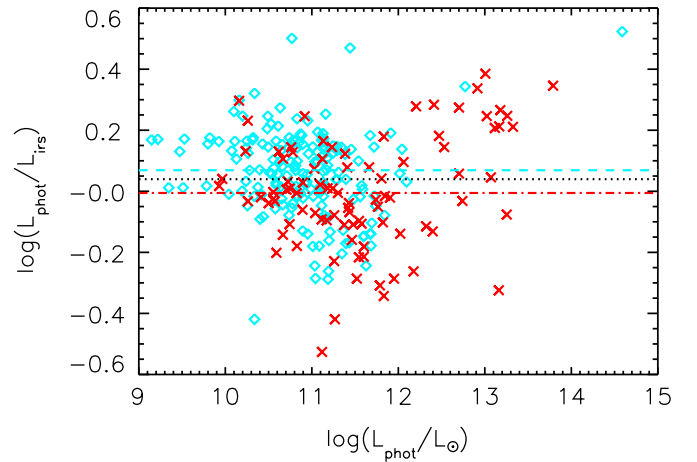
**Figure 4.** (a) Top panel: the distribution of the total infrared luminosity of the 5MUSES sample. The dotted line represents the whole sample with known redshift. The blue, yellow, and red solid lines represent the SB, composite, and AGN sources in the sample. The SBs and AGN dominate the lower and higher ends of the luminosity distribution, respectively. (b) Bottom panel: the distribution of the redshifts of the 5MUSES sample. The symbols are the same as in (a).

(A color version of this figure is available in the online journal.)

This comparison suggests that in IR-selected samples, the mid-IR spectrum could be used as an important indicator for  $L_{\text{IR}}$  when no longer wavelength data are available. However, for cold sources, the IRS-only method might underestimate  $L_{\text{IR}}$  by  $\sim 17\%$ , due to the lack of information on the peak of the SED. For warm sources, although  $L_{\text{IR}}$  estimated from the IRS-only method generally agrees with the value estimated from mid-to-far-IR SED, the associated uncertainty is rather large. Thus, for an individual galaxy, the  $L_{\text{IR}}$  predicted by its mid-IR SED could be a factor of 1.5 off from its intrinsic value for a significant subset of the population.

### 3.3. Estimating the Total IR Luminosity from a Single Band

Using *Spitzer* data, we have obtained accurate estimates of the total infrared luminosities for 5MUSES. In the absence of multi-wavelength data, single-band luminosities have often been used to estimate  $L_{\text{IR}}$  (Sajina et al. 2007; Papovich et al. 2007; Pope et al. 2008; Rieke et al. 2009; Bavouzet et al. 2008; Symeonidis et al. 2008). However, the fractional contribution of these photometric bands to the total infrared luminosity varies substantially depending on the dominant energy source. Because



**Figure 5.** Ratio of the  $L_{\text{IR}}$  derived from using IRAC 5.8, 8.0 and MIPS 24, 70, and  $160\ \mu\text{m}$  photometry over  $L_{\text{IR}}$  predicted by IRS spectra vs.  $L_{\text{IR}}$ . The diamonds represent cold sources with  $f_{24\ \mu\text{m}}/f_{70\ \mu\text{m}} < 0.2$  and the crosses represent the warm sources with  $f_{24\ \mu\text{m}}/f_{70\ \mu\text{m}} > 0.2$ . The dotted line indicate the median of the luminosity ratios ( $L_{\text{phot}}/L_{\text{IR}} = 1.10$ ,  $1\sigma = 0.16$  dex). The dashed line indicates the median ratio for the cold sources ( $L_{\text{phot}}/L_{\text{IR}} = 1.17$ ,  $1\sigma = 0.14$  dex) and the dot-dashed line indicates the median ratio for the warm sources ( $L_{\text{phot}}/L_{\text{IR}} = 0.99$ ,  $1\sigma = 0.18$  dex).

(A color version of this figure is available in the online journal.)

the IRS spectrum provides an unambiguous way to identify the energy source for 5MUSES galaxies, our sample is ideal for investigating the difference in the fractional contributions of single-band luminosities to  $L_{\text{IR}}$  in different types of objects.

In Figure 6, we plot the ratio of several luminosity bands to  $L_{\text{IR}}$ . The PAH luminosities are plotted on the left panel and continuum luminosities are on the right. The dotted, dashed, and dash-dotted lines, respectively, stand for the median ratios for SB, composite, and AGN-dominated sources. Clearly the fractional contribution of a certain band to  $L_{\text{IR}}$  is highly dependent on the type of the object, e.g., the monochromatic  $24\ \mu\text{m}$  continuum luminosity  $\nu L_{\nu}$  accounts for  $\sim 13\%$  of the total IR luminosity for SB galaxies, while it can contribute on average 30% of  $L_{\text{IR}}$  in AGNs. The difference in the ratio of PAH luminosity to  $L_{\text{IR}}$  is less significant for different types of objects, because in order to be included on the left panel of this plot, the AGN-dominated sources also need to have a solid detection of PAH feature that could be measured by PAHFIT, i.e., strong AGN sources are excluded. The mean ratios of  $L_{\text{singleband}}/L_{\text{IR}}$  are summarized in Table 3. Finally, we also provide our calibration of using single band luminosity to estimate  $L_{\text{IR}}$  in the Appendix.

## 4. AROMATIC FEATURE DIAGNOSTICS

### 4.1. The Average Spectra

We derive the stacked SEDs for the SB, composite and AGN dominated sources in the 5MUSES sample, combining the low-resolution IRS spectra in the mid-IR with the MIPS photometry at FIR. Although we do not have optical spectroscopy to classify the object types with the Baldwin, Phillips, & Terlevich (BPT) diagram (Baldwin et al. 1981; Kewley et al. 2001), the equivalent widths of PAH features can be used as indicators of star formation activity. The  $6.2$  and  $11.3\ \mu\text{m}$  PAH bands are relatively isolated with little contamination from nearby features, which is important for unambiguously defining the local continuum. However, the  $11.3\ \mu\text{m}$  band is located on the shoulder of  $9.7\ \mu\text{m}$  silicate feature. Thus, its integrated flux and











**Table 2**  
(Continued)

ID	Name	R.A. (J2000)	Decl. (J2000)	Redshift <sup>a</sup>	$f_{24\ \mu\text{m}}$ (mJy)	$6.2\ \mu\text{m}$ EW	$\log(L_{\text{IR}}/L_{\odot})$
5MUSES-314	5MUSES_J171913.57+584509.1	17 <sup>h</sup> 19 <sup>m</sup> 13 <sup>s</sup> .5	+58 <sup>d</sup> 45 <sup>m</sup> 08 <sup>s</sup> .9	0.318(2)	8.8	<0.243	11.42 ± 0.12
5MUSES-315	5MUSES_J171933.37+592742.8	17 <sup>h</sup> 19 <sup>m</sup> 33 <sup>s</sup> .3	+59 <sup>d</sup> 27 <sup>m</sup> 42 <sup>s</sup> .7	0.139(2)	7.6	0.495 ± 0.005	11.28 ± 0.07
5MUSES-316	5MUSES_J171944.91+595707.7	17 <sup>h</sup> 19 <sup>m</sup> 44 <sup>s</sup> .9	+59 <sup>d</sup> 57 <sup>m</sup> 07 <sup>s</sup> .1	0.069(2)	14.4	0.753 ± 0.005	10.73 ± 0.05
5MUSES-317	5MUSES_J172043.28+584026.6	17 <sup>h</sup> 20 <sup>m</sup> 43 <sup>s</sup> .3	+58 <sup>d</sup> 40 <sup>m</sup> 26 <sup>s</sup> .9	0.125(2)	9.7	0.498 ± 0.006	11.14 ± 0.03
5MUSES-318	5MUSES_J172044.86+582924.0	17 <sup>h</sup> 20 <sup>m</sup> 44 <sup>s</sup> .9	+58 <sup>d</sup> 29 <sup>m</sup> 23 <sup>s</sup> .9	1.697(1)	5.3	<0.094	13.07 ± 0.05
5MUSES-319	5MUSES_J172159.43+595034.3	17 <sup>h</sup> 21 <sup>m</sup> 59 <sup>s</sup> .3	+59 <sup>d</sup> 50 <sup>m</sup> 34 <sup>s</sup> .2	0.028(2)	9.7	0.387 ± 0.031	9.78 ± 0.03
5MUSES-320	5MUSES_J172219.58+594506.9	17 <sup>h</sup> 22 <sup>m</sup> 19 <sup>s</sup> .6	+59 <sup>d</sup> 45 <sup>m</sup> 07 <sup>s</sup> .0	0.272(2)	7.8	<0.133	11.24 ± 0.02
5MUSES-321	5MUSES_J172228.04+601526.0	17 <sup>h</sup> 22 <sup>m</sup> 28 <sup>s</sup> .2	+60 <sup>d</sup> 15 <sup>m</sup> 26 <sup>s</sup> .2	0.742(2)	7.2	<0.111	12.40 ± 0.03
5MUSES-322	5MUSES_J172238.73+585107.0	17 <sup>h</sup> 22 <sup>m</sup> 38 <sup>s</sup> .8	+58 <sup>d</sup> 51 <sup>m</sup> 07 <sup>s</sup> .0	1.624(1)	6.7	<0.062	13.12 ± 0.04
5MUSES-323	5MUSES_J172313.06+590533.1	17 <sup>h</sup> 23 <sup>m</sup> 13 <sup>s</sup> .1	+59 <sup>d</sup> 05 <sup>m</sup> 33 <sup>s</sup> .1	0.108(2)	6.2	0.750 ± 0.037	10.85 ± 0.03
5MUSES-324	5MUSES_J172355.58+601301.7	17 <sup>h</sup> 23 <sup>m</sup> 55 <sup>s</sup> .5	+60 <sup>d</sup> 13 <sup>m</sup> 01 <sup>s</sup> .1	0.175(2)	5.4	0.905 ± 0.034	11.13 ± 0.02
5MUSES-325	5MUSES_J172355.97+594047.6	17 <sup>h</sup> 23 <sup>m</sup> 56 <sup>s</sup> .0	+59 <sup>d</sup> 40 <sup>m</sup> 47 <sup>s</sup> .4	0.030(2)	5.2	0.518 ± 0.098	9.35 ± 0.04
5MUSES-326	5MUSES_J172402.11+600601.4	17 <sup>h</sup> 24 <sup>m</sup> 02 <sup>s</sup> .1	+60 <sup>d</sup> 06 <sup>m</sup> 01 <sup>s</sup> .2	0.156(2)	8.0	0.461 ± 0.024	11.13 ± 0.03
5MUSES-328	5MUSES_J172546.80+593655.3	17 <sup>h</sup> 25 <sup>m</sup> 46 <sup>s</sup> .8	+59 <sup>d</sup> 36 <sup>m</sup> 55 <sup>s</sup> .3	0.035(2)	26.0	0.554 ± 0.041	10.49 ± 0.04
5MUSES-329	5MUSES_J172551.35+601138.9	17 <sup>h</sup> 25 <sup>m</sup> 51 <sup>s</sup> .3	+60 <sup>d</sup> 11 <sup>m</sup> 38 <sup>s</sup> .9	0.029(1)	27.3	0.454 ± 0.005	10.25 ± 0.03
5MUSES-330	5MUSES_J172619.80+601600.1	17 <sup>h</sup> 26 <sup>m</sup> 19 <sup>s</sup> .8	+60 <sup>d</sup> 16 <sup>m</sup> 00 <sup>s</sup> .0	0.924(1)	6.5	<0.039	12.35 ± 0.08

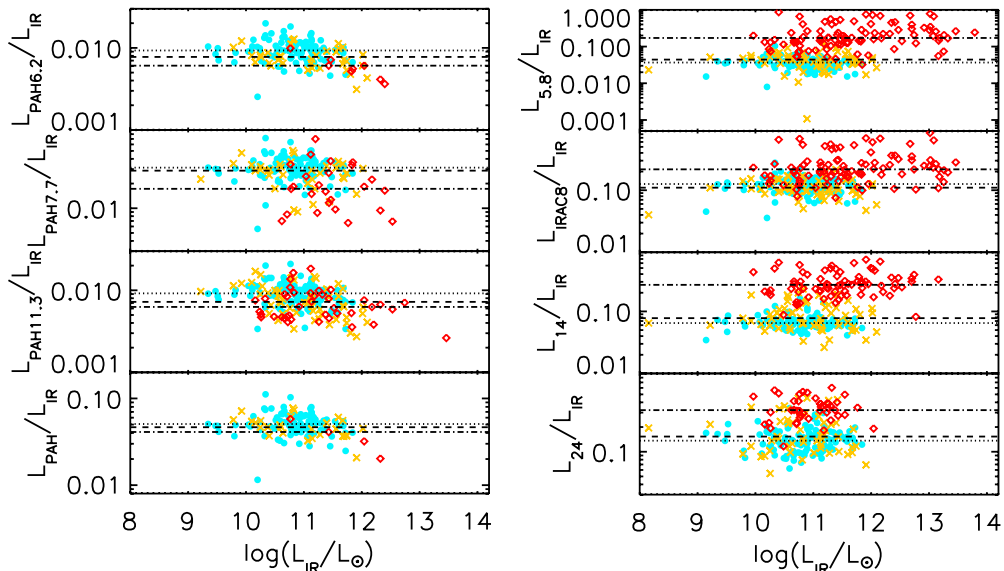
**Note.** <sup>a</sup> The redshifts obtained from NASA/IPAC Extragalactic Database are indicated with “1,” while the redshifts derived from IRS spectra are indicated with “2.”

(This table is also available in a machine-readable form in the online journal.)

**Table 3**  
Median Luminosity Ratios of the Sample

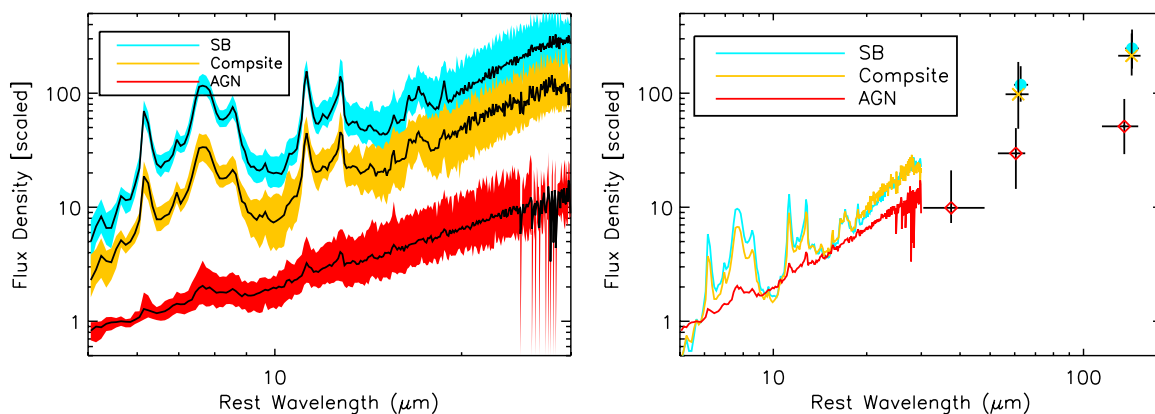
Luminosity Ratios	SB	Composite	AGN	Whole Sample
$\log(L_{\text{PAH}6.2\ \mu\text{m}}/L_{\text{IR}})$	$-2.03 \pm 0.13^{\text{a}}$	$-2.11 \pm 0.13$	$-2.22 \pm 0.14$	$-2.06 \pm 0.14$
$\log(L_{\text{PAH}7.7\ \mu\text{m}}/L_{\text{IR}})$	$-1.51 \pm 0.15$	$-1.54 \pm 0.18$	$-1.76 \pm 0.28$	$-1.53 \pm 0.20$
$\log(L_{\text{PAH}11.3\ \mu\text{m}}/L_{\text{IR}})$	$-2.04 \pm 0.13$	$-2.14 \pm 0.20$	$-2.20 \pm 0.18$	$-2.08 \pm 0.17$
$\log(L_{\text{PAH}6.2+7.7+11.3\ \mu\text{m}}/L_{\text{IR}})$	$-1.29 \pm 0.14$	$-1.33 \pm 0.12$	$-1.39 \pm 0.19$	$-1.31 \pm 0.14$
$\log(L_{5.8\ \mu\text{m}}/L_{\text{IR}})$	$-1.44 \pm 0.15$	$-1.36 \pm 0.29$	$-0.77 \pm 0.32$	$-1.33 \pm 0.42$
$\log(L_{\text{IRAC}8\ \mu\text{m}}/L_{\text{IR}})$	$-0.90 \pm 0.13$	$-0.96 \pm 0.15$	$-0.66 \pm 0.23$	$-0.86 \pm 0.22$
$\log(L_{14\ \mu\text{m}}/L_{\text{IR}})$	$-1.19 \pm 0.10$	$-1.11 \pm 0.21$	$-0.57 \pm 0.19$	$-1.12 \pm 0.31$
$\log(L_{24\ \mu\text{m}}/L_{\text{IR}})$	$-0.87 \pm 0.14$	$-0.82 \pm 0.23$	$-0.49 \pm 0.15$	$-0.81 \pm 0.22$

**Note.** <sup>a</sup> The dispersion is the  $1\sigma$  deviation for each group of objects.



**Figure 6.** Luminosity ratio of several bands over  $L_{\text{IR}}$  vs.  $L_{\text{IR}}$ . The blue circles, yellow crosses, and red diamonds represent the SB, composite, and AGN-dominated sources in 5MUSES. The dotted, dashed, and dash-dotted lines stand for the median ratios for the SB, composite, and AGN sources, respectively. The PAH luminosities are derived from PAHFIT measurements. The 5.8, 14, and 24  $\mu\text{m}$  luminosities are monochromatic luminosities calculated from the continua at these wavelengths. The IRAC 8  $\mu\text{m}$  luminosities are derived by convolving the rest-frame IRS spectra with the filter response curve of the IRAC 8  $\mu\text{m}$  band. The ratios and the associated uncertainties are also listed in Table 3.

(A color version of this figure is available in the online journal.)



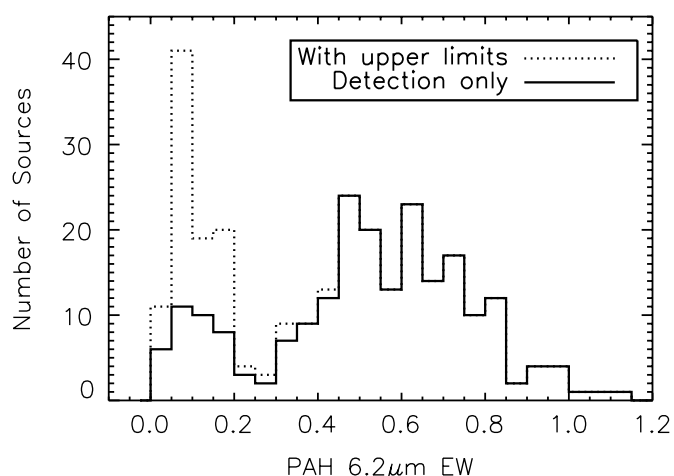
**Figure 7.** (a) Left panel: the median IRS spectra for SB, composite, and AGN-dominated sources from 5MUSES after normalizing at  $5.8 \mu\text{m}$ . The SEDs have been offset vertically. The shaded regions represent  $1\sigma$  uncertainties. (b) Right panel: the median SEDs for SB, composite, and AGN sources from mid-IR to FIR, normalized at  $5.8 \mu\text{m}$ .

(A color version of this figure is available in the online journal.)

underlying continuum are likely to be affected by dust extinction effects. As a result, in our discussion, we use the  $6.2 \mu\text{m}$  PAH EWs to classify objects. To be consistent with the studies in the literature, we have adopted the following criteria for our spectral classification: sources with  $\text{EW} > 0.5 \mu\text{m}$  are SB-dominated; sources with  $0.2 < \text{EW} \leq 0.5 \mu\text{m}$  are AGN–SB composite and sources with  $\text{EWs} \leq 0.2 \mu\text{m}$  are AGN dominated<sup>18</sup> (Armus et al. 2007). The PAH EWs for the sample are tabulated in Table 2. Out of the 280 sources for which redshifts have been obtained from optical or infrared spectroscopy, there are 123 SB galaxies (44%), 62 composite sources (22%), and 95 AGN-dominated sources (34%).

The  $5\text{--}30 \mu\text{m}$  composite spectra are derived by first normalizing individual spectra at rest frame  $5.8 \mu\text{m}$ , and then taking the median in each wavelength bin. In Figure 7(a), we show the typical SED for an SB galaxy in blue and AGNs in red, while the yellow line represents the median SED for SB–AGN composite sources in 5MUSES. The average SEDs have been offset vertically. The shaded regions represent the 16th and 84th percentile of the flux densities at each wavelength.

The MIPS 70 and  $160 \mu\text{m}$  photometry is crucial for constraining the SED shape of a galaxy and we have also included these data in the final typical SED. Because of the difference in redshift range for sources of different spectral types, we have divided the MIPS 70 and  $160 \mu\text{m}$  data into several rest-wavelength bins before we take the median. For SB and composite sources, we take two bins:  $40\text{--}70 \mu\text{m}$  and  $70\text{--}160 \mu\text{m}$ . For AGNs, we choose to have three bins due to their larger redshift range:  $30\text{--}50$ ,  $50\text{--}100$ , and  $100\text{--}160 \mu\text{m}$ . We take the median flux in each bin and assign the 16th and 84th percentile of the data points in the same bin as the uncertainties. The final median SEDs are presented in Figure 7(b). We can clearly see that besides having much less PAH emission in the mid-IR, the continuum in the AGNs also rises much more slowly than in the SB. The SED of the composite source is between the SB and AGNs and its shape is dependent on how we define a composite source. As can be seen in Figures 7 and 8, our definition of composite sources with  $0.2 \mu\text{m} < 6.2 \mu\text{m}$  PAH EW  $< 0.5 \mu\text{m}$  is likely biased toward star formation dominated sources (see Section 4.2).

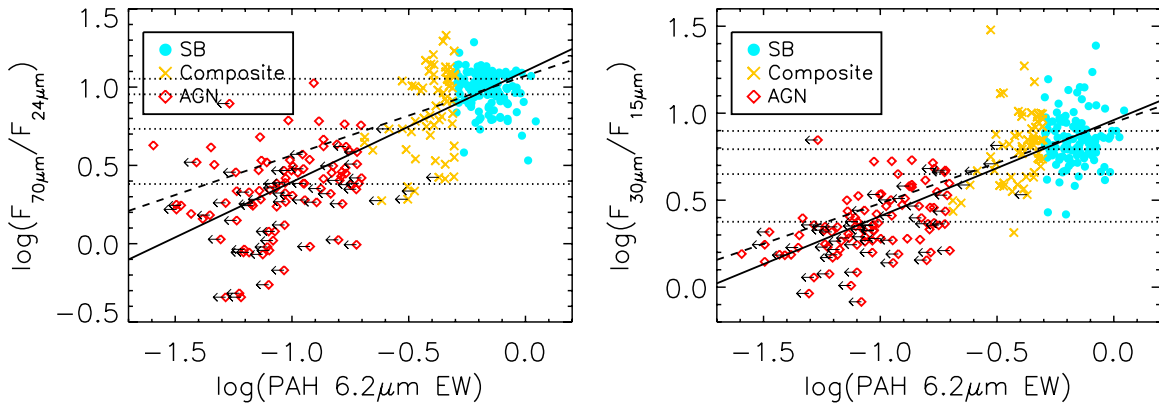


**Figure 8.** Histogram shows the distribution of the  $6.2 \mu\text{m}$  PAH EW for the 280 known- $z$  sources from the 5MUSES sample. The solid line represents sources which have detection for the  $6.2 \mu\text{m}$  feature, while the dotted line includes upper limits. It is clear that both the solid line and dotted line show a dip in the PAH EW distribution at  $0.2\text{--}0.3 \mu\text{m}$ . See the text for the detailed discussion on the bi-modality of the distribution.

#### 4.2. The Distribution of PAH EWs

With the superb sensitivity and spectral coverage of the IRS, we are able to quantify the strength of the PAH emission over nearly 2 orders of magnitude in its EW. The distribution of the  $6.2 \mu\text{m}$  PAH EWs for the 280 known-redshift galaxies in 5MUSES is shown in Figure 8. The solid line represents the distribution for sources with detection of the  $6.2 \mu\text{m}$  feature, while the dotted line also includes upper limits. We clearly observe a bimodal distribution in Figure 8, with two local peaks at  $\sim 0.1$  and  $\sim 0.6 \mu\text{m}$ . This is somewhat surprising because 5MUSES provides a representative sample completely selected based on IR flux densities and one would have expected a more continuous distribution. Although we still lack redshift information for 50 sources in our sample, the featureless power-law shape of their IRS spectra (except for a few cases where silicate absorption or very weak PAH feature is present) indicate that these are likely to be AGN dominated. Thus if they were included in Figure 8, they would most likely be located in the range between 0 and  $0.2 \mu\text{m}$ , and the bimodal distribution would not be affected. A similar bimodality is also observed in

<sup>18</sup> Sources with a significant old stellar population could also have a reduced  $6.2 \mu\text{m}$  PAH EW. As will be shown in Y. Shi et al. (2010, in preparation), the stellar emission contributes less than  $\sim 20\%$  to the  $6 \mu\text{m}$  continuum for our IR-selected sample of 5MUSES.



**Figure 9.** (a) Left panel: the continuum flux ratio of  $f_{70\mu\text{m}}/f_{24\mu\text{m}}$  vs. the  $6.2\mu\text{m}$  PAH EW. (b) Right panel: the continuum flux ratio of  $f_{30\mu\text{m}}/f_{15\mu\text{m}}$  vs. the  $6.2\mu\text{m}$  PAH EWs. The solid line is a fit to all the data points while the dashed line is a fit excluding sources with  $6.2\mu\text{m}$  PAH EW upper limits. We bin the objects according to their continuum slopes and have equal numbers of objects in each bin. The dotted lines indicate the boundaries of those bins.

(A color version of this figure is available in the online journal.)

the distribution of the  $11.3\mu\text{m}$  PAH EWs (not shown here). The observed bimodal distribution of the PAH EWs may be a result of the selection effect for this flux-limited sample: objects at higher redshifts are more likely to be AGNs and thus pile up at the low EW end. However, if we divide our sample into sources with  $z > 0.5$  and  $z < 0.5$ , the bimodal distribution is again observed in the  $z < 0.5$  population, although all the  $z > 0.5$  objects are located at the low EW end. Detailed population modeling is being performed and this issue will be addressed in a later paper.

### 4.3. PAH Properties versus Mid-IR and FIR Slopes

Another important physical parameter that is often used to quantify the dominant energy source of a galaxy is the ratio of warm to cold dust. It has been shown in previous studies (Desai et al. 2007; Wu et al. 2009) that the  $6.2$  and  $11.3\mu\text{m}$  PAH EWs of galaxies are usually suppressed in warmer systems dominated by AGNs, as indicated by the low flux ratios of *IRAS*  $f_{60}/f_{25}$ . For the 5MUSES sample, we have examined the correlation of the  $6.2\mu\text{m}$  PAH EWs with various continuum slopes, e.g.,  $f_{15}/f_{5.8}$ ,  $f_{30}/f_{5.8}$ ,  $f_{30}/f_{15}$ , and  $f_{70}/f_{24}$ . The rest-frame continuum fluxes are estimated from the final SED obtained from the fits in Section 3. We find that the continuum ratios of  $f_{30}/f_{15}$  and  $f_{70}/f_{24}$  have the strongest global correlation with the  $6.2\mu\text{m}$  PAH EWs and the correlation coefficients are both  $\sim 0.7$ .

In Figures 9(a) and (b), we plot the  $6.2\mu\text{m}$  PAH EW against  $f_{30}/f_{15}$  and  $f_{70}/f_{24}$ . The 5MUSES populations separate into two groups, one with steep spectra and high aromatic content, and the other with slow rising spectra and low aromatic content. The gap between SB and AGN-dominated sources is likely due to the selection effect of this sample. We should note that within each group, there is little if any correlation between the slope and the PAH EW, but it is the contrast between the two groups that gives the overall impression of a correlation. This is consistent with the studies of Veilleux et al. (2009), who have showed the power of using the  $7.7\mu\text{m}$  PAH EWs and  $f_{30}/f_{15}$  ratios as indicators of AGN activity, despite the large scatter associated with each parameter. To understand the variation in the PAH EWs and continuum slopes, we further divide our sample into smaller bins and estimate the average values in each bin. The sources are divided according to their  $f_{70}/f_{24}$  ratios or  $f_{30}/f_{15}$  ratios and we assign an equal number of objects to each bin. We find that sources in the first three bins with  $\log(f_{30}/f_{15}) > 0.65$

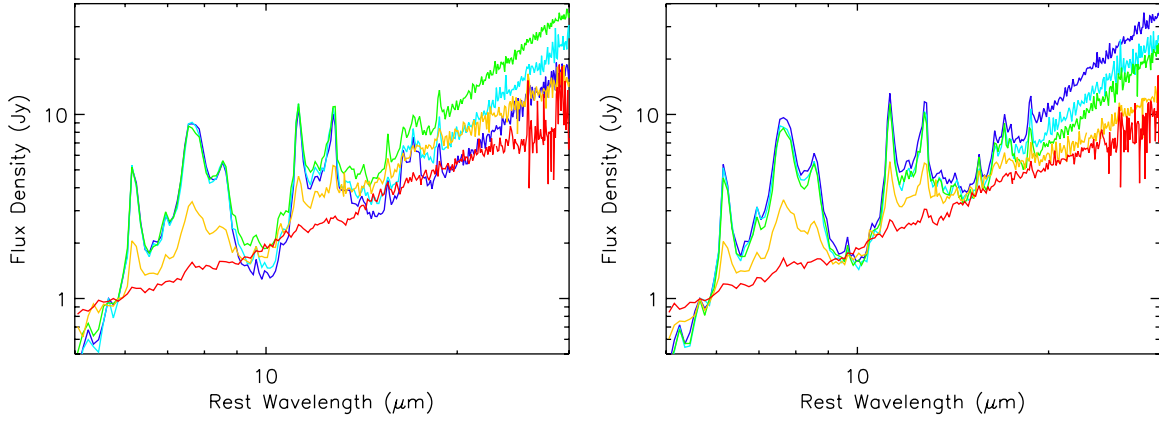
or  $\log(f_{70}/f_{24}) > 0.73$ <sup>19</sup> all have median  $6.2\mu\text{m}$  PAH EWs of  $\sim 0.60\mu\text{m}$  and dispersion of  $\sim 0.2$  dex, which again confirms our observation that within the group of starburst galaxies, there is little correlation between the slope and aromatic content. Sources with  $\log(f_{30}/f_{15}) < 0.38$  or  $\log(f_{70}/f_{24}) < 0.38$  are clearly AGN-dominated with very low PAH EW. The median values and the associated uncertainties of the  $6.2\mu\text{m}$  PAH EWs and continuum ratios are summarized in Table 4.

We also investigate the variation in the ratio of  $L_{\text{PAH}}/L_{\text{IR}}$  when the galaxy color indicated by the continuum slope changes. We use the sum of the PAH luminosity from the  $6.2\mu\text{m}$ ,  $7.7\mu\text{m}$  complex, and  $11.3\mu\text{m}$  complex to represent  $L_{\text{PAH}}$ , measured from the composite spectra derived for each bin. It is clear that the PAH fraction stays nearly constant for starburst-dominated systems, while its contribution drops significantly when AGN becomes more dominant (see Table 4). It has been shown that the PAH luminosity can contribute  $\sim 10\%$  in star-forming galaxies (Smith et al. 2007). For our sample, we find that  $L_{\text{PAH}}$  contributes  $\sim 5\%$  to  $L_{\text{IR}}$ . This ratio is lower than the SINGS results. We have only taken the  $6.2$ ,  $7.7$ , and  $11.3\mu\text{m}$  bands into account,<sup>20</sup> while the SINGS studies include all the PAH emitting bands in the mid-IR. Since the  $6.2$ ,  $7.7$ , and  $11.3\mu\text{m}$  bands account for  $\sim 68\%$  of the power in PAH emission (Smith et al. 2007), our  $L_{\text{PAH}}/L_{\text{IR}}$  ratio can be converted to  $\sim 7.5\%$  for the total PAH contribution to  $L_{\text{IR}}$ . This is still slightly lower than the SINGS results, but consistent within uncertainties.

Finally, for each group of continuum slope sorted spectra, we derive typical  $5\text{--}30\mu\text{m}$  SEDs by taking the median flux densities in every wavelength bin after normalizing at rest frame  $5.8\mu\text{m}$ . This will be useful for SED studies when only galaxy colors estimated from broadband photometry are available. These composite SEDs are shown in Figure 10. Then we explore whether the derivation of total IR luminosity from broadband photometry varies with galaxy color. We assume  $L_{\text{IR}}$  is correlated with  $L_{24\mu\text{m}}$  and  $L_{70\mu\text{m}}$  in the following manner and derive the  $a$  and  $b$  coefficients in each  $f_{70}/f_{24}$  continuum

<sup>19</sup> If the spectral index is defined as  $\alpha = \log(f_1/f_2)/\log(\nu_1/\nu_2)$ , then the continuum slope ratios of  $\log(f_{30}/f_{15}) > 0.65$  can be translated to  $\alpha_{30-15} < -2.17$  and  $\log(f_{70}/f_{24}) > 0.73$  can be converted to  $\alpha_{70-24} < -1.57$ .

<sup>20</sup> The S/N ratios of the 5MUSES spectra are much lower than SINGS, thus, we only include the strongest PAH bands.



**Figure 10.** (a) Left panel: the typical mid-IR SEDs in each bin of different  $f_{70 \mu\text{m}}/f_{24 \mu\text{m}}$  ratios. (b) Right panel: the typical SEDs in each bin of different  $f_{30 \mu\text{m}}/f_{15 \mu\text{m}}$  ratios. All the SEDs have been normalized at  $5.8 \mu\text{m}$ . The colors represent the average spectra derived in each  $f_{70 \mu\text{m}}/f_{24 \mu\text{m}}$  (or  $f_{30 \mu\text{m}}/f_{15 \mu\text{m}}$ ) color bins listed in Table 4.

(A color version of this figure is available in the online journal.)

**Table 4**  
Median PAH Strengths and Continuum Ratios of the Sample

$\log(f_{30}/f_{15})^a$	$\log(f_{70}/f_{24})$	$6.2 \mu\text{m}$ PAH EW <sup>b</sup>	$\log(L_{\text{PAH}}/L_{\text{IR}})^c$	$a$	$b$
$>0.898$	$0.99^{+0.08}_{-0.17}$	$0.57^{+0.18}_{-0.16}$ (56) <sup>d</sup>	-1.40	$0.65 \pm 0.10$	$0.94 \pm 0.14$
$0.793-0.898$	$0.97^{+0.11}_{-0.18}$	$0.62^{+0.21}_{-0.13}$ (56)	-1.31	$0.79 \pm 0.33$	$0.74 \pm 0.61$
$0.650-0.793$	$1.04^{+0.05}_{-0.35}$	$0.58^{+0.17}_{-0.28}$ (55)	-1.29	$0.70 \pm 0.28$	$0.94 \pm 0.65$
$0.376-0.650$	$0.57^{+0.42}_{-0.21}$	$0.19^{+0.36}_{-0.09}$ (55)	-1.54	$0.41 \pm 0.07$	$1.72 \pm 0.31$
$<0.376$	$0.25^{+0.21}_{-0.29}$	$0.08^{+0.05}_{-0.04}$ (53)	-2.09	$0.50 \pm 0.03$	$1.04 \pm 0.18$
$0.76^{+0.13}_{-0.23}$	$>1.053$	$0.61^{+0.15}_{-0.14}$ (56)	-1.29	$0.62 \pm 0.07$	$0.57 \pm 0.10$
$0.69^{+0.18}_{-0.35}$	$0.954-1.053$	$0.61^{+0.15}_{-0.14}$ (56)	-1.31	$0.33 \pm 0.10$	$0.99 \pm 0.18$
$0.85^{+0.18}_{-0.42}$	$0.733-0.954$	$0.60^{+0.18}_{-0.21}$ (55)	-1.36	$0.41 \pm 0.02$	$0.52 \pm 0.06$
$0.61^{+0.32}_{-0.31}$	$0.381-0.733$	$0.16^{+0.25}_{-0.08}$ (56)	-1.60	$0.47 \pm 0.01$	$0.52 \pm 0.06$
$0.57^{+0.31}_{-0.30}$	$<0.381$	$0.08^{+0.08}_{-0.03}$ (52)	-2.07	$0.44 \pm 0.02$	$0.23 \pm 0.04$

**Notes.**

<sup>a</sup> We sort the spectra by the continuum slope and divide the objects into five groups, in which each group have the same number of sources (56).

<sup>b</sup> The upper limits are also included.

<sup>c</sup> The PAH luminosity is the sum of the  $6.2$ ,  $7.7$ , and  $11.3 \mu\text{m}$  PAH luminosities measured from the composite spectra.

<sup>d</sup> The number in the parenthesis indicates the number of objects for which we have measured the  $6.2 \mu\text{m}$  PAH EW or PAH luminosity.

slope bin (all in rest-frame):

$$\log L_{\text{IR}} = a \log L_{24 \mu\text{m}} + b \log L_{70 \mu\text{m}} \quad (1)$$

The values of  $a$  and  $b$  coefficients are summarized in Table 4. To illustrate the variations in each slope bin, we plot the ratio of  $L_{\text{IR}}/L_{24 \mu\text{m}}$  versus  $L_{70 \mu\text{m}}/L_{24 \mu\text{m}}$  in Figure 11(a). The sources are colored according to their  $f_{70}/f_{24}$  ratios. We clearly observe that when normalized by the monochromatic  $24 \mu\text{m}$  luminosity,  $L_{\text{IR}}$  is strongly correlated with  $L_{70 \mu\text{m}}$  and the slopes in each continuum ratio bin become steeper when  $L_{70 \mu\text{m}}/L_{24 \mu\text{m}}$  increase, except in the last slope bin (see also the  $b$  coefficients). We fit a second-order polynomial to the data and find the correlation to be

$$\log \frac{L_{\text{IR}}}{L_{24 \mu\text{m}}} = (0.476 \pm 0.005) + (0.509 \pm 0.010) \log \frac{L_{70 \mu\text{m}}}{L_{24 \mu\text{m}}} + (0.370 \pm 0.022) \left( \log \frac{L_{70 \mu\text{m}}}{L_{24 \mu\text{m}}} \right)^2. \quad (2)$$

The above equation is derived based on the 5MUSES data. The majority (90%) of the  $24 \mu\text{m}$  luminosities of these 280 galaxies

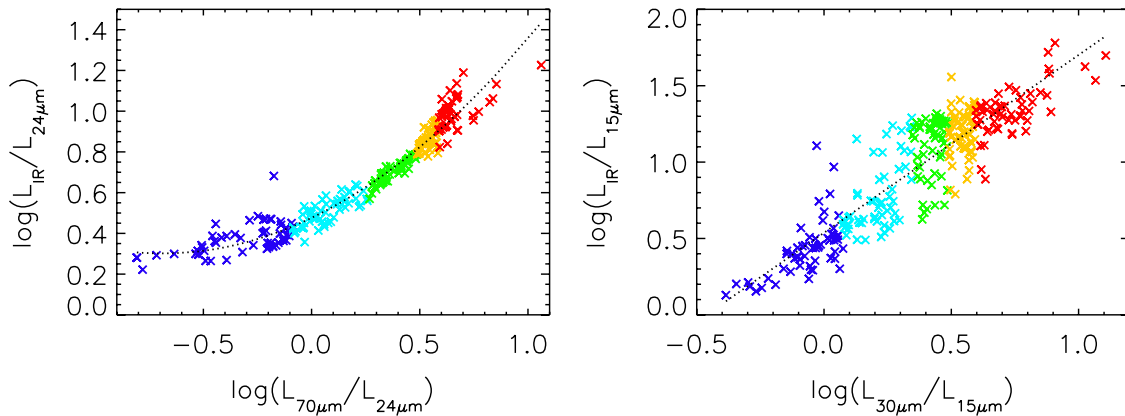
are between  $10^{9.0} L_{\odot}$  and  $10^{12.0} L_{\odot}$ . The ratio of  $f_{70 \mu\text{m}}/f_{24 \mu\text{m}}$  ranges from 0.45 to 34. Our result is consistent with a similar correlation derived by Papovich & Bell (2002), while it diverges for sources with low  $f_{70 \mu\text{m}}/f_{24 \mu\text{m}}$  ratios, since their modeling work has focused on star-forming galaxies only.

We repeat the same exercise for our sample binned with the  $f_{30}/f_{15}$  ratios. In Figure 11(b), we find that  $L_{\text{IR}}$  is correlated with  $L_{30 \mu\text{m}}$  when both quantities are normalized by  $L_{15 \mu\text{m}}$ , although with very large scatter. The dotted line is a linear fit to the data. For a given  $L_{30 \mu\text{m}}/L_{15 \mu\text{m}}$  ratio,  $L_{\text{IR}}/L_{15 \mu\text{m}}$  can span as much as a factor of 5. The median values in each group binned by the  $f_{30}/f_{15}$  ratios are also summarized in Table 4.

#### 4.4. The Variation in PAH Band-to-Band Strength Ratios

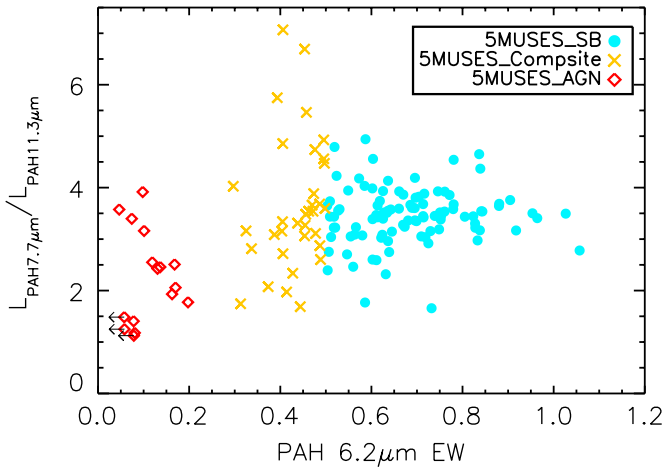
The luminosity ratio of different PAH bands is thought to be a function of the grain size and ionization state (Tielens 2008). In Figure 12, we compare the PAH luminosity ratios of  $L_{\text{PAH}7.7 \mu\text{m}}/L_{\text{PAH}11.3 \mu\text{m}}$  with the  $6.2 \mu\text{m}$  PAH EWs for the

<sup>21</sup> We choose to use the  $L_{\text{PAH}7.7 \mu\text{m}}/L_{\text{PAH}11.3 \mu\text{m}}$  ratio in this study for easier comparison with literature results, such as Smith et al. (2007) and O'Dowd et al. (2009).



**Figure 11.** (a) Left panel: the ratios of  $L_{\text{IR}}/L_{24\mu\text{m}}$  vs.  $L_{70\mu\text{m}}/L_{24\mu\text{m}}$ . The sources are colored according to their  $f_{70}/f_{24}$  ratios. The dotted line is a second-order polynomial fit to the data. (b) Right panel: the ratios of  $L_{\text{IR}}/L_{15\mu\text{m}}$  vs.  $L_{30\mu\text{m}}/L_{15\mu\text{m}}$ . The sources are colored according to their  $f_{30}/f_{15}$  ratios. The dotted line is a linear fit to the data.

(A color version of this figure is available in the online journal.)



**Figure 12.** PAH luminosity ratio of  $L_{\text{PAH}7.7\mu\text{m}}/L_{\text{PAH}11.3\mu\text{m}}$  vs. the 6.2  $\mu\text{m}$  PAH EW for 5MUSES. The AGN-dominated sources appear to have lower  $L_{\text{PAH}7.7\mu\text{m}}/L_{\text{PAH}11.3\mu\text{m}}$  ratios than the composite or SB-dominated sources. The mean ratios are  $3.45 \pm 0.55$ ,  $3.65 \pm 1.28$ , and  $2.26 \pm 0.89$ , respectively, for SB, composite, and AGN.

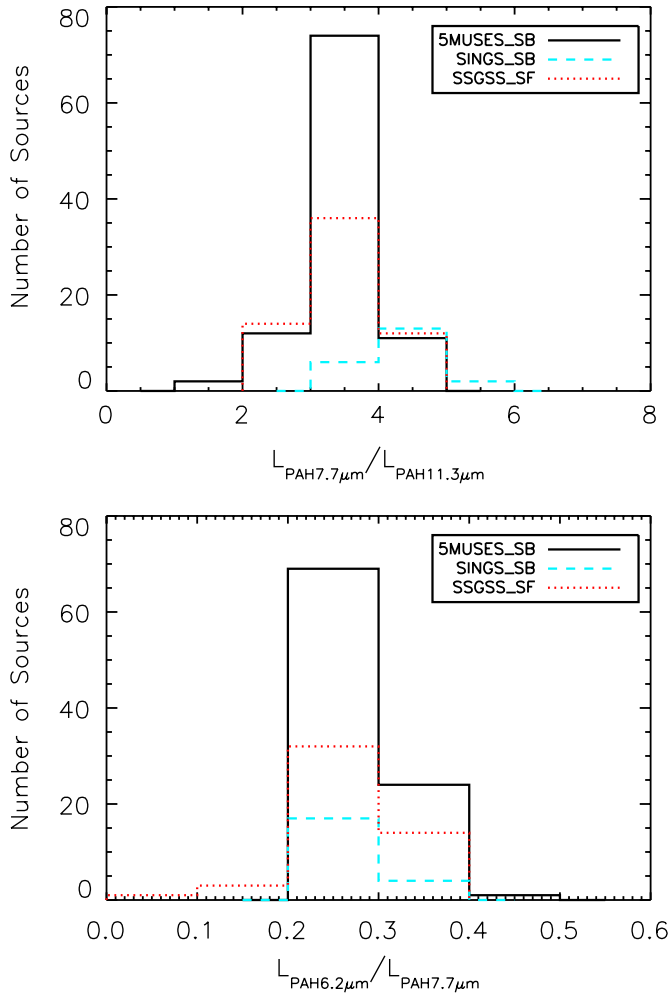
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5MUSES sample. Only sources with  $S/N > 3$  from PAHFIT measurements for the 7.7 and 11.3  $\mu\text{m}$  bands are included in this plot. We find that the AGN-dominated sources on average have lower  $L_{\text{PAH}7.7\mu\text{m}}/L_{\text{PAH}11.3\mu\text{m}}$  ratios than the composite or SB-dominated sources. The mean  $\log(L_{\text{PAH}7.7\mu\text{m}}/L_{\text{PAH}11.3\mu\text{m}})$  ratios for AGN, composite, and SB galaxies in 5MUSES are  $0.32 \pm 0.18$ ,  $0.53 \pm 0.15$  and  $0.53 \pm 0.08$ , respectively. This is consistent with the studies on the nuclear spectra of low luminosity star-forming galaxies from SINGS (Smith et al. 2007), which also show decreased  $L_{\text{PAH}7.7\mu\text{m}}/L_{\text{PAH}11.3\mu\text{m}}$  ratios in spectra with AGN signals. Smith et al. (2007) suggest that this change in the ratio of  $L_{\text{PAH}7.7\mu\text{m}}/L_{\text{PAH}11.3\mu\text{m}}$  is likely due to the destruction of the smallest PAHs by hard photons from the AGN. On the other hand, AGN are less extinguished than SB or composite sources, thus if PAHFIT underestimates the extinction correction, it will preferentially underestimate the 11.3  $\mu\text{m}$  fluxes more than the 7.7  $\mu\text{m}$  feature in SB/Composite sources, thus resulting in the elevated ratios of  $L_{\text{PAH}7.7\mu\text{m}}/L_{\text{PAH}11.3\mu\text{m}}$  in SB/composite systems.

In Figure 13(a), we show the histogram of the  $L_{\text{PAH}7.7\mu\text{m}}/L_{\text{PAH}11.3\mu\text{m}}$  ratios for the SB-dominated sources in 5MUSES. We have overplotted the values from the SINGS sample. To make a fair comparison, we remeasure the PAH luminosity and EWs for the SINGS nuclear spectra using the same method as 5MUSES and classify the sources with 6.2  $\mu\text{m}$  PAH EWs larger than 0.5  $\mu\text{m}$  as SB-dominated. We have also included the distribution of the  $L_{\text{PAH}7.7\mu\text{m}}/L_{\text{PAH}11.3\mu\text{m}}$  ratios from the UV/SDSS selected star-forming galaxies sample of SSGSS (O'Dowd et al. 2009). For this last sample, the star-forming galaxies are classified from optical spectroscopy using the BPT diagram method (Baldwin et al. 1981; Kewley et al. 2001). We find that the distribution for SB galaxies in 5MUSES and SSGSS is similar, while both samples appear to have lower  $L_{\text{PAH}7.7\mu\text{m}}/L_{\text{PAH}11.3\mu\text{m}}$  ratios than the nuclear spectra of SINGS SB galaxies. The mean  $\log(L_{\text{PAH}7.7\mu\text{m}}/L_{\text{PAH}11.3\mu\text{m}})$  ratio for SINGS starbursts is  $0.63 \pm 0.06$  while it is  $0.53 \pm 0.08$  for 5MUSES starbursts. This might be a resolution effect: if the physical conditions at the nuclear region of a galaxy indeed modifies the distribution of the  $L_{\text{PAH}7.7\mu\text{m}}/L_{\text{PAH}11.3\mu\text{m}}$  ratios, it might be visible only in the spectra taken through apertures with small projected sizes. The median redshift for the SB-dominated sources in the 5MUSES sample is 0.12, while the median redshift for the SSGSS sample is 0.08. At the redshift of 0.08, 1'' corresponds to 1.53 kpc. The IRS spectra (for SL, the slit width is  $\sim 3''/6$ ) of 5MUSES and SSGSS sources are integrated from the whole galaxy, thus diluting the signature of the nuclear regions. Smith et al. (2007) have shown the changes in the  $L_{\text{PAH}7.7\mu\text{m}}/L_{\text{PAH}11.3\mu\text{m}}$  ratios in spectra extracted from bigger to smaller apertures in two star-forming galaxies: the  $L_{\text{PAH}7.7\mu\text{m}}/L_{\text{PAH}11.3\mu\text{m}}$  ratios measured from *star-forming galaxy* spectra extracted with smaller apertures are higher than those measured from larger apertures, consistent with our results. More recently, Pereira-Santaella et al. (2010) have suggested that the 11.3  $\mu\text{m}$  PAH feature is more extended than the 6.2 or 7.7  $\mu\text{m}$  PAH from a spatially resolved mapping study of local luminous infrared galaxies. They have observed lower  $L_{\text{PAH}6.2\mu\text{m}}/L_{\text{PAH}11.3\mu\text{m}}$  ratios in the nucleus consistent with our results. We also show the distribution of  $L_{\text{PAH}6.2\mu\text{m}}/L_{\text{PAH}7.7\mu\text{m}}$  ratios in Figure 13(b). No significant difference has been observed between the 5MUSES, SINGS, and SSGSS samples.

Finally in Figure 14, we present the variation in PAH band-to-band ratios for the three strongest bands at 6.2, 7.7, and





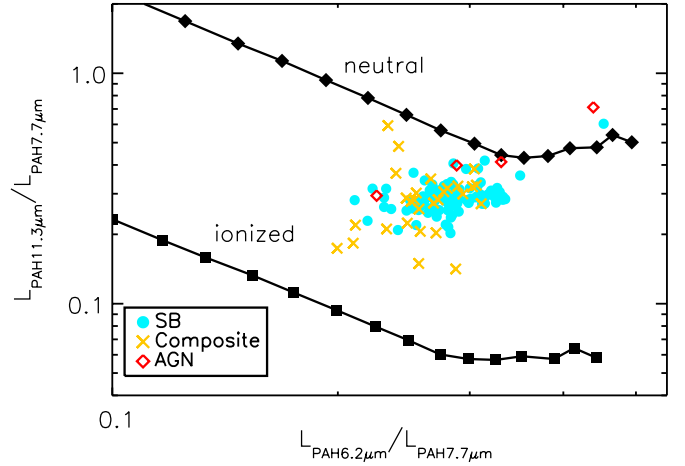
**Figure 13.** (a) Top panel: a comparison of the distribution of PAH luminosity ratio of  $L_{\text{PAH}7.7\mu\text{m}}/L_{\text{PAH}11.3\mu\text{m}}$  for the IR classified SB-dominated sources from 5MUSES, SINGS and the optically classified SF-dominated sources in SSGS. (b) Bottom panel: same as (a), but for the PAH luminosity ratio of  $L_{\text{PAH}6.2\mu\text{m}}/L_{\text{PAH}7.7\mu\text{m}}$ . The SB and SF galaxies in 5MUSES and SSGS appear to have a similar distribution for both the  $L_{\text{PAH}7.7\mu\text{m}}/L_{\text{PAH}11.3\mu\text{m}}$  and  $L_{\text{PAH}6.2\mu\text{m}}/L_{\text{PAH}7.7\mu\text{m}}$  ratios, while the SINGS nuclear spectra appear to show higher  $L_{\text{PAH}7.7\mu\text{m}}/L_{\text{PAH}11.3\mu\text{m}}$  ratios for the SB-dominated galaxies.

(A color version of this figure is available in the online journal.)

11.3  $\mu\text{m}$  of the 5MUSES sample. Only sources with  $S/N > 3$  from PAHFIT measurements for all three PAH bands are included in this figure. The two dark lines represent the traces for fully neutral or fully ionized PAH molecules with different numbers of carbon atoms predicted from modeling work (Draine & Li 2001). The  $L_{\text{PAH}7.7\mu\text{m}}/L_{\text{PAH}11.3\mu\text{m}}$  ratios span a range of a factor of 5 while the  $L_{\text{PAH}6.2\mu\text{m}}/L_{\text{PAH}7.7\mu\text{m}}$  ratios only vary by a factor of 2. The uncertainty in the  $L_{\text{PAH}7.7\mu\text{m}}/L_{\text{PAH}11.3\mu\text{m}}$  ratios is 0.09 dex and it is 0.05 dex for the  $L_{\text{PAH}6.2\mu\text{m}}/L_{\text{PAH}7.7\mu\text{m}}$  ratios. This narrow range of  $L_{\text{PAH}6.2\mu\text{m}}/L_{\text{PAH}7.7\mu\text{m}}$  ratios is consistent with the values for the SINGS nuclear sample (Smith et al. 2007), while we have not observed any sources with extremely low  $L_{\text{PAH}6.2\mu\text{m}}/L_{\text{PAH}7.7\mu\text{m}}$  ratios ( $< 0.2$ ) as has been found in the SSGS sample (O’Dowd et al. 2009).

#### 4.5. PAH Band Ratio versus $[\text{Ne III}]/[\text{Ne II}]$

Because of the large difference in ionization potentials of the  $\text{Ne}^{++}$  (41 eV) and  $\text{Ne}^+$  (21.6 eV) ions, the ratio of  $[\text{Ne III}]/[\text{Ne II}]$  is often used as a tracer of the hardness of the radiation field.

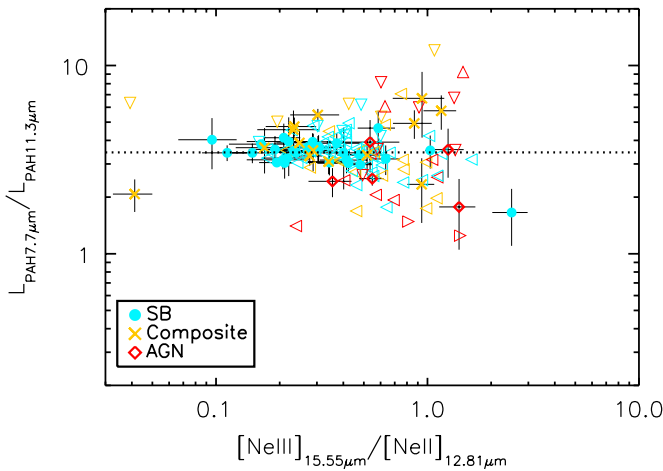


**Figure 14.** PAH band-to-band ratios of  $L_{\text{PAH}11.3\mu\text{m}}/L_{\text{PAH}7.7\mu\text{m}}$  vs.  $L_{\text{PAH}6.2\mu\text{m}}/L_{\text{PAH}7.7\mu\text{m}}$ . The lines represent the expected ratios for neutral (upper line) and ionized (lower line) PAHs from model predictions. Note we have fewer objects in this figure than in Figure 12 because we require the source to have  $S/N > 3$  for all three PAH features (6.2, 7.7, and 11.3  $\mu\text{m}$ ) to be included. (A color version of this figure is available in the online journal.)

The  $[\text{Ne III}]$  15.55  $\mu\text{m}$  and  $[\text{Ne II}]$  12.81  $\mu\text{m}$  lines are among the strongest lines emitted in the mid-IR and because differential extinction effects between their wavelengths are small, they are particularly valuable. We use the IRS low-res spectra to identify and measure these lines.<sup>22</sup> The line fluxes measured from low-resolution spectra have on average an uncertainty of  $\sim 20\%$ .

In Figure 15, we show the flux ratios of  $L_{\text{PAH}7.7\mu\text{m}}/L_{\text{PAH}11.3\mu\text{m}}$  versus  $[\text{Ne III}]/[\text{Ne II}]$ . The solid symbols denote detections while the open triangles represent upper/lower limits. We overplot the median  $L_{\text{PAH}7.7\mu\text{m}}/L_{\text{PAH}11.3\mu\text{m}}$  for SB-dominated sources in 5MUSES as the dotted line. We find that the SB, composite and AGN-dominated sources (including sources with upper/lower limits) are almost evenly distributed on the two sides of the dotted line. However, the AGNs with solid detections on both axes do appear to have lower  $L_{\text{PAH}7.7\mu\text{m}}/L_{\text{PAH}11.3\mu\text{m}}$  ratios in general. As has been discussed in Section 4.4, this is consistent with the studies of Smith et al. (2007) using the SINGS nuclear spectra. We note that the 5MUSES sample does not have sources with extreme  $L_{\text{PAH}7.7\mu\text{m}}/L_{\text{PAH}11.3\mu\text{m}}$  ratios comparable to the lowest ones reached by SINGS. This is probably because the SINGS spectra probe smaller, more central and thus more AGN-dominated regions. It should also be noted that the AGN luminosities in 5MUSES are substantially higher than SINGS. Our results are consistent with O’Dowd et al. (2009), who have studied a UV–SDSS selected sample at  $z \sim 0.1$  and do not observe extreme  $L_{\text{PAH}7.7\mu\text{m}}/L_{\text{PAH}11.3\mu\text{m}}$  ratios either. We also note that the range of  $[\text{Ne III}]/[\text{Ne II}]$  ratios is similar for all three groups of objects that we have classified based on their 6.2  $\mu\text{m}$  PAH EWs. This is consistent with the study of Bernard-Salas et al. (2009), who found no correlation between the PAH EWs and the  $[\text{Ne III}]/[\text{Ne II}]$  ratios in a sample of starburst galaxies. However, in more extreme radiation field conditions, such as low-metallicity environments, PAH EWs have been observed to anti-correlate with the radiation field hardness indicated by  $[\text{Ne III}]/[\text{Ne II}]$  ratios (Wu et al. 2006).

<sup>22</sup> For the 5MUSES sample, only 21 out of 330 sources have IRS high-resolution spectra, which limits our ability to probe the full dynamic range covered by the whole sample. Thus, we use the low-resolution spectra to measure the  $[\text{Ne II}]$  and  $[\text{Ne III}]$  fluxes to compare with the PAH band-to-band ratios.



**Figure 15.** Flux ratios of [Ne III]/[Ne II] vs. the PAH luminosity ratios of  $L_{\text{PAH}7.7 \mu\text{m}}/L_{\text{PAH}11.3 \mu\text{m}}$ . The blue, yellow, and red open triangles represent upper/lower limits for the SB, composite, and AGN in 5MUSES and the directions the triangles face are consistent with the directions of the limits. The dotted line is the median  $L_{\text{PAH}7.7 \mu\text{m}}/L_{\text{PAH}11.3 \mu\text{m}}$  ratio for the SB-dominated sources on this plot.

(A color version of this figure is available in the online journal.)

## 5. CONCLUSIONS

We have studied a flux-limited ( $f_{24 \mu\text{m}} > 5 \text{ mJy}$ ) representative sample of 330 galaxies surveyed with the IRS on board the *Spitzer Space Telescope*. Secure redshifts of 280 objects have been obtained from optical or infrared spectroscopy. The redshifts of the 5MUSES sample ranges from 0.08 to 4.27, with a median value of 0.144. This places the 5MUSES sample at intermediate redshift, which bridges the gap between the nearby bright sources known from previous studies and the  $z \sim 2$  objects pursued in most of the IRS follow-up observations of deep  $24 \mu\text{m}$  surveys. The simple selection criteria ensure that our sample provides a complete census of galaxies with crucial information on understanding the galaxy evolution processes.

Using mid-IR spectroscopy and mid-to-far IR photometry, we have obtained accurate estimates on the total infrared luminosities of 5MUSES galaxies. This is achieved by minimizing the  $\chi^2$  to find the best-fit template from our newly constructed empirical SED library built upon recent *Spitzer* observations. The availability of longer wavelength data also greatly reduces the uncertainties in  $L_{\text{IR}}$ . When only one IRS spectrum is available, one can still predict the shape of the FIR SED from the mid-IR and estimate  $L_{\text{IR}}$ , albeit with substantially larger uncertainties (0.2 dex). The IRS-only method does not introduce a systematic bias when estimating  $L_{\text{IR}}$  for warm sources, but could underestimate the  $L_{\text{IR}}$  by  $\sim 17\%$  for cold sources, due to the lack of information sampling the peak of the SED. The fractional contribution of single-band luminosity to  $L_{\text{IR}}$  varies depending on the dominant energy source and the average values have been calculated for the SB, composite, and AGN-dominated sources, as well as the whole sample.

We analyze the properties of the PAH emission in our sample using the IRS spectra. The PAH EWs show a bimodal distribution, which might be related to the selection effect of the sample. The starburst and AGN-dominated sources form two clumps when comparing the continuum slopes and PAH EWs, while there is little discernible correlation within each group. Average spectra binned with the  $6.2 \mu\text{m}$  PAH EWs, the continuum slopes of  $\log(f_{30}/f_{15})$  and  $\log(f_{70}/f_{24})$  have been derived to show the typical SED shapes. The variation in PAH

EW and  $L_{\text{PAH}}/L_{\text{IR}}$  ratios when galaxy color changes have also been inspected. The galaxy color provides essential constraint on estimating the total infrared luminosity from broadband photometry.

We have also inspected the band-to-band PAH intensity ratios with regard to different spectral types. The  $L_{\text{PAH}7.7 \mu\text{m}}/L_{\text{PAH}11.3 \mu\text{m}}$  ratios in AGN-dominated sources in 5MUSES are on average lower than the SB or composite sources. The SB, composite, and AGN-dominated sources have mean  $\log(L_{\text{PAH}7.7 \mu\text{m}}/L_{\text{PAH}11.3 \mu\text{m}})$  ratios of  $0.53 \pm 0.08$ ,  $0.54 \pm 0.15$  and  $0.32 \pm 0.18$ , respectively. The mean  $\log(L_{\text{PAH}7.7 \mu\text{m}}/L_{\text{PAH}11.3 \mu\text{m}})$  ratio for the SB-dominated sources in 5MUSES is lower than the mean ratio derived from the nuclear spectra of SB galaxies in SINGS ( $0.63 \pm 0.06$ ), which might indicate a difference in the physical conditions near the nucleus versus over the entire galaxy. At the median redshift of our sample, the IRS SL slit width corresponds to a few kpc, thus even if the ionization state or grain size distribution is different at the nuclear level, the signal might get diluted when we study the integrated spectrum and would result in the different  $\log(L_{\text{PAH}7.7 \mu\text{m}}/L_{\text{PAH}11.3 \mu\text{m}})$  ratio distribution.

Finally, we provide our calibration of using PAH luminosity or mid-IR continuum luminosity to estimate  $L_{\text{IR}}$  in the [Appendix](#). We have shown that single-band luminosities trace the  $L_{\text{IR}}$  differently in SB or AGN-dominated sources and we provide calibrations for each object type. This technique will be useful for luminosity estimates when no multi-wavelength data are available.

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## APPENDIX

### ESTIMATING THE TOTAL INFRARED LUMINOSITY FROM PAH OR MONOCHROMATIC CONTINUUM LUMINOSITIES

In Section 3, we have discussed in detail our method to estimate the total infrared luminosities for the 5MUSES sources. The empirical library of SED templates built from *Spitzer* observations, as well as the availability of photometric and spectroscopic data from mid-IR to FIR for 5MUSES, allows us to have precise estimates on their  $L_{\text{IR}}$ . We have shown in Figure 5 the importance of having FIR data in determining the total energy output in the infrared. However, for high redshift galaxies, FIR observations are not always available. *Herschel* Space Observatory will provide FIR measurements from 70 to  $500 \mu\text{m}$  to reveal the properties of cold dust in many systems. For now, we provide our calibration of estimating  $L_{\text{IR}}$  from several bands in the mid-IR and discuss its applications. The following correlations are derived by performing a linear fit to the 5MUSES data with equal weight on each object because the dispersion of the data point in the  $x$ - $y$  plane is larger than the measurement errors.

As has been shown in many studies, the infrared SED of a starburst galaxy is drastically different from that of an AGN (Brandl et al. 2006; Hao et al. 2007; Armus et al. 2007). Because of these substantial variations in the SED shapes, it is crucial to calibrate the luminosity estimates for each spectral type. Here, we provide our luminosity calibrations based on the three spectral types: starburst, composite, and AGN. The following PAH luminosities are derived from the PAHFIT method.

1. 6.2  $\mu\text{m}$  PAH: with a wavelength cut at 28  $\mu\text{m}$  for the *James Webb Space Telescope (JWST)*, the 6.2  $\mu\text{m}$  PAH feature might be the only PAH band that could be observed to quantify star formation activities in  $z \sim 3$  sources when *JWST* is launched.

For SB sources:

$$\log L_{\text{IR}} = (2.40 \pm 0.22) + (0.96 \pm 0.03) \log L_{\text{PAH}6.2 \mu\text{m}}. \quad (\text{A1})$$

For composite sources:

$$\log L_{\text{IR}} = (1.76 \pm 0.32) + (1.04 \pm 0.04) \log L_{\text{PAH}6.2 \mu\text{m}}. \quad (\text{A2})$$

For AGN sources:

$$\log L_{\text{IR}} = (-0.58 \pm 0.58) + (1.30 \pm 0.06) \log L_{\text{PAH}6.2 \mu\text{m}}. \quad (\text{A3})$$

2. 7.7  $\mu\text{m}$  PAH: the 7.7  $\mu\text{m}$  PAH complex is the strongest band among the various PAH features. It is often used to estimate the total infrared luminosities for the  $z \sim 1-2$  sources pursued in IRS observations of 24  $\mu\text{m}$  selected sources.

For SB sources:

$$\log L_{\text{IR}} = (2.30 \pm 0.26) + (0.91 \pm 0.003) \log L_{\text{PAH}7.7 \mu\text{m}}. \quad (\text{A4})$$

For composite sources:

$$\log L_{\text{IR}} = (1.80 \pm 0.44) + (0.98 \pm 0.05) \log L_{\text{PAH}7.7 \mu\text{m}}. \quad (\text{A5})$$

For AGN sources:

$$\log L_{\text{IR}} = (3.45 \pm 0.90) + (0.83 \pm 0.09) \log L_{\text{PAH}7.7 \mu\text{m}}. \quad (\text{A6})$$

3. 11.3  $\mu\text{m}$  PAH: the 11.3  $\mu\text{m}$  band is another strong PAH band in the mid-IR that is relatively isolated from other PAH bands. However, the integrated fluxes from this band might be affected by the 9.7  $\mu\text{m}$  silicate feature.

For SB sources:

$$\log L_{\text{IR}} = (2.18 \pm 0.22) + (0.98 \pm 0.03) \log L_{\text{PAH}11.3 \mu\text{m}}. \quad (\text{A7})$$

For composite sources:

$$\log L_{\text{IR}} = (1.49 \pm 0.43) + (1.07 \pm 0.05) \log L_{\text{PAH}11.3 \mu\text{m}}. \quad (\text{A8})$$

For AGN sources:

$$\log L_{\text{IR}} = (2.22 \pm 0.36) + (1.00 \pm 0.04) \log L_{\text{PAH}11.3 \mu\text{m}}. \quad (\text{A9})$$

4. 6.2+7.7+11.3  $\mu\text{m}$  PAH: in normal star-forming galaxies, the PAH emission accounts for  $\sim 10\%$ – $15\%$  of the total infrared luminosities (Smith et al. 2007), while this fraction is smaller for local ULIRGs (Armus et al. 2007). Here we use the sum of the three strongest PAH bands, the 6.2, 7.7, and 11.3  $\mu\text{m}$  PAH luminosities to represent the total PAH luminosities. However, when using the correlation

provided here, one needs to keep in mind that the properties of PAHs studied in the local universe might be different at high  $z$ , as has already been revealed in the study of several  $z \sim 2$  luminous infrared galaxies (Sajina et al. 2007; Pope et al. 2008). Understanding the PAH contribution in our intermediate-redshift sample would also be instrumental for tackling the problem of whether and how PAH emission evolves with redshift in future studies.

For SB sources:

$$\log L_{\text{IR}} = (1.82 \pm 0.25) + (0.95 \pm 0.03) \times \log L_{\text{PAH}6.2+7.7+11.3 \mu\text{m}}. \quad (\text{A10})$$

For composite sources:

$$\log L_{\text{IR}} = (0.73 \pm 0.36) + (1.06 \pm 0.04) \times \log L_{\text{PAH}6.2+7.7+11.3 \mu\text{m}}. \quad (\text{A11})$$

For AGN sources:

$$\log L_{\text{IR}} = (-2.13 \pm 1.01) + (1.35 \pm 0.10) \times \log L_{\text{PAH}6.2+7.7+11.3 \mu\text{m}}. \quad (\text{A12})$$

5. 5.8  $\mu\text{m}$  monochromatic continuum luminosity: the 5.8  $\mu\text{m}$  continuum luminosity provides a crude estimate of  $L_{\text{IR}}$ . In AGN-dominated sources, the 5.8  $\mu\text{m}$  continuum will be elevated due to the presence of very hot dust component. This is also a band that is available for most of the high-redshift samples observed by *Spitzer*, and for *JWST* when it is launched.

For SB sources:

$$\log L_{\text{IR}} = (1.94 \pm 0.25) + (0.95 \pm 0.03) \log L_{5.8 \mu\text{m}}. \quad (\text{A13})$$

For composite sources:

$$\log L_{\text{IR}} = (2.68 \pm 0.45) + (0.87 \pm 0.05) \log L_{5.8 \mu\text{m}}. \quad (\text{A14})$$

For AGN sources:

$$\log L_{\text{IR}} = (2.34 \pm 0.29) + (0.85 \pm 0.03) \log L_{5.8 \mu\text{m}}. \quad (\text{A15})$$

6. IRAC 8  $\mu\text{m}$ : the rest-frame IRAC 8.0  $\mu\text{m}$  band has included both dust continuum emission and PAH emission from the 7.7, 8.3, and 8.6  $\mu\text{m}$  PAH band (if present). It provides a useful channel for estimating  $L_{\text{IR}}$  from PAH features when no spectroscopy is available.

For SB sources:

$$\log L_{\text{IR}} = (1.60 \pm 0.21) + (0.93 \pm 0.02) \log L_{\text{IRAC}8 \mu\text{m}}. \quad (\text{A16})$$

For composite sources:

$$\log L_{\text{IR}} = (1.45 \pm 0.26) + (0.95 \pm 0.03) \log L_{\text{IRAC}8 \mu\text{m}}. \quad (\text{A17})$$

For AGN sources:

$$\log L_{\text{IR}} = (1.70 \pm 0.26) + (0.90 \pm 0.02) \log L_{\text{IRAC}8 \mu\text{m}}. \quad (\text{A18})$$

7. 14  $\mu\text{m}$  monochromatic continuum luminosity: the 14  $\mu\text{m}$  is an important band in the mid-IR that is still sensitive to the AGN emission.

For SB sources:

$$\log L_{\text{IR}} = (1.44 \pm 0.16) + (0.97 \pm 0.02) \log L_{14 \mu\text{m}}. \quad (\text{A19})$$

For composite sources:

$$\log L_{\text{IR}} = (1.76 \pm 0.37) + (0.93 \pm 0.04) \log L_{14 \mu\text{m}}. \quad (\text{A20})$$

For AGN sources:

$$\log L_{\text{IR}} = (1.62 \pm 0.29) + (0.90 \pm 0.03) \log L_{14 \mu\text{m}}. \quad (\text{A21})$$

8.  $24 \mu\text{m}$  monochromatic continuum luminosity: here, we refer to the  $24 \mu\text{m}$  continuum luminosity averaged in  $1 \mu\text{m}$  range, instead of the rest-frame MIPS  $24 \mu\text{m}$  band. This is because if we use the MIPS  $24 \mu\text{m}$  band, sources at  $z > \sim 0.3$  will be eliminated from this study due to the limited wavelength coverage of its rest-frame mid-IR spectra. The sources we use in the calibration mostly have  $10^{10} L_{\odot} < L_{\text{IR}} < 10^{12} L_{\odot}$  and no quasars have been included in this calibration because of the wavelength cut. Since our sample is selected at  $24 \mu\text{m}$ , it tends to favor warmer sources, which also needs to be kept in mind when using these relations.

For SB sources:

$$\log L_{\text{IR}} = (1.56 \pm 0.23) + (0.93 \pm 0.02) \log L_{24 \mu\text{m}}. \quad (\text{A22})$$

For composite sources:

$$\log L_{\text{IR}} = (1.64 \pm 0.44) + (0.91 \pm 0.04) \log L_{24 \mu\text{m}}. \quad (\text{A23})$$

For AGN sources:

$$\log L_{\text{IR}} = (1.67 \pm 0.47) + (0.89 \pm 0.05) \log L_{24 \mu\text{m}}. \quad (\text{A24})$$

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