DUST PROPERTIES AND STAR FORMATION RATES IN STAR-FORMING DWARF GALAXIES

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Received 2007 May 23; accepted 2007 October 28

ABSTRACT

We have used the Spitzer Space Telescope to study the dust properties of a sample of star-forming dwarf galaxies. The differences in the mid-infrared spectral energy distributions for these galaxies, which, in general, are low-metallicity systems, indicate differences in the physical properties, heating, and/or distribution of the dust. Specifically, these galaxies have more hot dust and/or very small grains and less PAH emission than either spiral or higher luminosity starburst galaxies. As has been shown in previous studies, there is a gradual decrease in PAH emission as a function of metallicity. Because much of the energy from star formation in galaxies is reradiated in the mid-infrared, star formation rate indicators based on both line and continuum measurements in this wavelength range are coming into more common usage. We show that the variations in the interstellar medium properties of galaxies in our sample, as measured in the mid-infrared, result in over an order of magnitude spread in the computed star formation rates.

Subject headings: dust, extinction — galaxies: abundances — galaxies: dwarf — galaxies: starburst — infrared: galaxies

Online material: color figures

1. INTRODUCTION

Mid-infrared (MIR) observations probe the dusty interstellar medium and dust-enshrouded star formation in galaxies. The spectral energy distribution (SED) in this region is shaped by this star formation, but it can also be affected by the presence (or lack) of dust grains of varying size, differences in metallicity, and radiation from an older population of stars (Li & Draine 2002). One of the first studies of the MIR spectra of a large sample of galaxies, including the low-metallicity system II Zw 40, was performed by Roche et al. (1991). More recent observations have been used to understand how these different properties affect a galaxy’s SED. With the advent of the Spitzer Space Telescope and the Infrared Space Observatory, the facilities are now available to make deep observations in the MIR. These data are being used to study the interstellar medium and to measure the star formation rate (SFR) in galaxies in both the nearby and distant universe.

Some detailed, broadband, MIR observations of low-metallicity galaxies have shown that these systems display a wide range of colors, which implies a wide range of interstellar medium properties (Rosenberg et al. 2006; Engelbracht et al. 2005; Hogg et al. 2005). A more detailed examination of the dust properties of low-metallicity galaxies has been performed for some of the best-known low-metallicity galaxies using infrared spectroscopy (Wu et al. 2006, 2007; Houck et al. 2004b; Hunt et al. 2005, 2006; Madden et al. 2006). These observations have provided evidence that there is a relationship between how much polycyclic aromatic hydrocarbon (PAH) emission is detectable in these systems and their metallicity. In the two lowest metallicity galaxies known, I Zw 18 and SBS 0335–052, no PAH emission is detected even in deep observations (Wu et al. 2007; Houck et al. 2004b; Thuan et al. 1999). Several models for the decrease in PAH emission...
with metallicity have been proposed, including destruction of PAH molecules by the hard radiation field in low-metallicity systems because the dust opacity is low in these environments (Galliano et al. 2005; Madden et al. 2006), destruction in the shocks created by supernova blast waves (O’Halloran et al. 2006), and an intrinsic lack of PAH molecules in young systems because the PAHs are produced in low-mass stars that have not yet evolved (Dwek 2005; Galliano et al. 2008).

Using the measured MIR properties of galaxies to determine their SFRs requires an understanding of the properties that affect the heating of the dust responsible for the MIR emission. At high redshift, in particular, the effect of metallicity on MIR emission may become more significant if a larger fraction of the galaxy population consists of low-metallicity systems. The relationships between MIR flux density and SFR may not be the same as those for the more luminous and metal-rich systems for which the relationships were determined (e.g., Rosenberg et al. 2006; Wu et al. 2006; Engelbracht et al. 2005). Emission from very small grains and warmer dust is seen in low-metallicity galaxies, but much less emission from PAH molecules is detected relative to spiral and higher luminosity starburst galaxies (Madden & Galliano 2005; Hunt et al. 2005). For example, in the Small Magellanic Cloud, where the metallicity is low, the dust properties, absorption, and emissivity are significantly different from what is seen in the Milky Way, indicating that metal-rich galaxies are not a proxy for their lower metallicity counterparts (Li et al. 2006).

The star-forming dwarf galaxies that are discussed here have been studied previously in the Spitzer Infrared Array Camera (IRAC) bands and have been found to have a wide range in MIR colors (Rosenberg et al. 2006). Here we look in greater detail at the SEDs for these systems, as well as the relationship between dust properties and metallicity, and the measurements of star formation in the MIR and ultraviolet (UV). The data are presented in § 2. A detailed look at flux density ratios and the MIR SEDs of these galaxies are examined in § 3 to answer the question, as best as the data will allow, do these galaxies exhibit PAH emission? The measured SFRs determined from the optical, MIR, and UV data are discussed and compared in § 4, and the results are summarized in § 5.

2. DATA

2.1. Sample Selection and Optical Data

The galaxies in this study are low-luminosity star-forming galaxies selected from the KPNO International Spectroscopic Survey (KISS) in the Boötes field. These systems have been observed both as a part of the KISS survey and by several other surveys at optical, infrared, and UV wavelengths, including the NOAO Deep Wide-Field Survey (NDWFS; Jannuzi & Dey 1999; R. T. Jannuzi et al. 2008, in preparation), the Spitzer IRAC Shallow Survey (Eisenhardt et al. 2004), and a shallow Spitzer MIPS survey. Rosenberg et al. (2006) provides a discussion of the Spitzer IRAC Shallow Survey data for these objects.

KISS is a modern objective-prism survey. It combines the methodology of many of the classic wide-field color- and line-selected surveys, e.g., Markarian (1967), Smith et al. (1976), MacAlpine et al. (1977), Wasilewski (1983), and Zamorano et al. (1994), with the higher sensitivity of a CCD detector. The survey method is described in detail by Salzer et al. (2000). KISS selects objects for inclusion in the survey lists if they possess a strong (>5 σ) emission line in their low-dispersion objective-prism spectra. The survey has been carried out in two distinct spectral regions: the blue portion (4800–5500 Å), where the primary line observed is [O III] λ5007, and the red region (6400–7200 Å), where galaxies are selected by their Hα emission. The current sample of galaxies were chosen from the Jangren et al. (2005, hereafter KR3) list of Hα emission-line galaxy (ELG) candidates. The objective-prism passband imposes a redshift limit on the sample of z < 0.095. The selection criteria used to define the sample were that the galaxies exhibit spectra consistent with heating by star formation processes (i.e., AGNs were excluded) and that they have a B-band absolute magnitude $M_B > -18.0$ (for $H_0 = 75$ km s$^{-1}$ Mpc$^{-1}$, although four are slightly brighter than this limit when they are corrected for extinction). Thus, these galaxies are selected to be star-forming dwarf galaxies.

These criteria produced a list of 26 galaxies within the NDWFS Boötes area. However, of these 26 galaxies, only 19 overlap with the Spitzer Shallow Survey area, because the Spitzer survey field is smaller than the NDWFS field. We discuss only these 19 galaxies in our analysis. Many of these galaxies also turn out to be low metallicity; the median metallicity of the sample is $\log [O/H] + 12 = 8.17 (0.32 Z_\odot)$. With the exception of one supersolar and one slightly sub solar galaxy, they are all significantly sub solar ($< 0.6 Z_\odot$; see Rosenberg et al. 2006 for sample details).

All of the KISS ELG candidates in the Boötes field possess higher dispersion follow-up slit spectra (Salzer et al. 2005) that have been used to verify the reality of the putative emission lines seen in the objective-prism spectra, calculate accurate redshifts, and distinguish between the various activity types that might be present in a line-selected sample (e.g., star-forming galaxies vs. AGNs). These follow-up spectra provide us with a great deal of useful information (e.g., accurate redshifts, emission-line fluxes and line ratios, reddening and metallicity estimates). The combination of the accurate $B$ and $V$ photometry from the original survey lists with these follow-up spectra allow for the construction of a fairly complete picture of the properties of the KISS ELGs.

Table 1 contains some of the optical parameters for the galaxies in this sample. More details about the KISS data and parameters can be obtained from KR3.

2.2. Spitzer Multiband Imaging Photometer Data

The far-IR observations of the Boötes field were performed using the “medium scan” mode of the MIPS instrument (Rieke et al. 2004) on board the Spitzer Space Telescope. This mode allows for efficient coverage of large areas of sky with simultaneous observations at 24, 70, and 160 μm. The MIPS detector at 24 μm is characterized by a resolution of 2.45′′ pixel$^{-1}$ on an array of 128 × 128 elements, the 70 μm detector has a resolution of 9.98′′ pixel$^{-1}$ on an array of 32 × 16 elements, and at 160 μm, the effective array operates with two rows of 20 16′′ × 18′′ pixels separated by one row of nonfunctional pixels. The point-spread function (PSF) in the MIPS images is characterized by a full width at half-maximum (FWHM) of 6′′, 18′′, and 40′′ at 24, 70, and 160 μm, respectively. Data were reduced using the MIPS Data Analysis Tool (Gordon et al. 2005). The astrometry of the final mosaic was calibrated against 2MASS (Jarrett et al. 2000) and is accurate to 0.3′′ rms. The effective integration time per sky pixel was ~90, ~40, and ~8 at 24, 70, and 160 μm, respectively.

At 24 μm 18 of the 19 galaxies were detected, while 11 galaxies were detected at 70 μm, and only 3 were detected at 160 μm. Photometry was performed with PSF fitting using the IRAF DAOPHOT software (Stetson 1987). At each wavelength an empirical PSF was constructed from the brightest objects found in
the mosaic. The flux density of each source was derived from the
scaled, fitted PSF plus a slight correction to account for the finite
size of the modeled PSF. For the cases where residual emission
was found in the 24 μm image after the PSF subtraction, aperture
photometry was performed within a region large enough to ac-
tcount for the extended emission of the object. Only five sources
show extended emission at 24 μm, and all of the targets appear
resolved at 70 and 160 μm. For the nondetections at 70 and
160 μm, we adopted an upper limit based on the noise. This
noise was derived as the dispersion of the flux measured within fixed-
diameter apertures randomly placed over blank sky regions of
the image. The flux densities for all of the sources are presented
in Table 2.

2.3. Spitzer 16 μm Imaging

The galaxies in this sample were all imaged at 16 μm with the
blue peak-up camera on the Spitzer Infrared Spectrograph (IRS;5

5 The IRS was a collaborative venture between Cornell University and Ball
Aerospace Corporation, funded by NASA through the Jet Propulsion Labora-
tory and the Ames Research Center.

| KISSR | f16 (mJy) | σ16 (mJy) | f24 (mJy) | σ24 (mJy) | f70 (mJy) | σ70 (mJy) | f160 (mJy) | σ160 (mJy) | fFUV (μJy) | σFUV (μJy) |
|-------|-----------|------------|-----------|-----------|-----------|-----------|------------|-----------|-----------|-----------|
| 2292  | 1.27      | 0.08       | 2.35      | 0.07      | ...       | ...       | <120       | ...       | 74.98     | 0.69      |
| 2300  | 0.77      | 0.05       | 1.72      | 0.05      | <15       | ...       | <120       | ...       | 31.26     | 0.50      |
| 2302  | <0.1      | ...        | <0.24     | ...       | <15       | ...       | <120       | ...       | 92.42     | 0.84      |
| 2309  | 0.32      | 0.02       | 0.92      | 0.06      | <15       | ...       | <120       | ...       | 111.00    | 0.88      |
| 2316  | 3.39      | 0.20       | 4.09      | 0.10      | 52        | 4         | 150        | 33        | 19.40     | 0.33      |
| 2318  | 1.17      | 0.07       | 2.06      | 0.05      | 15        | 4         | <120       | ...       | 7.96      | 0.29      |
| 2322  | 0.49      | 0.03       | 0.82      | 0.08      | <15       | ...       | <100       | ...       | 154.30    | 1.31      |
| 2326  | 1.43      | 0.08       | 3.77      | 0.05      | 29        | 3         | <100       | ...       | 117.80    | 0.80      |
| 2338  | 2.85      | 0.17       | 6.56      | 0.09      | 25        | 5         | <100       | ...       | 49.46     | 0.55      |
| 2344  | 1.41      | 0.08       | 3.73      | 0.03      | 71        | 6         | 210        | 33        | 581.44    | 2.04      |
| 2346  | 0.98      | 0.06       | 2.20      | 0.04      | <15       | ...       | <120       | ...       | 27.23     | 0.54      |
| 2349  | 10.72     | 0.64       | 26.20     | 0.09      | 154       | 7         | 190        | 33        | 276.85    | 1.53      |
| 2357  | <0.3      | ...        | <0.38     | 0.06      | <15       | ...       | <120       | ...       | 75.33     | 0.95      |
| 2359  | 0.94      | 0.05       | 2.30      | 0.07      | 20        | 4         | <100       | ...       | 11.87     | 0.31      |
| 2368  | 4.34      | 0.26       | 7.51      | 0.08      | 30        | 10        | <120       | ...       | 113.90    | 1.24      |
| 2382  | 0.81      | 0.05       | 1.00      | 0.07      | 34        | 7         | <120       | ...       | 242.74    | 1.40      |
| 2398  | 0.74      | 0.04       | 1.05      | 0.05      | 20        | 3         | <120       | ...       | 128.21    | 0.36      |
| 2403  | <0.2      | ...        | 0.47      | 0.04      | <15       | ...       | <120       | ...       | 21.20     | 0.47      |
| 2406  | 1.00      | 0.06       | 2.09      | 0.08      | 27        | 6         | <120       | ...       | 164.71    | 0.44      |
Houck et al. 2004a; Werner et al. 2004). The targets were observed as part of the IRS guaranteed time observing program on 2006 January 18 and 19. The 19 galaxies were observed with a five-position random dither pattern in order to oversample the PSF on the 1.8′′ × 1.8′′ pixels of the IRS Short-Low Si:As detector. The observing time was 30 s per position, for a total onsource integration time per target of 157 s.

The data were processed by the Spitzer Science Center pipeline (ver. 13.2). The two-dimensional images were converted from slopes after linearization correction, subtraction of darks, and cosmic-ray removal. The resulting images were divided by the photometric flat, and a world coordinate system was determined using the reconstructed pointing of the telescope. Final rectified, shifted, co-added image mosaics were produced by the pipeline. The astrometric accuracy of our images is better than 2″, and the FWHM of the PSF is 3.5″.

Photometry was performed using fixed apertures of 3 pixels in radius. The flux conversion factor was 0.01375 MJy sr⁻¹ (e⁻ s⁻¹)⁻¹, and the aperture loss correction factor used was 1.38, as described in version 2.0 of the IRS Data Handbook. Our photometric uncertainties are less than ~6% based on the uncertainty in the photometric calibrators that were used. Ultimately, 16 of the 19 sources were detected in these images. The flux densities for all of the galaxies are presented in Table 2.

### 2.4. Spitzer IRAC Data

The majority of the NOAO Deep Wide Field in Boötes was mapped in the 3.6, 4.5, 5.7, and 8.0 μm bands in 2004 January (Eisenhardt et al. 2004) using IRAC aboard Spitzer. The IRAC coverage of 8.5 deg² was reached by tiling the 5′ × 5′ field of view over the region. Each position in the survey field was observed with three 30 s IRAC frames, resulting in a depth of 19.1, 18.3, 15.9, and 15.2 Vega magnitudes (5 σ) at 3.6, 4.5, 5.8, and 8.0 μm, respectively. A full discussion of the data and the reduction procedures is presented by Rosenberg et al. (2006). All 19 galaxies were detected in all four bands.

### 2.5. Galaxy Evolution Explorer Data

Archival UV imaging for all of the galaxies in this sample was available from the Galaxy Evolution Explorer (GALEX; Martin et al. 2005). These images were taken as a part of the Deep Imaging Survey and span a wide range in exposure time. For all of the systems, near-UV (NUV) images in the 1750–2800 Å band are available, and for a small subset (six) of the objects, far-UV (FUV) imaging in the 1350–1750 Å band is available. The data have been processed through the standard GALEX reduction pipeline, producing photometric images with an angular resolution of 5.6″ (FWHM) in the NUV and 4″ (FWHM) in the FUV.

Photometry was performed on the archival images using the e11apse task in the STSDAS module to IRAF. The regions around the galaxies were first masked to exclude the flux from neighboring sources. Most of the galaxies were then fit with circular apertures (for the three distinctly elliptical galaxies, KISSR 2302, 2357, and 2359, elliptical apertures were used to minimize the noise). In order to calculate the total UV counts for the galaxy, the size of the apertures was allowed to grow until the background was reached as determined by the curve of growth of the flux. The counts in each aperture were converted to fluxes using the GALEX calibration values⁷ (Morrissey et al. 2005). The results are presented in Table 2.

### 3. DUST DIAGNOSTICS

#### 3.1. Mid-Infrared Emission from Star-Forming Dwarf Galaxies

The existence of PAH emission from dwarf and low-metallicity galaxies has been discussed by several different groups (e.g., Wu et al. 2006; Rosenberg et al. 2006; Engelbracht et al. 2005; Madden et al. 2006; Hunt et al. 2005; Madden 2000). This subject is of increasing interest because these molecules provide a probe of the star formation environment and, therefore, can be used as a measure of the SFR in galaxies. Rosenberg et al. (2006) showed that the [3.6] – [8.0] colors of these galaxies span the full range of late-type galaxy colors. The presence of some star-forming dwarfs with very red infrared colors indicates that even some metal-poor dwarf galaxies which have low line-of-sight internal reddening, as measured by the eHα parameter, have a significant amount of dust. Nevertheless, the only way to definitively determine whether a galaxy exhibits PAH emission is through infrared spectroscopy, but only a small number of sources are bright enough to be measured in this way.

To assess the degree to which PAH emission is present in the galaxies in this sample, information from broadband flux ratios was combined with an examination of the galaxies’ SEDs (a description of the SED fitting procedures is presented in Appendix A). The fitting process provides a comparison of the rough shape of the SED measured from the broadband data with a set of galaxy templates. The relevant pieces of information are given in Table 3. The general trends in the data are presented here, while a detailed description of the results for each galaxy in the sample is included in Appendix B. The template-fitting approach used here is not ideal, because it does not provide a physical measurement of the stars, dust, and PAHs and because the templates are not derived from low-metallicity galaxies. As has been shown by Marshall et al. (2007) and Galliano et al. (2008), a proper analysis of the dust, PAH emission, and stellar starburst component is not possible using only the IRAC and MIPS photometric points, even in “simple” star-forming galaxies, because of the degeneracy in these components’ contributions to the near-/mid-IR spectrum of the galaxy. As a result, these templates provide only a general guide to the properties of the galaxies and are used to answer two basic questions: (1) are the SEDs of dwarf starbursts similar to those of “normal” and starburst galaxies, and (2) do dwarf starbursts have “detectable” PAH emission?

Figures 1–6 provide diagnostics of the PAH and dust emission properties of galaxies. The model template fits to the galaxy SEDs (which were not fit at the 5.8 and 8.0 μm points, where PAH emission has the largest impact) are shown in Figures 1–3. The galaxies that have significant PAH emission (Fig. 1) either exceed the models at 8 μm or have 8 μm fluxes that are within 3 σ of the models. Alternatively, all of the galaxies without PAH emission either have large reduced χ² for the template fits (the lowest χ²red = 9.8) or the templates exceed the data by at least 3 σ at 8 μm. All of the other galaxies fall between these two criteria and are listed as having questionable PAH emission, which probably means that they have a low level of PAH emission. However, a definitive and/or quantitative assessment of the PAH emission from this intermediate category cannot be made without spectroscopy. Note that there are also three galaxies for...
The 8 μm flux of the best-fit template SED.

b The 8 μm flux measured for the galaxy.

c The difference between the model and the galaxy 8 μm flux.

d The error in the measured 8 μm flux.

The number of σ difference between the model and the data at 8 μm.

The reduced χ² of the fit between the data and the template SED.

The 8 μm–to–24 μm flux ratio.

The 8 μm–to–16 μm flux ratio.

The fraction of the infrared emission coming from regions with U > 10^2 in the Draine & Li (2007) models.

The assessment of whether the galaxy has significant PAH emission.

which SEDs are not plotted because the long-wavelength data necessary to constrain the fits do not exist.

Figure 4 shows the relationship between the quality of the fit to the SED template and the 8 μm–to–8 μm continuum ratio. The fit is worse for large values of log(σχ²). The ratio of 8 μm emission to the 8 μm continuum provides an alternate method for determining the existence of PAH emission. Those galaxies that have detectable PAH emission have a flux ratio that is larger than 1. This method of separating the galaxies is in agreement with the examination of the SEDs and would place KISSR 2359 in the PAH detections category and KISSR 2309 in the nondetections category.

Figure 5 shows the relationship between ratios of the 8 μm emission and the dust continuum at shorter and longer wavelengths. The division of galaxies into systems that exhibit PAH emission and those that do not based on the relationship between the 8 μm fluxes and the models as discussed above agrees well with the divisions established by Engelbracht et al. (2005) based on the relationship between the 8 μm emission and the dust continuum. The 8 μm excess above the dust continuum for galaxies with PAH emission is reflected in the flux density ratio, f(8.0)/f(24) > 0.3. The galaxies for which the SEDs do not definitively determine the nature of the PAH emission populace both the “PAH” and “no-PAH” regions of the plot. KISSR 2292, 2318, and 2322 look like galaxies with PAH emission using this measure, while KISSR 2309 looks like a galaxy without PAH emission, and KISSR 2359 is on the boundary between the two regions.

Figure 6 shows how the ratio between the 8 μm emission and the hot dust continuum is related to the slope of the hot dust continuum. The 8 μm flux has been stellar-subtracted assuming f_e(8.0) = 0.232f_e(3.6) (Helou et al. 2004; the correction at 8 μm is very small and the stellar contribution at 16 and 24 μm is ignored because it is negligible). The blackbody that was fit to the galaxy SED (see Appendix A for details) is not used for this subtraction because the templates also include some stellar light, so this extrapolation from the 3.6 μm flux is more appropriate. In general, the galaxies that do not exhibit PAH emission have small values for both of these ratios, f_e(8.0)/f_e(24) < 0.2 and f_e(8.0)/f_e(16) < 0.3, while all of the galaxies that exhibit PAH emission have f_e(8.0)/f_e(16) > 0.9. The galaxies for which the SED fitting was not able to distinguish between PAH and no-PAH emission fall between these two groups in their f_e(8.0)/f_e(16) ratio, and all fall below the starburst galaxy model curves. The PAH and no-PAH galaxies are better separated in this plot than they are with the other MIR flux ratios. In particular, the galaxies are well separated using the f_e(8.0)/f_e(16) ratio.

For a small number of these galaxies, 70 and 160 μm data exist, and the models described in Draine & Li (2007) can be used to investigate a possible explanation for the differences between the SEDs of these galaxies and those of the templates. These models include PAH material in addition to dust, which consists of a mixture of carbonaceous and amorphous silicate grains that have sizes consistent with the observed wavelength-dependent extinction in the Milky Way while allowing the PAH abundance and the radiation field to vary. While the smaller number of data points inserted into the model should caution against overinterpretation of the results, they do allow for comparison of a few of our dwarfs with some more “normal” galaxies. This comparison provides at least one explanation of the differences we see between our galaxies.
and the model templates. The parameters we derive from the model include \( q_{\text{PAH}} \), the fractional contribution of PAHs to the dust; a parameterization of the heating of the dust by starlight in the intensity range between \( U_{\min} \) and \( U_{\max} \), given by

\[
\frac{dM_{\text{dust}}}{dU} = (1 - \gamma)M_{\text{dust}}(U - U_{\min})^\alpha + \gamma M_{\text{dust}} \left( \frac{(U_{\max}^{1 - \alpha}) - (U_{\min}^{1 - \alpha})}{U_{\max}^{1 - \alpha} - U_{\min}^{1 - \alpha}} \right) U^{-\alpha};
\]

and \( f_{\text{PDR}} \), the fraction of the IR luminosity that is radiated in regions where \( U > 10^2 \). We follow the prescription in Draine & Li (2007) for estimating these quantities for the galaxies possessing enough data. For the galaxies without 160 \( \mu \)m detections we use the 3 \( \sigma \) value as an upper limit and obtain a lower limit by assuming that between 70 and 160 \( \mu \)m the galaxy’s SED is Rayleigh-Jeans, which defines \( F_{70}/F_{160} = 11.94 \).

For KISSR 2316 and 2344, which both have PAH emission, \( U_{\min} \sim 2 \), \( q_{\text{PAH}} = 3.2\% \) and 1.8\%, \( \gamma \sim 0.01 \) and 0.001, and

![Figure 1](https://example.com/figure1.png)

**Fig. 1.**—SEDs for the sample galaxies that show evidence for PAH emission. The circles represent the observations. The dashed line shows the best-fit blackbody representing the stellar component of the model. The dotted line shows the best-fit dust template from the Lagache et al. (2003; T1) and Dale & Helou (2002; T2) models. The solid line is the sum of the stellar and dust fits to the data. The value of T1 (Lagache templates) or T2 (Dale templates) in the legends refers to the best-fit template; it is a measurement of the shape of the spectrum, not of the infrared luminosity, as it is not dependent on the luminosity scaling. The dust templates are only fit longward of 8.0 \( \mu \)m (i.e., not including the 5.8 and 8.0 \( \mu \)m points). The reduced \( \chi^2 \) values for the fits are given in the legends. [See the electronic edition of the Journal for a color version of this figure.]
$f_{\text{PDR}} = 7.6\%$ and $3.8\%$, respectively. For several other PAH-emitting galaxies with limits on the 160 $\mu$m flux, the range of $f_{\text{PDR}}$ can be computed. For KISSR 2406, $f_{\text{PDR}} = 5.8\%$–6.9\%, while for KISSR 2382 and 2398 the fraction is below the plot/fit range. Only a small fraction of the dust emission in galaxies that exhibit clear PAH emission comes from high stellar intensity regions, according to these models. The Draine & Li (2007) dust diagnostics for KISSR 2349, which does not show PAH emission, indicate that $U_{\text{min}} \sim 5$, $q_{\text{PAH}} = 1.12\%$, $\gamma \sim 0.09$, and $f_{\text{PDR}} = 40\%$. For galaxies for which we only have 160 $\mu$m limits, KISSR 2326, 2338, and 2368, $f_{\text{PDR}} = 15\%$–20\%, 31\%–35\%, and 30\%–34\%, respectively. The value of $f_{\text{PDR}}$ derived for these dwarf galaxies is much higher than the values for the galaxies examined by Draine & Li (2007). This difference in $f_{\text{PDR}}$ may indicate that these galaxies are experiencing the destruction of PAHs in the photodissociation regions. These galaxies, which do not show PAH emission, have model parameters indicating a stronger radiation field and more of the IR luminosity originating
in high-intensity regions where it is more difficult for the PAHs to survive.

Why is the shape of high infrared luminosity templates of normal metallicity galaxies more consistent with the observed SED of these low-luminosity, low-metallicity dwarf galaxies (specifically, KISSR 2338, 2349, and 2368)? One of the primary reasons that the high-luminosity templates fit these objects better is that they peak at shorter wavelengths and, in general, have a steeper (redder) spectral slope in the 8–70 μm range, which is also observed in these dwarfs. In addition, the fits may be thrown off by minimal or absent PAH emission, since all of the templates include the PAH features. This also explains why the fits to PAH-deficient sources are poor. A more physical reason for the poor fits may be that for these compact galaxies the specific SFRs (normalized) by mass are high, so, like in the ultraluminous infrared galaxies (ULIRGs), more of the PAHs...
are being destroyed in high-intensity radiation. In particular, it may be that the area outside of the star formation region, where most of the PAH emission originates, is smaller in the galaxies that lack PAH emission because the H ii regions are beginning to overlap.

3.2. How Do Dust Properties Relate to Metallicity?

Metallicity is a parameter that can shape the properties of the interstellar medium in galaxies and span a wide range both within and between galaxies. We explore how metallicity affects properties of the dust observable in the MIR emission from these systems.

Figure 7 shows the variations in the ratio of the PAH emission at 8.0 μm to the dust continuum at 24 μm with metallicity. Both the galaxies from this sample and the blue compact dwarf galaxies (Wu et al. 2006) show a weaker correlation (correlation coefficient $\rho_{XY} = 0.36$) than the systems in the Engelbracht et al. (2005) sample (correlation coefficient $\rho_{XY} = 0.75$). Star-forming dwarf galaxies span a wide range in 8 μm–to–24 μm flux density ratio: over an order of magnitude at log $[O/H] + 12 = 8.2$. The transition from a high flux density ratio to a low ratio at log $[O/H] + 12 = 8.2$, as claimed by Engelbracht et al. (2005), appears to be more of a slow transition with a large galaxy-to-galaxy variation at metallicities around this transition value. Several of the galaxies in the log $[O/H] + 12 = 8.0$–8.2 range exhibit PAH emission, and there is a nearly 2 orders of magnitude spread in the 8 μm–to–24 μm flux density ratio in this metallicity range.

Figure 8 shows the relationship between metallicity and the 16 μm–to–24 μm flux density ratio for this survey and the 16 μm–to–22 μm flux density ratio for the blue compact dwarf galaxies (Wu et al. 2006). This flux density ratio is a measure of the continuum slope in these galaxies. Fluxes measured at 24 and 22 μm should be comparable because the bands are wide (5.5 and 7 μm, respectively), the spectrum is fairly smooth in this flux range, and the relative K-corrections should be small; for a standard dust SED, the 16 μm–to–22 μm flux density ratio would be slightly larger. There is an increase in the flux density ratio with increasing metallicity, but the spread at any given metallicity is large. For any given metallicity there is a wide range in the slope of the dust continuum, but on average the lower metallicity galaxies have a steeper slope. As mentioned previously, this steeper slope implies hotter dust, which may be explained by higher radiation density and increased emission from very small grains in these dwarf galaxies.

Figures 7 and 8 demonstrate that these galaxies exhibit a wide range of emission and/or dust properties at any given metallicity; there is a wide range in the PAH-to-continuum ratio (Fig. 7) and in the continuum slope (Fig. 8).

4. STAR FORMATION RATE INDICATORS

SFR plays an important role in the evolution of galaxies. As the high-redshift universe becomes more and more accessible, star formation and its evolution can be studied over a wider range of epochs (e.g., Madau et al. 1996; Steidel et al. 1999; Giavalisco et al. 2004). Estimates of the evolution in the SFR come from indicators that span the spectrum from the rest-frame UV (e.g., Madau et al. 1996; Bouwens & Illingworth 2006) to the optical
(e.g., Gallego et al. 2002; Hogg et al. 1998) to the infrared (e.g., Wu et al. 2005; Calzetti et al. 2005). All of the SFR indicators commonly used make assumptions about the metallicity, stellar make-up, star formation mode (continuous vs. instantaneous star formation), and/or interstellar medium properties of the systems. In general, the conversion from flux to SFR assumes a standard IMF in a solar-metallicity galaxy with interstellar medium properties consistent with a "normal" galaxy in the local universe. In order to use these indicators at higher redshift, where low-metallicity star-forming galaxies may be more prevalent, the connection between flux and SFR must be evaluated for a range of metallicity and galaxy type. Because it contains a large fraction of low-metallicity systems, this sample can be used to compare the effect of galaxy metallicity on the SFRs calculated at different wavelengths.

4.1. Description of Star Formation Rate Indicators

Spitzer is now providing an unprecedented view of galaxies in the MIR over a wide range of redshifts. At these wavelengths, PAH emission and the dust continuum are the primary contributors to the flux. The dust emission at 12 μm was first shown to be linearly correlated with a galaxy’s bolometric luminosity by Spinoglio et al. (1995) using data from IRAS. More recently, correlations have been found between 15 μm emission and the total infrared luminosity (TIR; Chary & Elbaz 2001), between both 8 and 24 μm emission and the radio continuum emission from galaxies (Wu et al. 2005), and between combinations of 8 and 24 μm emission and TIR (Calzetti et al. 2005). In the UV, GALEX (Martin et al. 2005) is opening up another window on...
star formation in the local universe and providing a probe of the emission from the youngest and hottest stars in galaxies. This section is devoted to a comparison of SFRs derived using indicators from these different wavelength ranges. Several of the methods are obviously inappropriate for these galaxies, but the goal is to understand the errors in the calculated SFR using standard techniques, so we apply them for the sake of comparison.

1. Several authors have built libraries of galaxy templates that can be used to estimate TIR from the 24 μm flux densities (Dale et al. 2001; Chary & Elbaz 2001; Dale & Helou 2002; Lagache et al. 2003; Chanial 2003) alone. For this measurement only the 24 μm flux density is used to predict the total infrared emission, not the full SED shape. As shown by Le Floc’h et al. (2005), these templates all produce similar results; we adopt the Chary & Elbaz (2001) results here without concern that this will bias our findings significantly. A single template was derived for each luminosity bin (see Chary & Elbaz 2001 for details) and can be used to predict the TIR from the 24 μm luminosity. The Kennicutt (1998b) conversion was then used to derive the SFR from TIR. The galaxies that were used to derive these templates are Arp 220, NGC 6090, M82, and M51, which were selected to represent ULIRGs, LIRGs, “starbursts,” and “normal galaxies,” respectively. An additional set of far-infrared templates from Dale et al. (2001) were added to span a wider range of spectral shapes. In § 3.1 we use a similar set of templates from Lagache et al. (2003) and Dale et al. (2001) to fit the sources in this sample and found that, in many of the cases, the shape of the low-luminosity templates was not appropriate for fitting the galaxies. The difference between the low-luminosity template shape and the galaxy SED will introduce an error in determining the SFR.

2. Wu et al. (2005) used a sample of star-forming galaxies in the Spitzer First Look Survey to study the correlations between 8 and 24 μm luminosity with 1.4 GHz and Hα luminosities. These correlations were used to derive the 1.4 GHz luminosity from either 8 or 24 μm luminosities, which was then used to calculate SFR using the Kennicutt (1998b) conversion. Most of the Wu et al. (2005) systems are normal galaxies, but a few dwarfs are included and appear to show a different slope between the MIR and radio luminosity. The difference in the normal and dwarf galaxy slopes is probably driven by a lack of PAH emission (Figs. 1 and 2) and the wide range of continuum slopes (Fig. 8). The more recent calibration of the conversion between 24 μm luminosity and SFR from Calzetti (2008) does not produce significantly different results than the Calzetti et al. (2005) results plotted here.

3. Calzetti et al. (2005) showed that there is a correlation between log [μL(24)/TIR] and log [Lα/(8)/(24)] for H ii regions in NGC 5194. The SFR was calculated using the Kennicutt (1998b) conversion from TIR. Calzetti et al. (2005) use log [Lα/(8)/(24)] instead of just 8 or 24 μm luminosity because the scatter from the ratio is lower. However, there are still region-to-region differences in the correlation between flux density ratio and SFR for the H ii regions in NGC 5194, all of which are high metallicity (they are consistent with 2 Z⊙ ≤ Z ≤ 3 Z⊙), so the scatter is probably worse when studying objects that cover a range in metallicity.

4. The total infrared SFR has been calculated using the 24, 70, and 160 μm data for the three galaxies for which all of these data are available using the method for deriving TIR described by Dale et al. (2005). The SFR was then calculated using the Kennicutt (1998b) conversion from TIR. For the galaxies for which 24 and 70 μm data are available but the 160 μm observation was a nondetection (an additional eight galaxies), we use the 3 σ upper limit at 160 μm to place an upper limit on the TIR. We also obtain a lower limit on the luminosity of these galaxies by assuming that between 70 and 160 μm the galaxy’s SED is Rayleigh-Jeans, which defines F70/F160 = 11.94.

5. SFRs for all of the galaxies in this sample have been computed from the Hα line fluxes measured from the KISS objective-prism spectra. These spectra reflect the total Hα emission from the galaxy because they are derived from objective-prism observations. A full description of the line-flux measurements and calibration is given by KR3. In order to compute the SFRs for these galaxies from the Hα flux, the measurements must be corrected for the presence of blended [N ii] emission (these are low-resolution spectra) and absorption. These corrections are derived from slit spectra. The absorption correction is derived using the reddening coefficient derived from the Balmer line ratios, cHβ. From the [N ii] and absorption-corrected Hα fluxes, the SFRs were computed using the standard prescription from Kennicutt (1998a).

6. In addition to using the standard methods for computing SFR from the Hα emission, we use a method that takes into account the harder radiation field in low-metallicity galaxies (Lee et al. 2002). The stellar population synthesis models on which the standard conversion is based assume a softer radiation field than what exists in these low-metallicity systems. This prescription was derived for a sample of KISS galaxies for which the selection criteria were the same as for these objects. The resulting SFRs are lower than what is obtained using the standard models because the harder radiation field produces more Hα emission for a given SFR.

7. The UV emission from galaxies comes from the youngest, hottest stars. Kennicutt (1998a) provides a conversion from the UV luminosity to the SFR which can be computed across the UV band because young stars produce a flat spectrum in this region. The UV SFR for these galaxies has not been corrected for absorption, so it is a lower limit which measures only the amount of star formation not buried behind dust. Therefore, the SFR measured this way is complementary to that measured in the MIR, where all of the emission is coming from the reradiation from dust in the galaxy. We compute the total SFR as described in Bell et al. (2005) as Ψ/M⊙yr⁻¹ = 9.8 × 10⁻¹¹(LIR + 2.2LUV). We use the Calzetti et al. (2005) measurement of LIR because the values are generally between the other MIR results. As with the infrared measurement, the sum of the MIR and UV measurements could overestimate the SFR if some of the PAH emission is excited by an older stellar population.

The SFRs computed using all of the above methods are reported in Table 3.

4.2. Comparison of Star Formation Rates

Do all measurements of SFR give the same answer, and under what conditions are the derived SFRs comparable? The answer to this question is critical if measurements of SFR from the MIR and UV are going to be used along with Hα to compute SFR density over a wide range of redshift. Measurements of SFR calculated from the mid-infrared, Hα, and UV data are presented in Table 4. Figure 9 shows the relationship between the MIR measurements of SFR and the metallicity-corrected Hα SFR (left panel) and between SFR measured over a wide range of wavelengths and the metallicity-corrected Hα SFR (right panel). The errors due to galaxy photometry on all of these data points (and those in the subsequent SFR plots), with the exception of the NUV values, are smaller than the points. The NUV SFRs are the
TABLE 4
INFRARED, OPTICAL, AND UV SFRs OF KISS GALAXIES

| KISSR  | SFR_{CE}^{a,b} | SFR_{8\text{\mu}m}^{a,c} | SFR_{24\text{\mu}m}^{a,d} | SFR_{SFR^C_{22}}^{a,e} | SFR_{H\alpha}^{a,f} | SFR_{H\alpha+\nu}^{a,g} | SFR_{TRIR}^{b,h} | SFR_{NUV}^{b,i} | SFR_{FUV}^{b,j} |
|--------|----------------|--------------------------|--------------------------|----------------------|------------------|---------------------|------------------|----------------|----------------|
| 2292... | 0.30           | 0.10                     | 0.21                     | 0.09                 | 0.19             | 0.07                | ...              | 0.19           | ...            |
| 2300... | 0.32           | 0.02                     | 0.22                     | 0.02                 | 0.26             | 0.08                | ...              | 0.11           | ...            |
| 2302... | <0.05          | 0.01                     | <0.02                    | 0.00                 | 0.09             | 0.09                | ...              | 0.22           | ...            |
| 2309... | 0.09           | 0.01                     | 0.06                     | 0.01                 | 0.10             | 0.03                | ...              | 0.20           | ...            |
| 2316... | 0.70           | 0.65                     | 0.56                     | 0.48                 | 0.81             | 0.68                | 0.79             | 0.08           | ...            |
| 2318... | 1.66           | 0.61                     | 1.21                     | 0.54                 | 1.12             | 1.12                | 0.5-2.1          | 0.13           | ...            |
| 2322... | 0.12           | 0.05                     | 0.07                     | 0.04                 | 0.14             | 0.05                | ...              | 0.39           | ...            |
| 2326... | 0.38           | 0.03                     | 0.28                     | 0.04                 | 0.35             | 0.15                | 0.1-0.3          | 0.25           | ...            |
| 2338... | 1.23           | 0.09                     | 1.07                     | 0.12                 | 0.51             | 0.19                | 0.3-0.7          | 0.23           | 0.18           |
| 2344... | 0.12           | 0.08                     | 0.08                     | 0.06                 | 0.10             | 0.04                | 0.16             | 0.34           | 0.26           |
| 2346... | 0.41           | 0.04                     | 0.31                     | 0.05                 | 0.24             | 0.07                | ...              | 0.11           | ...            |
| 2349... | 0.64           | 0.05                     | 0.61                     | 0.06                 | 0.24             | 0.09                | 0.32             | 0.18           | ...            |
| 2357... | 0.11           | 0.05                     | 0.07                     | 0.04                 | 0.20             | 0.09                | ...              | 0.30           | ...            |
| 2359... | 1.87           | 0.31                     | 1.40                     | 0.32                 | 3.59             | 2.09                | 0.6-2.0         | 0.21           | 0.14           |
| 2368... | 1.26           | 0.09                     | 1.08                     | 0.12                 | 0.54             | 0.18                | 0.3-1.0         | 0.47           | ...            |
| 2382... | 0.09           | 0.07                     | 0.06                     | 0.05                 | 0.08             | 0.04                | 0.1-0.2         | 0.38           | 0.22           |
| 2398... | 0.15           | 0.13                     | 0.10                     | 0.09                 | 0.17             | 0.08                | 0.1-0.4         | 0.36           | 0.26           |
| 2403... | 0.13           | 0.02                     | 0.08                     | 0.02                 | 0.19             | 0.09                | ...              | 0.10           | ...            |
| 2406... | 0.27           | 0.13                     | 0.19                     | 0.19                 | 0.19             | 0.09                | 0.1-0.4         | 0.42           | 0.32           |

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Fig. 9.— Comparison of SFR indicators with respect to the SFR calculated from H\alpha with a correction for metallicity. The left panel shows a comparison of the MIR indicators, while the right panel shows the H\alpha not corrected for metallicity, the Calzetti et al. (2005) MIR values, the NUV measurement, and the combined NUV and MIR values. Because of a difference in the calibration between the Calzetti et al. (2005) MIR SFR and the Bell et al. (2005) combined MIR and NUV SFR, there are a couple of galaxies for which the Calzetti et al. (2005) MIR SFR is slightly higher than the combined SFR. [See the electronic edition of the Journal for a color version of this figure.]
exception because the values are all lower limits, since no correction has been made for extinction. There is also a distance error associated with these measurements, but they will only shift all of the points up or down without altering their relative separations (i.e., it will not change the spread between the points). These plots show that there is a spread of over an order of magnitude in the SFR measurement for a given galaxy, and the disagreement occurs for both high- and low-SFR sources. However, the plot also shows that several of the methods give similar answers. The Chary & Elbaz (2001) and the 24 μm Wu et al. (2005) values are similar, as are the 8 μm Wu et al. (2005) and the Calzetti et al. (2005) values. These values agree because they were derived in a consistent way for normal galaxies and from the same fluxes (24 and 8 μm, respectively). The spread in the derived SFRs points to a systematic difference in the calculation of these values due to either the intrinsic spread in the luminosity-SFR relationships or a physical difference between these galaxies and those for which the luminosity-SFR relationship was derived.

In general, the measurements based on 24 μm luminosity (Chary & Elbaz 2001; Wu et al. 2005) tend to indicate a higher SFR than the 8 μm (Wu et al. 2005) or 8 plus 24 μm (Calzetti et al. 2005) measurements. This result is consistent with the 8 μm−to−Hα correlation having a steeper slope for dwarf galaxies than it does for more luminous galaxies, as was found in the Wu et al. (2005) study. For six galaxies in this sample the SFR derived from the 8 μm flux is about an order of magnitude lower than that derived from the 24 μm flux. All six of these galaxies are low-metallicity systems (Z ≤ 0.25 Z⊙) that have SEDs which show no evidence for PAH emission. KISSR 2359, which has low PAH emission, has an 8 μm derived SFR that is 4.5 times smaller than the 24 μm SFR. Clearly, the 8 μm emission is not a good SFR indicator for low-metallicity objects that may not exhibit PAH emission. Alternatively, the 24 μm SFR seems, in general, to overpredict the SFR in these galaxies relative to the Hα measurement. The galaxies in this sample are, in general, very compact systems with hot radiation fields because they tend to also be low-metallicity systems. These conditions appear to be driving the heating of hot dust and/or very small grains that dominate in the region between 8 and 24 μm, as has been seen previously in low-metallicity systems (Madden et al. 2006). The difference between the 24 μm and Hα SFRs is certainly affected by the incorrect calibration of the 24 μm SFR for these galaxies, which comes about because the SEDs shown in § 3.1 are not well fit by the low-luminosity templates.

The right panel in Figure 9 shows the SFR computed using several different indicators, including the Calzetti et al. (2005) MIR indicator and the NUV emission. The SFRs computed in the NUV have not been corrected for extinction. For the highest SFR systems (which are also the highest metallicity ones), the lack of an extinction correction has led to a lower measurement of the SFR. However, for most of the systems, the SFR computed in the UV is larger than that computed from the Hα, despite the fact that extinction has not been taken into account. One factor in the high-UV SFR may be that the there is a metallicity dependence that has not been accounted for. However, the significant excess in the UV SFR, even for galaxies that have metallicities ≥0.5 Z⊙, indicates that this is probably not the only factor. A higher SFR measured in the UV than in Hα, attributed to declining star formation from a young but quasi-stellar burst, has also been seen for intergalactic star-forming regions in NGC 5291 (Boquien et al. 2007). A declining SFR in the KISS galaxies would explain the discrepancy between the Hα and UV SFRs, since the timescale in the UV is about 10 times longer than it is in Hα. However, this timescale argument would not explain why the UV SFR is higher than the MIR SFR, which does not decline as quickly. A different explanation would be that the interstellar medium has been blown out in these systems so that there is much less gas and dust surrounding the star-forming region. This explanation is consistent with the MIR spectroscopic results for a similar sample of galaxies which provides evidence for supernova-driven bubbles surrounding the star formation regions (O’Halloran et al. 2008). A much more detailed analysis would be required to assess whether there was a strong burst of star formation in the recent past that could have blown away the gas and dust. The plot includes the combined MIR and NUV SFR using the Bell et al. (2005) formulation. For two of the galaxies, the total SFR is smaller than the Calzetti et al. (2005) MIR SFR alone because there is a small difference in the calibration in the two methods. This calibration uncertainty is a systematic error in all of the calculations, and these results are consistent within that error.

Figure 10 shows the MIR SFR as a function of the Hα SFR with symbol types specifying those galaxies with and without PAH emission. For the galaxies that appear to have PAH emission, the 8 and 24 μm measurements of SFR are, in all but one case, in good agreement with the Hα values. For galaxies that do not show evidence for PAH emission, the SFR computed from the 8 μm flux is lower than what is measured from the Hα emission, while the value computed from the 24 μm emission is higher in all but one case. The dispersion in the values of SFR computed in the MIR for these galaxies appears to be driven by a difference in the properties of the interstellar medium in these galaxies. Both the PAH emission and the shape of the MIR continuum differ from those of normal galaxies both in a lack of PAH emission and in excess emission from hot dust and/or small grains.

Figure 11 shows the relationship between the SFR ratio—SFR from a given indicator divided by the metallicity-corrected Hα SFR—as a function of metallicity. The left panel shows this
ratio for the MIR indicators. The right panel shows the ratio for the Calzetti et al. (2005) MIR SFR, the NUV SFR, and the combination of the MIR and NUV SFRs. For the MIR SFR, the two measures that are derived from the 24 μm emission are the most highly correlated with metallicity. For the 8 μm computed SFRs, a trend with metallicity is not clear in these data. The NUV SFRs for the highest metallicity systems are low because of extinction, but there is no clear trend among the lower metallicity systems.

This sample has three galaxies that have the properties of dusty starbursts: KISSR 2316, 2318, and 2359. These systems all have SFRs calculated from the total infrared emission that are much higher than that calculated from the NUV (which is not corrected for extinction). These galaxies are some of the most luminous systems in the sample, and the two with known metallicities are the highest metallicity systems. Since the derivation of the SFR indicators in the MIR has generally been based on dusty starbursts, one might expect the most consistency in the derived SFRs from these systems. The rates calculated from Hα, 8 μm, and the total infrared are fairly consistent for KISSR 2316 and 2318 (the UV values are low because they are not corrected for extinction). However, the SFRs computed for KISSR 2359 are more problematic. This source has the highest Hα SFR (3.59 M⊙ yr⁻¹; not correcting for metallicity because the source is close to Z⊙) in the sample. The 24 μm SFRs from the Chary & Elbaz (2001) models and from the Wu et al. (2005) correlation are 1.87 and 1.40, respectively. These are smaller than the Hα values, but given the spread in the models and correlation they are still consistent. However, the 8 μm SFR from the Wu et al. (2005) correlation is only 0.31, significantly less than what is measured from the other methods. The lower value for the 8 μm emission may be a reflection of a substantial portion of the infrared emission coming from a high-intensity region where the PAHs are destroyed.

5. SUMMARY

Star-forming dwarf galaxies have a wide range of dust properties that are quite different from those of the spiral and massive starburst galaxies. These differences most likely result from a combination of the harder radiation field, the more compact structure of these systems, possibly a lack of dust due to destruction in shocks or delayed injection, and either a different composition, different heating, or different distribution of the dust in the interstellar medium.

We have used broadband SEDs and color-color diagrams to determine the presence or absence of PAH emission in the sample galaxies. It appears that one of the best indicators of PAH emission may be the 8 μm to 16 μm flux ratio. Mid-infrared (MIR) spectroscopy, which is not available at this time, is required to confirm these results. Nevertheless, the combination of the SEDs and the color-color plots provides more information on the presence or absence of PAH emission than the trend of color with metallicity that was evident from only the Spitzer IRAC data (Rosenberg et al. 2006).

One of the most striking properties of the galaxies in this sample is that, despite their simplicity in being compact systems dominated by a small number of H ii regions, they have a wide range of infrared properties. There are low-metallicity systems that show some evidence for PAH emission (KISSR 2322, Z = 0.24 Z⊙) and high-metallicity systems for which PAH emission is uncertain (KISSR 2359, Z = 0.91 Z⊙), indicating that metallicity is not the only parameter driving the presence and/or strength of the PAH emission features.

It is not only the PAH emission features in these star-forming dwarf galaxies that are different from the spirals and massive starbursts, but also the shapes of the MIR continua. Many of these galaxies have steep, red MIR continua similar to those...
observed by Gallais et al. (2004) in starburst galaxies, observed by Madden et al. (2006) and Hunt et al. (2006) in low-metallicity galaxies, and modeled by Galliano et al. (2005) as being due to emission from very small grains.

Applying the model of Draine & Li (2007) provides one possible interpretation of the differences between the SEDs of the dwarf galaxies and the model templates. The galaxies for which the MIR flux ratios indicate a lack of PAH emission have a large fraction of their infrared emission coming from the photodissociation regions (15%–40%) relative to galaxies for which the MIR flux ratios indicate the presence of PAH emission (2%–8%). PAHs are more likely to be destroyed in the high-intensity photodissociation regions, which would explain why the PAH fraction is lower where these regions dominate. A physical model that might explain this circumstance would be that the H II regions are beginning to overlap, thereby shrinking the relative volume of the lower intensity regions.

The effect of metallicity on the star formation rate (SFR) in galaxies is well studied (Lee et al. 2004; Kewley et al. 2004; Moustakas et al. 2006), primarily with respect to the optical indicators. At 24 μm we see a clear connection between the derived SFR and metallicity, but the connection is not as clear at 8 μm, where other factors must be dominating the dispersion in the relationship between flux density and SFR.

The differences between these star-forming dwarf galaxies and the majority of systems that have been studied in the infrared have two major consequences: (1) MIR spectral templates do not provide a good fit to the systems, and (2) the methods that have been developed to determine the SFR from MIR observations do not work well in these systems. Because these galaxies are different from the majority of galaxies that have been studied in the MIR, some caution needs to be exercised in fitting spectral templates and deriving MIR SFRs, particularly at higher redshift, where more information is often not available and compact star-forming systems may be more prevalent.

This work is based in part on observations made with the Spitzer Space Telescope, which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with NASA. Support for this work was provided by NASA through an award issued by JPL/Caltech. J. L. R. acknowledges support from NSF grant AST 03-02049. E. L. F.’s work was supported through NASA/JPL by the Spitzer Fellowship program. J. S. gratefully acknowledges support for the KISS project from the NSF through grants AST 95-53020, AST 00-71114, and AST 03-07766. V. C. would like to acknowledge partial support from EU ToK grant 39965.

APPENDIX A

DESCRIPTION OF SED FITTING PROCEDURE

The SEDs were studied by fitting model templates to each galaxy. The 5.8 and 8.0 μm points, which are most affected by PAH emission, were excluded from the fitting so that we could compare the photometry with the models at these wavelengths. Note that ~10% or less of the 8.0 μm emission in these galaxies is from stellar photospheres; most of the emission is from the dust continuum or PAH features.

The models consist of an ensemble of starburst galaxy model templates produced by Lagache et al. (2003) and normal star-forming galaxy templates by Dale & Helou (2002). Each template is identified by a galaxy luminosity. However, the templates are used to model the shape of the SED and are not necessarily dependent on the luminosity of the source (we ignore the luminosity scaling). These templates sample the MIR colors of both normal galaxies and ULIRGs. The Lagache et al. (2003) models also include a single “normal” (nonstarburst) galaxy template. For many of the galaxies, the fits are constrained only by the 16 and 24 μm data points.

In order to fit the broadband data, “synthetic” data points for the IRAC 3.6 and 4.5 μm, IRS 16 μm, and MIPS 24, 70, and 160 μm bands were created by convolving the template spectra with the filter response functions. To fit the near-infrared portion of the SED, a blackbody spectrum with a temperature in the range 5000–10,000 K was added to the template model. A least-squares technique was then used to determine the best-fit template plus blackbody (steps of 1000 K were used to determine the best-fit temperature) with the appropriate scaling factors. The temperature of the chosen blackbody did not have a significant effect on the SED fit.

Out of the 19 sample galaxies, three are not detected at 16 μm, and one of these is also not detected at 24 μm. Template fitting was not performed for these three sources because there were not enough long-wavelength points to derive meaningful constraints.

APPENDIX B

DESCRIPTION OF INDIVIDUAL GALAXY SEDs

B1. GALAXIES THAT SHOW PAH EMISSION

KISSR 2344 has 8 μm emission that is significantly in excess of the best-fitting SED template model. As can be seen in Table 3, this galaxy also has one of the largest values for f8(8)/f8(24), f8(8)/f16(16), and R1. While this galaxy probably does have some of the largest values for each of these parameters, differences in the size of the apertures used at each of these wavelengths could affect these numbers. A difference between the apertures would tend to increase the fluxes at the shorter wavelengths with respect to the longer wavelengths. This is the only galaxy in the sample for which this should be a significant issue, since most of the others are unresolved or barely resolved.

KISSR 2406 has a metallicity of log [O/H] + 12 = 8.3 and PAH emission in excess of the best-fit template models. In addition, this galaxy falls well within the PAH-emitting galaxy regions in Figures 5 and 6 and has a small fraction of its infrared luminosity coming from the highest intensity regions (fPAH = 6–7).

KISSR 2316 is the highest metallicity system in the sample (log [O/H] + 12 = 8.8) and has PAH emission that is only 1 σ below the best-fit model template. As with KISSR 2406, the galaxy falls well within the PAH-emitting galaxy regions in Figures 5 and 6 and has a small fraction of its infrared luminosity coming from high-intensity regions.
KISSR 2398 has a metallicity of \( \log [O/H] + 12 = 8.4 \) and 8 \( \mu \)m emission that is only 1 \( \sigma \) below the best-fit model template. The diagnostics from the other plots, Figures 5 and 6, also agree with this being a PAH-emitting galaxy. KISSR 2382 has a metallicity of \( \log [O/H] + 12 = 8.2 \) and 8 \( \mu \)m emission that is 3 \( \sigma \) below the best-fit model template. However, the galaxy falls well within the PAH-emitting galaxy regions in Figures 5 and 6.

B2. GALAXIES THAT SHOW NO EVIDENCE OF PAH EMISSION

KISSR 2326 shows no evidence for PAH emission; the data are 30 \( \sigma \) below the best-fit template at 8.0 \( \mu \)m in this log \( [O/H] + 12 = 8.2 \) galaxy. This galaxy falls well within the no-PAH regions in Figures 5 and 6.

KISSR 2346 shows no evidence for PAH emission, and the data are 58 \( \sigma \) below the best-fit template at 7 \( \mu \)m in this low-metallicity (log \( [O/H] + 12 = 7.8 \)) galaxy. This galaxy falls well within the no-PAH regions in Figures 5 and 6.

KISSR 2300 shows no evidence for PAH emission. The best-fit dust template is 70 \( \sigma \) above the 8.0 \( \mu \)m flux from this galaxy. There is no evidence for a rise in the spectrum above the continuum level at these wavelengths for this galaxy that has log \( [O/H] + 12 = 7.9 \). In addition, this galaxy clearly occupies the no-PAH region in Figures 5 and 6.

KISSR 2338 shows no evidence for PAH emission and is a log \( [O/H] + 12 = 8.1 \) metallicity galaxy. Even the best-fit dust template, which is the template for a ULIRG, gives an extremely poor fit to these data (\( \chi^2 = 16.3 \)). This galaxy shows an excess at 5.8, 8.0, and 16 \( \mu \)m that seems to indicate an unusually large contribution from hot dust and/or very small grains. The galaxy falls well within the no-PAH regions in Figures 5 and 6.

KISSR 2349 shows no evidence for PAH emission and has a metallicity of \( \log [O/H] + 12 = 8.1 \). Even the best-fit template gives a poor fit to the data (\( \chi^2 = 9.8 \)). Similar to KISSR 2338, the best-fit template is for a ULIRG, and there appears to be an excess (although not quite as great as for KISSR 2338) of hot dust and/or very small grain emission. This galaxy falls well within the no-PAH regions in Figures 5 and 6.

KISSR 2368 shows no evidence for PAH emission and is a log \( [O/H] + 12 = 8.0 \) galaxy. Even the best-fit dust template, which, similar to KISSR 2338 and 2349, is a ULIRG template, provides an extremely poor fit (\( \chi^2 = 21.9 \)). As with the other two galaxies, there is some evidence for an excess of hot dust and/or very small grains. This galaxy falls well within the no-PAH regions in Figures 5 and 6.

B3. GALAXIES FOR WHICH THE EXISTENCE OF PAH EMISSION IS UNCERTAIN

KISSR 2309 is a low-metallicity galaxy (log \( [O/H] + 12 = 8.0 \)) which has an 8 \( \mu \)m flux density that is 7 \( \sigma \) below the best-fit SED template. In Figure 5 the galaxy falls within the no-PAH region. In Figure 6 KISSR 2309 is the left-most galaxy in the no-PAH region with error bars that touch the tracks for the spectral templates which include PAH emission.

KISSR 2322 is another low-metallicity galaxy (log \( [O/H] + 12 = 8.0 \)) which has an 8 \( \mu \)m flux density that is 7 \( \sigma \) below the best-fit SED template. In contrast to KISSR 2309, KISSR 2322 falls within the PAH-emitting region in Figure 5 and between the PAH and no-PAH galaxies in Figure 6.

KISSR 2359 is a high-metallicity galaxy (log \( [O/H] + 12 = 8.6 \)), yet it has an 8 \( \mu \)m flux density that is 14 \( \sigma \) below the best-fit SED template. In Figure 5 the galaxy falls just outside the no-PAH region, although the error bars overlap with the region. In Figure 6 KISSR 2359 has the second lowest value of \( f_r(8)/f_r(16) \) of the galaxies for which the PAH classification is uncertain, placing it closer to the no-PAH galaxies than the PAH-emitting ones.

KISSR 2318 has an unknown metallicity and an 8 \( \mu \)m flux density that is 12 \( \sigma \) below the best-fit SED template. Nevertheless, this galaxy falls well within the PAH-emitting galaxy region in Figure 5 and has one of the higher \( f_r(8)/f_r(16) \) ratios of the galaxies with uncertain PAH emission in Figure 6.

KISSR 2292 is another fairly low-metallicity galaxy (log \( [O/H] + 12 = 8.1 \)) which has an 8 \( \mu \)m flux density that is 13 \( \sigma \) below the best-fit SED template. The galaxy falls in the PAH-emitting region in Figure 5 and has one of the higher \( f_r(8)/f_r(16) \) ratios of the galaxies with uncertain PAH emission in Figure 6.

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