SPITZER OBSERVATIONS OF LOW-LUMINOSITY ISOLATED AND LOW SURFACE BRIGHTNESS GALAXIES

J. L. Hinz, M. J. Rieke, G. H. Rieke, C. N. A. Willmer, K. Miselt, C. W. Engelbracht, and M. Blaylock
Steward Observatory, University of Arizona, 933 North Cherry Avenue, Tucson, AZ 85721; jhinz@as.arizona.edu, mrieeke@as.arizona.edu, grieeke@as.arizona.edu, cnaw@as.arizona.edu, kmiselt@as.arizona.edu, cengelbracht@as.arizona.edu, blaylock@as.arizona.edu

AND

T. E. Pickering
MMT Observatory, University of Arizona, Tucson, AZ 85721; tim@mmto.org

Received 2006 November 9; accepted 2007 April 13

ABSTRACT

We examine the infrared properties of five low surface brightness galaxies (LSBGs) and compare them with related but higher surface brightness galaxies, using Spitzer Space Telescope images and spectra. All the LSBGs are detected in the 3.6 and 4.5 μm bands, representing the stellar population. All but one are detected at 5.8 and 8.0 μm, revealing emission from hot dust and aromatic molecules, although many are faint or pointlike at these wavelengths. Detections of LSBGs at the far-infrared wavelengths of 24, 70, and 160 μm are varied in morphology and brightness, with only two detections at 160 μm, resulting in highly varied spectral energy distributions. Consistent with previous expectations for these galaxies, we find that detectable dust components exist for only some LSBGs, with the strength of dust emission dependent on the existence of bright star-forming regions. However, the far-infrared emission may be relatively weak compared with normal star-forming galaxies.

Subject headings: galaxies: evolution — galaxies: photometry

1. INTRODUCTION

LSBGs, defined as those with B-band central surface brightnesses μ₀,B fainter than 23.0 mag arcsec⁻², appear to have followed a very different evolutionary history from high surface brightness galaxies (e.g., McGaugh 1992; Knezek 1993). Their stellar populations, stellar masses, current star formation rates, and other properties appear to differ significantly from their high surface brightness counterparts, and little is known about their corresponding dust properties. A better understanding of these differences is needed in order to understand how they evolved to their present state.

It has been generally assumed, even though a population of red LSBGs has been discovered (O’Neil et al. 1997b), that they contain little dust, and dust reddening has not been considered an important effect (e.g., Bothun et al. 1997; Bell et al. 2000). LSBGs have low star formation rates, with suspected modest bursts in the range of 10⁻³ to 10⁻² M☉ yr⁻¹ (e.g., Vallenari et al. 2005) and low metallicities, with almost all LSBGs at or less than about one-third solar (McGaugh 1994; Rönnback & Bergvall 1995). Their low metallicities imply that the dust to gas ratios should be systematically lower than in their high surface brightness galaxy counterparts, and the fact that the Infrared Astronomical Satellite (IRAS; Neugebauer et al. 1984) and the Infrared Space Observatory (ISO; Kessler et al. 1996) were only able to detect two of these galaxies seems to indicate that dust is much less important in LSBGs. Furthermore, any data acquired with these observatories would not have been adequate to characterize dust temperatures or spatial distributions.

That dust plays a relatively minor role in the evolution of LSBGs is further reinforced by observations of highly transparent galaxies that appear to have multiple distant galaxies seen through their disks (O’Neil et al. 1997a; P. Knezek 2006, private communication). This has been confirmed by a more detailed analysis of the dust opacity of LSBG disks in comparison to those of high surface brightness galaxies, where LSBGs appear effectively transparent (Holwerda et al. 2005).

In addition, Pickering & van der Hulst (1999) attempted to detect dust in LSBGs using submillimeter observations from the James Clerk Maxwell Telescope (JCMT) with the Submillimeter Common-User Bolometric Array (SCUBA). Ten galaxies were observed, two of which were detected at 850 μm, with only one detected at 450 μm. They combined their submillimeter data with existing IRAS data, finding dust temperatures in the range 15–20 K. None of their very LSB (μ₀ ≤ 23.5) galaxies were detected, and they concluded that the lack of detection in the lowest surface brightness galaxies was consistent with previous lines of evidence that only modest amounts of dust could exist.

Spitzer provides the opportunity to study any dust that may exist at low levels in LSBGs. The increased sensitivity relative to previous observations gives a higher likelihood of the detection of diffuse dust emission that echoes the LSBGs’ diffuse optical appearance. In addition, the resolution of the Spitzer imaging instruments allows for analysis of dust temperature, mass, and spatial distribution in LSBGs that was not possible before, making it feasible to address crucial issues regarding chemical evolution and dust production. We present here the infrared properties of a small sample of LSBGs with the full suite of Spitzer instruments.

2. OBSERVATIONS

All Spitzer observations presented here are part of the Dust in Low Surface Brightness Galaxies Guaranteed Time Observation Program (ID 62), whose principal investigator is M. J. Rieke.

2.1. Sample

The galaxies in this sample were selected to be some of the brightest and closest known LSBGs, many taken from the work of Pickering (1998). Two galaxies are high surface brightness, low-metallicity isolated late-type spirals that are included for the purpose of comparison with the LSBGs. Table 1 summarizes general information for each galaxy. The objects were chosen such that the infrared background cirrus was low, improving the
chances of detection of the faintest emission associated with each galaxy, and with sufficiently large angular diameters for resolution with the Spitzer instruments. Here we briefly outline their main properties and unique characteristics.

2.1. Low Surface Brightness Galaxies

Malin 1.—One of the best known LSBGs (Bothun et al. 1987; see Barth [2007] for a more recent view) and the largest gas-rich LSBG, later observed and found to be too bright, or that it qualifies as a type of LSB disk using a “diffuseness” index in- ternal surface brightness. (It is possible either that it was a candi- date LSBG, does not qualify as one, due to its bright cen- teral surface brightness. (McGaugh et al. 1995).

UGC 6575.—This Magellanic dwarf spiral (e.g., Schneider et al. 1990; McGaugh et al. 1995) has a very low surface brightness disk (Schombert & Bothun 1988) and has the faintest $M_B$ of our sample. It does not have any regions of distinct star formation or an extended H\,\i\, envelope (van Zee et al. 1995).

UGC 6151.—Another Magellanic spiral with a small core of optical emission surrounded by faint diffuse emission with little structure. McGaugh et al. (1995) noted that the galaxy contains “quite a few faint H\,\ii\ regions.”

UGC 6614.—Has a star-forming distinctive ring and a parti- cularly extended disk that can be traced to at least 130 \arcsec\ (van der Hulst et al. 1993). It is the most metal-rich LSBG known and is considered to be a “cousin” to Malin 1, due to their similar properties. The H\,\i\, data show that there is a central depression in the gas distribution, which has led to discordant flux measure- ments in the literature (Bothun et al. 1985; Giovanelli & Haynes 1989; Pickering et al. 1997; Matthews et al. 2001), although the most recent of these works agree.

UGC 9024.—This galaxy has a very low surface brightness disk coupled with a normal bulge. It has been suggested that the large disk plus bulge indicates that it is a transition object between average-sized LSBGs with no bulge and giant Malin 1 type galax- ies (McGaugh et al. 1995).

2.1.2. High Surface Brightness Galaxies

UGC 6879.—This object, while in the Impey et al. (1996) catalog of LSBGs, does not qualify as one, due to its bright cen- tral surface brightness. (It is possible either that it was a can- didate LSBG, later observed and found to be too bright, or that it qualified as a type of LSB disk using a “diffuseness” index in- volving the disk scale length; see Sprayberry et al. [1995] for de- tails). This galaxy is one of the few in the program to have been detected by IRAS, with photometry measurements at 60 and 100 \mu\,m and upper limits at 12 and 25 \mu\,m. It also has a detection at 850 \mu\,m by SCUBA (Pickering & van der Hulst 1999), making it an excellent candidate for further study in the mid- and far-IR at the higher sensitivity and resolution of Spitzer.

UGC 10445.—A nearby starbursting dwarf spiral. The Spitzer images of this object have been examined in detail in Hinz et al. (2006). It also has available IRAS and ISO measurements.

2.2. Data

Each galaxy was observed with the Infrared Array Camera (IRAC; Fazio et al. 2004) at all four wavelengths (3.6, 4.5, 5.8, and 8.0 \mu\,m), in one $5' \times 5'$ field with a frame time of 30 s and with a dither of five positions Gaussian, for a total integration time of 150 s per object per wavelength. IRAC data were reduced at the Spitzer Science Center (SSC) with the S14.0.0 pipeline. The IRAC spatial resolution is $\sim 2''$ in all bands.

The Multiband Imaging Photometer for Spitzer (MIPS; Rieke et al. 2004) data for the sample were observed in photometry mode at 24, 70, and 160 \mu\,m. The integration times on all galaxies were 690 s at 24 \mu\,m, 252 s at 70 \mu\,m, and 42 s at 160 \mu\,m. The MIPS data were reduced using the Data Analysis Tool, version 3.00 (DAT; Gordon et al. 2005), the same techniques that are used to calibrate the instrument itself. Two independent reduc- tions were carried out to test for systematic errors on these faint sources; the results agreed closely for both reductions. The MIPS spatial resolutions are 6\arcsec, 18\arcsec, and 40\arcsec\ at 24, 70, and 160 \mu\,m, respectively. Data for the IRAC and MIPS observations are given in Table 1. The MIPS 24 \mu\,m observations for UGC 5675 appear to be corrupted. The observations performed by Spitzer just prior to this object were deep, high-redshift observations and unlikely to introduce saturated objects that might have affected our data set. However, the southwestern corner of almost all the 24 \mu\,m data collection events have highly saturated pixels marked as NaN. Further processing and mosaicking of the image was impossible, and no information could be recovered.

Infrared Spectrograph (IRS; Houck et al. 2004) staring-mode observations were scheduled for only three of the targets in this program: Malin 1, UGC 6879, and UGC 10445. Galaxies were observed in the low-resolution 5.2–8.7 \mu\,m (SL2) and 7.4–14.5 \mu\,m (SL1) modes and in the low-resolution 14.0–21.3 \mu\,m (LL2) and 19.5–38 \mu\,m channels (LL1). Details of the observations, including dates, integration times, and slit position angles, are given in Table 2. The faint, diffuse, and complex nature of these sources makes such observations difficult. Spitzer’s onboard peak-up algorithm centroided on a source considered far from the intended target position for UGC 10445 and centroided on a bad pixel rather than Malin 1. Data were reduced with version S13.2.0 of the SSC data pipeline, with extractions using the pipeline de- veloped by the Formation and Evolution of Planetary Systems (FEPS) Legacy team (Hines et al. 2006).
Additional data are available for UGC 6879. These include the far- and near-ultraviolet (1350–1750 Å, \( \lambda_{\text{eff}} = 1516 \) Å, and 1750–2750 Å, \( \lambda_{\text{eff}} = 2267 \) Å, respectively) images from the Galaxy Evolution Explorer (GALEX; Martin et al. 2005) made available through the NASA Extragalactic Database (NED).

3. ANALYSIS

3.1. Morphology

Figure 1 shows an image of each galaxy in the sample at all the Spitzer wavelengths, with the exception of UGC 10445, which was presented by Hinz et al. (2006).

IRAC detects all galaxies in the sample at 3.6 and 4.5 μm, and all except for UGC 5675 at 5.8 and 8.0 μm. In general, the LSBGs are easily detected at the two shorter wavelength bands, representing the old stellar population, and difficult to image at

| Galaxy      | Date       | IRS Mode | Integration Time (s) | P.A. (deg) |
|-------------|------------|----------|----------------------|------------|
| Malin 1     | 2005 Jan 4 | SL       | 1707                 | -160.92    |
|             |            | LL       | 377.5                | 115.55     |
| UGC 6879    | 2004 Jun 27| SL       | 1707                 | 19.01      |
|             |            | LL       | 377.5                | -64.50     |
| UGC 10445   | 2004 Jul 14| SL       | 1707                 | 42.37      |
|             |            | LL       | 377.5                | -41.15     |

Note.—Complete details of observations can be retrieved via Spitzer’s Leopard database software.

Fig. 1.—Multiwavelength views of the galaxy sample. North is up and east is to the left. The field of view of each panel is \( \sim 4.5' \times 4.5' \). From right to left, starting with the top row: Digitized Sky Survey (DSS), the four IRAC bands, and the three MIPS bands. The exception to this is UGC 6879, which has: GALEX far-UV, GALEX near-UV, DSS, IRAC, MIPS, and SCUBA 850 μm. The scale for the DSS image is 1.7′, and for GALEX it is 5′. Pixel scales for all IRAC images are 1.2′. Pixels scales for the MIPS images are 1.245′ for 24 μm, 4.925′ for 70 μm, and 8.0′ for 160 μm. The SCUBA image has been rebinned to 1′ pixels from an original beamwidth of 15′. 
5.8 and 8.0 μm, with many having only pointlike detections at the longer wavelengths.

The MIPS observations of the LSBGs are varied. There are clear detections of all LSBGs at 24 μm (with the exception of the corrupted data of UGC 5675, as explained above), three detections at 70 μm, and two at 160 μm. Of these detections, two have extended emission at 24 μm while two have pointlike morphologies. At 70 μm, two are extended, with one pointlike, and at 160 μm two are extended, with no pointlike detections. A summary of this rough classification is given in Table 3, with LSBGs listed in the top five rows and HSBGs listed in the bottom two rows.

The difficulty of detecting emission at the longer wavelengths for the LSBGs is not simply a result of the decreased resolution. Figure 2 shows the three MIPS images of UGC 6614, with both the 24 and 70 μm images convolved with a kernel that transforms them to the resolution of the 160 μm data. The kernel was created using a Fourier technique on the MIPS point-spread functions (PSFs) generated by STiny Tim (K. D. Gordon et al. 2007, in preparation). The galaxy seems to be more extended at 70 μm than at 24 μm, consistent with the star-forming ring becoming more prominent, as shown in Figure 1. The signal-to-noise ratio (S/N) is too low at 160 μm to confirm this trend, but the image does show that the peak remains on the galaxy center, as defined at 24 and 70 μm. The changing brightness and morphology of the galaxy do not seem to be related to the resolution differences.

3.2. Photometry

Aperture photometry was conducted on all Spitzer images. Additional image processing in the form of background subtraction was first completed by subtracting a constant value from each image. The value of this constant was determined by masking stars in the foreground, then taking an average of all pixel values outside the aperture used for the galaxy photometry. For galaxies where the foreground contamination was particularly
high, we used a large region surrounding the galaxy to determine a background value that included a sampling of foreground stars. Table 3 shows the MIPS flux density values and their associated errors, along with the radii of apertures used. Table 4 shows the corresponding IRAC photometry values. Galaxies that are undetected at the various wavelengths have 3σ upper limits listed in Tables 3 and 4. Upper limits were calculated from the images themselves, using the mean value of the sky counts and adding 3 times the value of the standard deviation of the sky counts.

The photometric uncertainties are estimated to be 10% at 3.6 and 4.5 μm, and 15% at 5.8 and 8.0 μm. These values include a 3% absolute calibration uncertainty (Reach et al. 2005), a contribution for scattered light in an extended source (W. Reach 2006, private communication), and an uncertainty due to the sensitivity of the measurements to the background subtraction. The contribution of the scattered light is higher at 5.8 and 8.0 μm. We do not perform aperture corrections on the IRAC photometry, which in certain limiting cases can be up to 25%–30% for the 5.8 and 8.0 μm bands. In our case, it is difficult to determine this correction for the mixture of point and extended sources seen in the IRAC images. We mainly use the 8.0 μm images to establish the presence of aromatic feature emission in our galaxies, so uncertainties of this magnitude have no effect on our conclusions.

The MIPS flux calibration uncertainties are 4% at 24 μm, 7% at 70 μm, and 12% at 160 μm (Engelbracht et al. 2007; Gordon et al. 2007; Stansberry et al. 2007). Photometric uncertainties bring these values to total errors of 10% at 24 μm, 20% at 70 μm, and 20% at 160 μm.

3.3. Dust Modeling for UGC 6879

UGC 6879, with its bright detections at all IR wavelengths, can be analyzed in detail based on the mid-infrared and submillimeter photometry. Figure 3 shows the spectral energy distribution (SED) for this galaxy, including GALEX, Two Micron All Sky Survey (2MASS), IRAC, IRAS, Spitzer, and SCUBA...
data points. The emission by dust at the longer wavelengths can be modeled by an equation of the form

$$F_{\text{dust}}(\lambda) = \sum C_i \kappa_i(\lambda) B_\lambda(T_{D,i}),$$  

where $C_i = M_{\text{dust},i}/D^2$ ($D \sim 32$ Mpc), $\kappa_i$ is the mass absorption coefficient, $B_\lambda$ is the Planck function, $M_{\text{dust},i}$ is the dust mass, and the sum extends over the number of dust components. We adopt a two-component dust model consisting of warm and cool silicate grains ($a \sim 0.1 \mu$m). Further details regarding model assumptions and the fitting process can be found in Hinz et al. (2006). The data set is best fitted by a model consisting of a warm silicate component at $T = 51.51^{+1.44}_{-1.28}$ K and a cool silicate component at $14.94^{+0.52}_{-0.58}$ K, shown in Figure 3, where the quoted error bars are 1 σ. We estimate the dust masses of UGC 6879 to be $8753^{+2360}_{-2017} M_\odot$ for the warm component and $3.50^{+0.60}_{-0.54} \times 10^7 M_\odot$ for the cool dust, where the quoted error bars are again 1 σ. As shown in Hinz et al. (2006), choosing carbonaceous grains in place of silicate grains only modestly affects these values.

3.4. Spectroscopy

Figure 4 shows the full IRS spectra for UGC 6879, Malin 1, and UGC 10445. We identify emission lines clearly detected in UGC 6879 and UGC 10445: [S iv], [Ne ii], and [S iii] (see, e.g., Smith et al. 2004). In addition, we see the broad emission features usually attributed to polycyclic aromatic hydrocarbons (PAHs). The data show the four main aromatic bands at 6.2, 7.7, 8.6, and 11.3 μm. The aromatic feature at 12.7 μm is likely to be contaminated by the [Ne ii] 12.8 μm line.

There are no spectral features detected in the Malin 1 spectrum. Despite the fact that Spitzer was not aligned on the coordinates given as the central nucleus of the galaxy, the large extent of Malin 1 ensures that IRS took data on some portion of the disk.
and the exposure time is long. Also, our photometry (Tables 3 and 4) shows the mid-IR excess to be very weak. It is likely that no aromatic features in Malin 1 are detectable with IRS in reasonable exposure times.

The spectra for UGC 6879 and UGC 10445 were fitted with the publicly available IDL tool PAHFIT, which was developed to decompose IRS spectra of PAH emission sources, with a special emphasis on the careful recovery of ambiguous silicate absorption, and weak, blended dust emission features (Smith et al. 2007). The spectra were first prepared for PAHFIT by eliminating points with negative flux or with low S/Ns (≤2). Table 5 shows the fluxes or equivalent widths (EWs) for the various features as given by PAHFIT. The 7.7 μm complex is a sum of the 7.4, 7.6, and 7.9 μm features. PAHFIT does not calculate uncertainties on EWs because it is difficult to compute uncertainties on the continuum of the spectrum. The errors given in Table 5 assume that the fractional errors on the EWs are the same as on the integrated features and thus are lower limits.

4. DISCUSSION

4.1. Comparison of UGC 6879 and UGC 10445

The temperature of the cool dust, \( T \sim 15 \) K, found for UGC 6879, a high surface brightness spiral, coincides with that found for the starbursting dwarf galaxy UGC 10445 (Hinz et al. 2006) using similar data and modeling techniques. It is also in agreement with the submillimeter temperature estimates of such dust in LSBGs by Pickering & van der Hulst (1999) and with infrared and submillimeter estimates of the temperatures of other low-metallicity environments such as dwarf galaxies (Popescu et al. 2002; Lisenfeld et al. 2002; Böttner et al. 2003). In addition, observations of normal-sized high surface brightness galaxies, including the Milky Way (Reach et al. 1995; Lagache et al. 1998), show that cool dust components exist, and it is becoming apparent that such a cool component is fairly ubiquitous across galaxy types (see the review by Tuffs & Popescu 2005).

The total calculated dust mass of UGC 6879 of \( \sim 3.5 \times 10^7 M_\odot \) falls within the range found for normal high surface brightness spiral galaxies of \( 10^6-10^8 M_\odot \) (e.g., Sodroski et al. 1997; Bendo et al. 2003) and is a factor of 10 higher than the mass values for

1 Available at http://turtle.as.arizona.edu/jdsmith/pahfit.php.
UGC 10445 (Hinz et al. 2006). The cool dust mass value for UGC 10445 is considered a lower limit due to the fact that MIPS data are insensitive to dust colder than $T = 15-20$ K. The SCUBA 850 $\mu$m detection of UGC 6879 allows us to better estimate the turnover of the SED. The better constrained fit puts somewhat tighter constraints on the dust mass.

The H\textsc{i} gas mass to dust mass ratio found for UGC 10445 was $\sim 500$ (Hinz et al. 2006). This was found to be inconsistent with the mean value of the ratio for normal spiral galaxies ($71 \pm 49$; Stevens et al. 2005), although the uncertainty in the dust mass value was large. The total H\textsc{i} mass for UGC 6879 is $1.10 \times 10^9 M_\odot$ (Sauty et al. 2003), giving a H\textsc{i} gas mass to dust mass ratio of $31^{+6}_{-5}$. This value is consistent with the Stevens et al. (2005) mean value.

4.2. Comparison between Low and High Surface Brightness Galaxies

Popescu et al. (2002) proposed that cool dust in galaxies is heated by the diffuse non-ionizing ultraviolet radiation produced by young stars, with a small contribution from the optical radiation produced by old stars. This appears to be borne out for the high surface brightness galaxies UGC 6879 and UGC 10445, for which the GALEX and 24 $\mu$m images pinpoint the active star formation sites, and the corresponding 160 $\mu$m emission traces the detectable cool dust. Figure 5 shows the central $B$-band surface brightnesses for the sample versus the ratio of 24 to 160 $\mu$m flux density. The lower the central optical surface brightness for each object, the lower this ratio appears to be. This implies that there are not large amounts of dust extinction; no highly obscured star formation is uncovered at 24 $\mu$m, and those galaxies with the lowest surface brightnesses, i.e., without bright star-forming regions, are not detected at 160 $\mu$m.

The appearance of broad aromatic emission spectral features in the isolated starbursting galaxies confirms the presence of dust grains indicated by the IRAC, MIPS, IRAS, and SCUBA images and photometry and by our dust modeling. Aromatic emission is believed to originate mostly from photodissociation envelopes at...
the edges of star-forming regions that are bathed in ultraviolet photons, with some suggestion that B stars no longer associated with H ii regions can also contribute to the heating (Spoon 2003; Calzetti et al. 2005). In the cases of UGC 6879 and UGC 10445, the high surface brightness galaxies for which we have IRS spectra, we clearly see star formation regions indicated by bright clumpy regions in the 24 μm images and the corresponding 8 μm emission that presumably accounts for the aromatic features.

In contrast, we see that the LSBG Malin 1 does not have dust emission at far-IR wavelengths, nor aromatic emission, which is not surprising, given the Popescu et al. (2002) model and explanation. Malin 1 exhibits no active star-forming regions detectable at any of the wavelengths that indicate such activity. Without those regions, UV photons cannot heat any existing dust to emit at long wavelengths, nor can the envelopes believed to be the site of aromatics exist. That is not to say that dust cannot exist in such an object, but simply that any such dust will not be heated and will not be detectable in far-IR images. This appears to be consistent with results for irregular dwarf galaxies, where aromatic emission is found only in the brightest H ii regions or where there is widespread, intense star formation (Hunter et al. 2006). Braine et al. (2000) calculated an average star formation rate over a lifetime of $10^{10}$ yr for Malin 1 of $5 M_\odot$ yr$^{-1}$ based on its I-band luminosity. From this value, following Scoville & Young (1983), they derived a far-IR luminosity and translated this to an expected flux density of $\sim$100 mJy at the IRAS 100 μm band. This was below the detection limit of IRAS and indeed was not detected. The longer integration times with MIPS now place that 1σ upper limit at 160 μm of $\sim$10 mJy, with Malin 1 still invisible. One explanation for this low-IR luminosity is that the current star formation rate is far below the average over the life of the galaxy.

In addition, simply scaling the two-component dust model for high surface brightness galaxy UGC 6879 down to the 24 μm flux density values for the LSBGs does not appear to fit their SEDs. A scaled model that fits, for instance, a 24 μm flux density of 0.018 Jy, would predict a 70 μm flux density of $\sim$0.4 Jy and a 160 μm flux density of $\sim$1.5 Jy. Comparing with the measurements of UGC 6614 shows 70 and 160 μm outputs only $\sim$25% of these predictions. The 160 μm output of UGC 6151 also appears to be somewhat below the expected value. Therefore, it appears that the emission at the longer wavelengths for at least some LSBGs is fundamentally different from that of high surface brightness galaxies and that they are not simply low-luminosity versions of normal galaxies. Either LSBGs do not produce or maintain dust in the same quantities as other galaxies, or the dust is much colder and therefore undetectable in the far-IR.

Comparisons of the Spitzer data for different LSBGs may also reveal differences in evolutionary history. Figure 6 shows the IR SEDs of all the galaxies in the sample. While the two high

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**TABLE 3**

| Galaxy   | Morph. (24 μm) | Morph. (70 μm) | Morph. (160 μm) | $F_v$ (24 μm) (Jy) | Radius (arcsec) | $F_v$ (70 μm) (Jy) | Radius (arcsec) | $F_v$ (160 μm) (Jy) | Radius (arcsec) |
|----------|----------------|----------------|----------------|-------------------|----------------|-----------------|----------------|-------------------|----------------|
| Malin 1  | Pointlike      | No detection  | No detection  | 4.3E-4 ± 4.3E-5   | 24.90          | <0.004          | <0.009         | <0.001            | <0.002         |
| UGC 5675 | …              | No detection  | No detection  | …                 | …              | …               | …              | …                 | …              |
| UGC 6151 | Extended       | Extended      | Extended      | 0.005 ± 5.0E-4    | 62.25          | 0.08 ± 0.02    | 49.25          | 0.29 ± 0.06       | 80             |
| UGC 6614 | Extended       | Extended      | Extended      | 0.018 ± 2.0E-3    | 62.25          | 0.08 ± 0.02    | 54.18          | 0.38 ± 0.08       | 56             |
| UGC 9024 | Pointlike      | Pointlike     | No detection  | 0.001 ± 1.0E-4    | 24.90          | 0.04 ± 0.01    | 24.63          | <0.02            | …              |
| UGC 6879 | Extended       | Extended      | Extended      | 0.027 ± 3.0E-3    | 62.25          | 0.44 ± 0.09    | 54.18          | 1.47 ± 0.29       | 56             |
| UGC 10445| Extended       | …              | …              | 0.025 ± 2.0E-3    | 105.8          | 0.55 ± 0.11    | 98.50          | 2.50 ± 0.50       | 120            |

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**Fig. 2.** — UGC 6614 at 24, 70, and 160 μm. The 24 and 70 μm images are convolved to the 160 μm resolution. The changing morphology and brightness of the galaxy at far-IR wavelengths do not appear to be a result of the resolution differences. North is up and east is to the left. The field of view of each panel is $\sim$4.0′ × 4.8′.
surface brightness galaxies have similar SEDs from 3.6 to 160 μm, the LSBGs show a variety of steepnesses between wavelengths. Some have steepnesses from 24 to 160 μm that are similar to the high surface brightness galaxies, while others are shallower (UGC 6614), and some appear to turn over after 70 μm (UGC 9024). For instance, UGC 6151 and UGC 6614 have very similar far-IR flux densities, yet UGC 6614 is much brighter in red giant light, as represented by the 3.6 μm flux densities, for all those values in conjunction with the rough metallicity formulations of Wegner et al. (2003) and Salzer et al. (2005) to obtain metallicities. Metallicities are notoriously difficult to determine for LSBGs, and the variety of sources used to obtain them for this sample may inflate errors. However, Figure 7 shows a weak correlation in the expected direction that higher metallicity galaxies have brighter absolute magnitudes at 24 μm. Absolute magnitudes are calculated using the MIPS 24 μm magnitude zero point of 7.17 ± 0.0815 calculated by Engelbracht et al. (2007). Average metallicities are taken from a variety of sources in the literature (de Naray et al. 2004; McGaugh 1994). Others are calculated using the Sloan Digital Sky Survey (SDSS) SkyServer.2

### 4.3. Metallicities and IR Properties of LSBGs

LSBGs are generally metal-poor, consistent with the well-known luminosity-metallicity (L-Z) relation for other galaxies (e.g., de Naray et al. 2004). In Figure 7 we show the metallicities of the entire HSBG plus LSBG sample versus the absolute magnitude at 24 μm. Absolute magnitudes are calculated using the MIPS 24 μm magnitude zero point of 7.17 ± 0.0815 calculated by Engelbracht et al. (2007). Average metallicities are taken from a variety of sources in the literature (de Naray et al. 2004; McGaugh 1994). Others are calculated using the Sloan Digital Sky Survey (SDSS) SkyServer.2

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**TABLE 4**

| Galaxy     | $F_\nu (3.6 \mu m)$ (Jy) | $F_\nu (4.5 \mu m)$ (Jy) | Radius (arcsec) | $F_\nu (5.8 \mu m)$ (Jy) | $F_\nu (8.0 \mu m)$ (Jy) | Radius (arcsec) |
|------------|--------------------------|--------------------------|----------------|--------------------------|--------------------------|----------------|
| Malin 1    | 1.74E-3 ± 1.74E-4        | 1.20E-3 ± 1.20E-4        | 18             | 6.87E-4 ± 1.03E-4        | 1.03E-3 ± 1.55E-4        | 18             |
| UGC 5675   | 1.22E-3 ± 1.12E-4        | 7.45E-4 ± 7.47E-5        | 30             | <2.03E-5                | <1.18E-4                | ...            |
| UGC 6151   | 4.60E-3 ± 4.60E-4        | 2.87E-3 ± 2.87E-4        | 60             | 2.47E-3 ± 3.71E-4        | 4.15E-3 ± 6.23E-4        | 60             |
| UGC 6614   | 2.45E-2 ± 2.45E-3        | 1.43E-2 ± 1.43E-3        | 108            | 1.66E-2 ± 2.49E-3        | 2.43E-2 ± 3.65E-3        | 60             |
| UGC 9024   | 3.10E-3 ± 3.10E-4        | 2.00E-3 ± 2.00E-4        | 60             | 9.00E-4 ± 1.35E-4        | 2.00E-3 ± 3.00E-4        | 24             |
| UGC 6879   | 2.15E-2 ± 2.15E-3        | 1.39E-2 ± 1.39E-3        | 108            | 2.05E-2 ± 3.00E-3        | 4.71E-2 ± 7.07E-3        | 60             |
| UGC 10445  | 2.00E-2 ± 2.00E-3        | 1.60E-2 ± 1.60E-3        | 78             | 2.10E-2 ± 3.15E-3        | 3.40E-2 ± 5.10E-3        | 78             |

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**FIG. 3.** SED of UGC 6879, showing GALEX, 2MASS, IRAC, IRAS, MIPS, and SCUBA data points. The IRAS data points at 12 and 25 μm are upper limits only. The solid line is a two-component dust model fitted to the four IRAC data points, two IRAS points, and three MIPS points. This model consists of a warm silicate component at $T = 52$ K (dashed line) and a cool silicate component at $T = 15$ K (dot-dashed line).

**FIG. 4.** IRS spectra rest wavelength vs. flux density for UGC 6879, UGC 10445, and Malin 1. The broad aromatic features and emission lines are indicated on the top and middle panels on both the UGC 6879 and UGC 10445 spectra. The Malin 1 spectrum is consistent with noise.

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2 Available at http://cas.sdss.org/dr5/en.
galaxies that are detected at those wavelengths (see Engelbracht et al. [2005] and their Figs. 1 and 2). We show $R_1$ versus $R_2$ and $R_2$ versus the metallicity of each galaxy in Figure 8. The data points have large error bars associated with the photometry so that trends are difficult to determine. We see that the values for the LSBGs are consistent with those found for normal galaxies by Engelbracht et al. (2005), occupying similar parameter space as their high surface brightness counterparts in both plots. Most of our sample has a relatively high 8 to 24 $\mu$m flux ratio, so the correlation of increasing $R_2$ with decreasing $R_1$ is not sampled by our galaxies. In fact, all the galaxies in our sample that are detected at both 8 and 24 $\mu$m have $R_2$ larger than 0.2, and all of the galaxies in the Engelbracht et al. (2005) with $R_2$ greater than this value have detected aromatic features. We see the same general metallicity trend as Engelbracht et al. (2005), with lower metallicity galaxies displaying weak aromatic emission, that is, diminishing 8 $\mu$m flux density relative to 24 $\mu$m flux density. One explanation for this trend is that harsh radiation fields in low-metallicity galaxies destroy PAH molecules (Galliano et al. 2003, 2005; Madden et al. 2006). This is unlikely to be the case for LSBGs, where the radiation fields are presumably not strong enough to destroy aromatics. Another explanation is that there are not enough carbon-rich asymptotic red giant branch stars

### Table 5

| Feature       | Flux (ergs s$^{-1}$ cm$^{-2}$) |
|---------------|---------------------------------|
| [S IV]        | 4.89E-16 ± 3.86E-16             |
| [Ne II]       | 4.98E-15 ± 4.74E-16             |
| [S III]       | 7.14E-15 ± 1.45E-15             |
| 7.7 $\mu$m complex EW ($\mu$m) | 13.57 ± 0.68 |
| [S IV]        | 2.36E-15 ± 3.75E-16             |
| [Ne II]       | 4.20E-15 ± 4.30E-16             |
| [S III]       | 2.39E-15 ± 1.63E-15             |
| 7.7 $\mu$m complex EW ($\mu$m) | 5.69 ± 1.83 |

Fig. 5.—$B$-band central surface brightnesses of the galaxy sample vs. the ratio of the flux densities at 24 and 160 $\mu$m. All objects are included except UGC 5675, which does not have data at 24 $\mu$m. Lower limits are given for Malin 1 and UGC 9024, which are not detected at 160 $\mu$m.

Fig. 6.—SEDs of all the galaxies showing the IRAC and MIPS data points. The high surface brightness galaxy data are shown with filled symbols, while the LSBG data are shown with open symbols. The arrows represent 3 $\sigma$ upper limits at 70 and 160 $\mu$m.

Fig. 7.—Metallicity and absolute magnitude at 24 $\mu$m for all the galaxies except UGC 5675, for which 24 $\mu$m data are not available. While it would be expected for the galaxies to follow the $L$-$Z$ trend, the difficulty in determining metallicities seems to have weakened the correlation.
necessary to create large amounts of aromatic molecules in low-metallicity galaxies.

5. SUMMARY

Spitzer data on five low surface brightness galaxies indicate that a fraction of these objects contain modest amounts of dust, despite their low metallicities and apparent transparency. The LSBGs are detected at all IRAC wavelengths, and two are detected at all of the MIPS wavelengths. Those LSBGs and late-type high surface brightness counterparts that have detectable dust appear to be the same galaxies that have the largest amounts of star formation, while those that do not have detectable dust are the most diffuse, least star-forming galaxies (e.g., Malin 1). One explanation for this is that any dust existing in galaxies has to be heated to temperatures in the range 15–20 K by ultraviolet photons escaping from star-forming regions before being detectable at far-IR and submillimeter wavelengths. The gathering evidence shows that modest amounts of dust can be created and maintained in a variety of environments and in galaxies of widely varying apparent formation histories. We also find that LSBGs exhibit less far-IR emission and greater variety in far-IR properties than is predicted by scaling related but higher surface brightness galaxy SEDs.

We thank Dean Hines and Jeroen Bouwman for allowing us to use the FEPS data reduction pipeline. This work is based 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. This research has made use of the NASA/IPAC Extragalactic Database (NED), which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

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Fig. 8.—Left: Mid-infrared colors of the galaxy sample, with $R_1$ and $R_2$ defined as in Engelbracht et al. (2005). Right: Galaxy metallicity as a function of the 8 to 24 μm color, $R_2$. Circles represent LSBGs, the square represents UGC 10445, and the triangle represents UGC 6879. The data points from Engelbracht et al. (2005) are shown as crosses. There is a slight upward trend of increasing aromatic strength with increasing metallicity.
