ABSTRACT

We present spectra taken with the Infrared Spectrograph on the Spitzer Space Telescope covering the 5–38 μm region of three ultraluminous infrared galaxies (ULIRGs): Mrk 1014 (z = 0.163), Mrk 463 (z = 0.051), and UGC 5101 (z = 0.039). The continua of UGC 5101 and Mrk 463 show strong silicate absorption suggesting significant optical depths to the nuclei at 10 μm. UGC 5101 also shows the clear presence of water ice in absorption. Polycyclic aromatic hydrocarbon (PAH) emission features are seen in both Mrk 1014 and UGC 5101, including the 16.4 μm line in UGC 5101. The fine-structure lines are consistent with dominant active galactic nucleus (AGN) power sources in both Mrk 1014 and Mrk 463. In UGC 5101 we detect the [Ne v] 14.3 μm emission line, providing the first direct evidence for a buried AGN in the mid-infrared. The detection of the 9.66 μm and 17.03 μm H₂ emission lines in both UGC 5101 and Mrk 463 suggest that the warm molecular gas accounts for 22% and 48% of the total molecular gas masses in these galaxies.

Subject headings: galaxies: active — galaxies: individual (Markarian 1014, Markarian 463, UGC 5101) — galaxies: Seyfert — galaxies: starburst — infrared: galaxies: quasars: general

1. INTRODUCTION

Ultraluminous infrared galaxies (ULIRGs), i.e., those galaxies with infrared luminosity L_{IR} \gtrsim 10^{12} L_\odot, have the power output of quasars yet emit nearly all of their energy in the mid- and far-infrared part of the spectrum. Most ULIRGs are found in interacting and merging systems (e.g., Armus et al. 1987; Sanders et al. 1988b; Murphy et al. 1996), where the merger has driven gas and dust toward the remnant nucleus, fueling a massive starburst, and either creating or fueling a nascent active galactic nucleus (AGN) (Mihos & Hernquist 1996). ULIRGs are rare in the local universe, comprising only 3% of the Infrared Astronomical Satellite (IRAS) Bright Galaxy Survey (Soifer et al. 1987), yet at z > 2–3, ULIRGs may account for the bulk of all star formation activity and dominate the far-infrared background (e.g., Blain et al. 2002).

Observations with the Infrared Observatory (ISO) satellite greatly expanded our understanding of the mid-infrared spectra of ULIRGs (e.g., Genzel et al. 1998; Lutz et al. 1999; Rigopoulou et al. 1999; Sturm et al. 2002; Tran et al. 2001). Diagnostic diagrams based on fine-structure and aromatic emission features (unidentified interstellar bands [UIBs] or polycyclic aromatic hydrocarbons [PAHs]) allowed some ULIRGs to be classified according to their dominant ionization mechanism. However, the complexities of the ULIRG spectra, the fact that many are likely composite AGN and starburst sources, and the limitations in sensitivity of the ISO spectrometers, left many ULIRGs, even at relatively low redshift, beyond the reach of these methods until now.

In order to adequately sample the local ULIRG population, we are obtaining mid-infrared spectra of a large number (>100) of ULIRGs having 0.02 < z < 0.93 with the Infrared Spectrograph (IRS) on the Spitzer Space Telescope, as part of the IRS guaranteed time program. These sources are chosen from the complete Bright Galaxy Sample (Soifer et al. 1987), the 1 Jy (Kim & Sanders 1998) and 2 Jy (Strauss et al. 1992) samples, and the Herschel/IRAS radio–far-IR sample of Stanford et al. (2000). In this paper, we present the first results from this program, focusing on three nearby ULIRGs (UGC 5101, Mrk 463, and Mrk 1014) whose spectra reflect the range of properties we expect from the sample as a whole.

UGC 5101 (z = 0.039) has a single, very red nucleus within a disturbed morphology suggestive of a recent interaction and mergerSanders et al. 1988b. Optically, UGC 5101 is classified as a LINER (Veilleux et al. 1995). It has a high brightness temperature (T > 10⁷ K) radio nucleus at 1.6 GHz, which is resolved with the VLBA (Lonsdale et al. 1995). ISO SWS and PH-T-S spectroscopy (Genzel et al. 1998) indicate a powerful, circumnuclear starburst. Ground-based, high-resolution mid-IR imaging (Soifer et al. 2000) indicates that ∼60% of the IRAS flux at 12 μm comes from the central 4″ and that nearly half of this arises in an unresolved core. Based on its IRAS colors, UGC 5101 is classified as a cold, starburst-dominated, far-infrared source. However, XMM-Newton data indicate an obscured, but luminous, hard X-ray source with L_{X}(2–10 keV) ∼ 5 \times 10^{39} ergs s⁻¹ and L_{X}(2–10 keV)/L_{IR} ∼ 0.002 suggestive of a buried AGN (Imanishi et al. 2003). Here

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we present the first direct infrared evidence for an AGN in UGC 5101.

Mrk 463 ($z = 0.0508$) is a merging system with two nuclei separated by about 4″ (Mazzarella et al. 1991). Both nuclei have Seyfert 2 optical spectra (Shuder & Osterbrock 1981), but broad lines are seen in scattered optical (Miller & Goodrich 1990) and direct near-infrared light (Goodrich et al. 1994; Veilleux et al. 1997). The eastern nucleus (Mrk 463e) is much redder ($V - K = 6.8$ mag), and has a luminous, steep-spectrum radio core (Mazzarella et al. 1991). Although the far-infrared luminosity of Mrk 463 ($5 \times 10^{11} L_\odot$) is slightly less than the canonical ULIRG cutoff of $10^{12} L_\odot$, the bolometric luminosity of this system is very high, and we refer to it as a ULIRG for the remainder of this paper.

Mrk 1014 ($z = 0.1631$) is a radio-quiet, infrared luminous QSO with broad optical emission lines (FWHM H$\beta > 4000$ km s$^{-1}$) and twin tidal tails indicative of a recent interaction and merger (MacKenty & Stockton 1984). Both Mrk 463 and Mrk 1014 are warm, far-infrared sources with $S_{25\mu m}/S_{60\mu m} = 0.74$ and 0.27, respectively (Sanders et al. 1988a).

| Property | UGC 5101 | Mrk 1014 | Mrk 463e |
|----------|----------|----------|----------|
| Date     | 2003 Nov 15 | 2004 Jan 7 | 2004 Jan 7 |
| PU target | BD +62°1078 | HD 121829 | HD 12382 |
| SL1 integration time (s) | 6 × 14 | 6 × 14 | 6 × 14 |
| SL2 integration time (s) | 6 × 14 | 6 × 14 | 6 × 14 |
| LL1 integration time (s) | 4 × 30 | 4 × 30 | 4 × 14 |
| LL2 integration time (s) | 4 × 30 | 4 × 30 | 6 × 14 |
| SH integration time (s) | 2 × 30 | 12 × 30 | 12 × 30 |
| LH integration time (s) | 2 × 60 | 8 × 60 | 8 × 60 |

Notes.—IRS observation details, including dates, peak-up target, and integration times are given for each galaxy. For each slit we list the cycles and ramp durations, where 6 × 14 s indicates six cycles of 14 s ramps, including both nod positions. The SL and LL observations for UGC 5101 were performed on 2004 March 23, while the SH and LH observations were performed on 2003 November 15.
Throughout the paper, we will adopt a flat, $\Lambda$-dominated universe ($H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$). The luminosity distances to UGC 5101, Mrk 463, and Mrk 1014 are then 170 Mpc, 223 Mpc, and 774 Mpc, and $1^\circ$ subtends 0.76, 0.98, and 2.77 kpc in projection, respectively.

### 2. OBSERVATIONS

Details of the observations are given in Table 1. The IRS is fully described in Houck et al. (2004). All three ULIRGs were observed in the two low-resolution ($64 < R < 128$; Short-Low [SL] and Long-Low [LL]) and two high-resolution ($R \sim 600$; Short-High [SH] and Long-High [LH]) IRS modules, using the staring mode Astronomical Observing Template (AOT). High accuracy blue peak-ups were performed on nearby 2MASS stars before offsetting to the target galaxies. For Mrk 463, the eastern nucleus, Mrk 463e, was centered in the IRS slits in all cases. While the separation of the nuclei is comparable to or less than the widths of the IRS slits, we expect Mrk 463e to dominate at all IRS wavelengths.

### 3. DATA REDUCTION AND ANALYSIS

All spectra were reduced using the IRS pipeline at the Spitzer Science Center. This reduction includes ramp fitting, dark-sky subtraction, droop correction, linearity correction, flat-fielding, and wavelength and flux calibration (see chap. 7 of the Spitzer Observers Manual and Decin et al. 2004 for details). The SL and LL data have had local background light subtracted, by differencing the two nod positions along the slit, before spectral extraction. As a final step, we have normalized the SL and LL one-dimensional spectra upward to match the 12 and 25 $\mu$m IRAS FSC data (Moshir et al. 1990). The final, average SL and LL spectra are displayed in Figure 1.

Since the SH and LH slits are too small for on-slit background subtraction, we have subtracted the expected background flux through each slit based on the model of Reach and coworkers. The SH and LH spectra were then scaled, on an order by order basis, to the corresponding low-resolution data. The average SH and LH spectra are shown in Figures 2 and 3.

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Fig. 2.—IRS Short-High spectra of Mrk 1014, Mrk 463e, and UGC 5101. Prominent emission lines are marked.

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8 See http://ssc.spitzer.caltech.edu/documents/background/.
respectively. While most high-resolution orders line up very well, there are slight offsets and residual curvature still visible in some orders (e.g., the bluest SH orders of Mrk 1014 and at rest wavelengths of 12 and 22 μm). Noisy areas at the red end of the SH and LH orders in order overlap regions are not shown or used in the fitting process. In SH, these noisy areas amount to typically 10–30 pixels at the red end of orders 13–20, corresponding to an area of decreased responsivity on the array.

4. RESULTS

4.1. Continuum and Absorption Features

The continua of Mrk 1014, Mrk 463e, and UGC 5101 are strikingly different. The low-resolution spectrum of UGC 5101 is a blend of a water ice (most easily seen as a strong absorption under the 6.2 μm PAH emission feature), and silicate-absorbed (at 9.7 and 18 μm) starburst spectrum (see Fig. 1). Much of the silicate absorption is filled in by the flanking PAH emission features. Adopting a smooth continuum anchored at 5.3–5.6, 14, and 34 μm, we derive optical depths of \( \tau_{9.7} = 0.75 \), \( \tau_{9.7} \geq 2 \), and \( \tau_{18} \geq 0.4 \). The extinction to the central source is thus at least \( A_V = 15–35 \) mag. As suggested by Spoon et al. (2002), the water ice features may indicate the presence of shielded molecular clouds along the line of sight to the nucleus. While the 5.7–7.5 μm absorption is dominated by water ice, the structure visible from 6.8 to 7.5 μm is consistent with hydrocarbon absorption at the level \( \tau_{6.85} \sim 0.16 \) expected from the 3.4 μm band (Imanishi et al. 2001), assuming an optical depth ratio of \( \tau_{6.85} / \tau_{3.4} = 0.238 \) (as measured for Sgr A* by Chiar et al. 2000).

Mrk 1014 shows no obvious silicate absorption, suggesting a rather clean line of sight at 10 μm to the Seyfert 1 nucleus. Mrk 463e is intermediate in its continuum properties between UGC 5101 and Mrk 1014. The most obvious continuum feature is the silicate absorption at 9.7 μm. Adopting a power-law continuum from 7 to 14 μm, we derive an optical depth \( \tau_{9.7} = 0.46 \), corresponding to \( A_V = 3–8 \) mag.

4.2. Emission Features

At high resolution, the IRS spectra of Mrk 1014, Mrk 463e, and UGC 5101 are dominated by unresolved atomic, fine-structure lines of Ne, O, Si, and S, covering a large range in
The [Ne iii] 14.3 μm line with a flux of 5.2(±0.7)×10^{-21} W cm^{-2} indicating a buried AGN. The measured [Ne v] 14.3 flux is approximately a factor of 3 below the upper limit set by Genzel et al. (1998). We also detect the [O iv] 25.89 μm line with a flux of 5.5(±1.4)×10^{-21} W cm^{-2}. A faint [Ne v] 24.3 μm line is also visible in the LH spectrum. The [S iii] 18.7(5)/[S iii] 33.4 and the [Ne v] 14.3/[Ne iv] 24.3 line flux ratios imply electron densities at or below 10^{2} cm^{-3}, and the [Ne iii] 15.5/[Ne ii] 12.8 line flux ratio implies a moderate excitation starburst (Verma et al. 2003). While the [Ne v] 14.3/[Ne ii] 12.8 and the [O iv] 25.9/[Ne ii] 12.8 line flux ratios (~0.1 in each case) are consistent with an AGN contribution of less than 10% to the total luminosity in this source (Sturm et al. 2002), the large optical depth to the nucleus, as evidenced by the deep silicate absorption, leaves open the possibility that the true contribution of the AGN to the bolometric power output in UGC 5101 may be larger than revealed by the mid-IR emission lines.

The H2 S(3) 9.66 μm and S(1) 17.04 μm pure rotational lines from warm molecular gas are seen in both UGC 5101 and Mrk 463e. In UGC 5101 the S(3)/S(1) line flux ratio is about 0.5, while in Mrk 463e it is ~1.3, implying warm gas temperatures (assuming LTE) of approximately 300 and 400 K, respectively. If the S(1) line emission is from an unresolved source in both cases, there is ~1.1 and 0.5×10^{2} M_o of warm molecular gas in UGC 5101 and Mrk 463e, respectively. These warm molecular gas emissions are 22% and 48%, respectively, of the total H2 masses (warm plus cold) in these galaxies for α = 0.8 M_o/(K km s^{-1} pc^2)^{-1} (Solomon et al. 1997; Evans et al. 2002).

We detect the 6.2, 7.7, 11.3, and 12.7 μm PAH emission features in UGC 5101, and all but the 12.7 μm feature in Mrk 1014 (see Figs. 1 and 2). A weak 7.7 μm feature may be present in the SL spectrum of Mrk 463e. In addition, we detect the 16.4 μm PAH feature (e.g., Moutou et al. 2000) in UGC 5101. To our knowledge, this is the first detection of this feature in a ULIRG, although it is seen in some nearby starburst galaxies (Sturm et al. 2000; Smith et al. 2004). The 7.7 μm line-to-continuum (L/C) ratios we measure for Mrk 1014, Mrk 463e, and UGC 5101 are 0.25, 0.05, and 1.1, respectively. A ratio of L/C ≥ 1.0 is usually taken to imply a dominant starburst contribution to the mid-infrared flux (Rigopoulou et al. 1999). The relatively strong 7.7 and 11.3 μm features in Mrk 1014 may indicate that a circumnuclear starburst is present in this Seyfert 1 galaxy.

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### TABLE 2

| Emission Features | Line (μm) | UGC 5101 | Mrk 1014 | Mrk 463e |
|-------------------|-----------|----------|----------|----------|
| PAH 6.2           | 190(11)   | 14.4(1.8)|          |          |
| [Ne ii] 12.8      | 55.2(2.5) | 7.8(0.8) | 11.6(0.7)|          |
| [Ne v] 14.3       | 5.2(0.7)  | 6.8(0.6)| 18.3(0.8)|          |
| [Ne ii] 15.5      | 23.9(1.4) | 13.3(1.1)| 51.8(2.5)|          |
| PAH 16.4          | 14.5(1.9) |          |          |          |
| [Ne ii] 18.7      | 9.8(0.7)  |          | 15.0(1.6)|          |
| [Ne v] 23.41      | 4.9(1.0)  | 5.1(0.5)| 20.4(1.7)|          |
| [O iv] 25.89      | 5.5(1.4)  | 13.5(1.5)| 72.3(1.2)|          |
| [S iii] 33.48     | 13.0(2.5) |          | 13.5(1.6)|          |
| [Si iv] 34.81     | 36.6(1)   |          | 30.3(5.9)|          |
|                  |           | 0.047    | 0.076    |          |

Notes.—For each line we give the central wavelength in microns, the flux in units of 10^{-21} W cm^{-2}, and the equivalent width, in microns, directly below. Formal uncertainties in the line fits (all single Gaussians except where noted) are listed in parentheses next to the fluxes. However, true uncertainties in the absolute line fluxes are generally ~20–25%. All lines were measured using the SMART spectral reduction package (Higdon et al. 2004).

a The [Ar ii] 6.98 line is blended with the H2 S(5) line in UGC 5101.

b The [Ne v] 7.65 line is blended with the H2 S(5) line in UGC 5101.
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