

Mid-Infrared Spectroscopy of Infrared Luminous Galaxies with Sub-Arcsecond Resolution ¹

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ABSTRACT

Low spectral resolution ($\Delta\lambda/\lambda \sim 50$) mid-infrared observations with high angular resolution ($0.3\text{--}0.5''$) using the Long Wavelength Spectrometer on the Keck I Telescope are reported of the nuclei of five highly luminous infrared bright galaxies. Spectra of eight distinct nuclei, ranging in luminosity from $\sim 10^{11}L_{\odot}$ to $> 10^{12}L_{\odot}$ have been obtained. Four of the nuclei show the characteristic PAH emission features, i.e. $11.3\mu\text{m}$ emission as well as the $8.6\mu\text{m}$ shoulder of the $7.7\mu\text{m}$ band. The other nuclei show either weak PAH emission bands or no evidence for these bands.

The high spatial resolution of the observations reveals extended emission in the $11.3\mu\text{m}$ PAH band associated with several of the compact nuclear sources. When proper account is taken of the diffuse PAH emission, most of the compact sources show little or no directly associated PAH emission. The diffuse PAH emission is extended over spatial scales of $100\text{--}500$ pc; its presence shows that there is significant circumnuclear UV/optical emission exciting the aromatic bands, most likely associated with circumnuclear starbursts.

After the spectra of the nuclear sources are corrected for the spectrum of the diffuse PAH emission, the peak apparent silicate optical depth at $9.7\mu\text{m}$ can be as great as

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15, corresponding to > 150 magnitudes of visible light extinction. Because of the large silicate optical depths, mid-infrared spectra are not probing the nature of the true nuclei in the most opaque compact sources.

Subject headings: luminous infrared galaxies, spectroscopy, infrared, galaxies individual: VV 114; IRAS 08572+3915; Markarian 463; Markarian 273; Arp 220

1. Introduction

Submillimeter observations (e.g. Eales et al. 2000, Blain et al. 1999) suggest that ultraluminous infrared galaxies (ULIRGs) at high redshift can account for the cosmic IR background (cf. Hauser & Dwek, 2001). If powered by star formation, these ULIRGs can account for as much star formation as the galaxies detected in the UV continuum. Alternatively, if the infrared luminosity is attributed to dust-enshrouded AGN, the cosmic IR background could be measuring the integrated accretion power generated over the history of the universe.

Such observations illustrate the importance of understanding the origin of the luminosity in infrared bright galaxies. Because these galaxies are by their nature dusty, the normal optical/near infrared diagnostics break down, since the luminosity sources are obscured by many magnitudes of visual extinction. Attributing the luminosity to dust enshrouded star formation or accretion onto black holes has drastically different consequences for assessing the star formation history of the universe.

Recent spectroscopic observations from ISO have suggested that spectroscopic diagnostics of the underlying power sources do exist within the mid-infrared. Genzel et al (1998) suggested that there is a correspondence between the presence of strong aromatic features (Polycyclic Aromatic Hydrocarbons, commonly referred to as PAHs) at 6.2, 7.7, 8.6 and 11.3 μm and other diagnostics of stellar ionizing radiation from young, massive stars, while weak or non-existent aromatic features are associated with infrared galaxies whose luminosity is generated via AGNs.

The ISO observations were hampered by the large observing beams, which included nearly all the infrared light from the galaxies, thereby combining both nuclear and circumnuclear emission. In Seyfert galaxies such as NGC 1068 and NGC 7469 (cf. Myer & Scoville 1987, Wilson et al. 1991), large observing beams include both a nuclear AGN and a circumstellar starburst, so that the integrated spectrum is a combination of radiation generated in multiple regions with widely varying excitation conditions.

Ground-based, airborne and space-based observations, e.g. Gillett et al. (1975a), Willner et al. (1977), Helou et al. (2000), Sturm et al.(2000) have demonstrated that the full suite of PAH features is readily seen in many galaxies. Indeed, as shown by Genzel et al. (1998), Lutz et al.(1998), Rigopoulou et al. (1999) and Tran et al. (2001) these bands can dominate the mid-infrared spectra of ULIRGs. The 11.3 μm feature is readily detectable, having a line to continuum strength roughly

half that of the $7.7\mu\text{m}$ band in nearby galaxies such as M82 (Gillett et al., Sturm et al.). Thus, the detection of PAH emission via the $11.3\mu\text{m}$ band should be nearly equivalent to using the broader $7.7\mu\text{m}$ complex of features. The presence of the $9.7\mu\text{m}$ silicate feature, which can produce strong absorption over the entire 8-13 μm region, complicates the interpretation of mid-infrared spectra. Silicate absorption has been shown to be quite strong in some galaxy spectra (Roche et al. 1991).

The upcoming launch of SIRTf, with its capability of studying the spectra of ULIRGs to redshifts substantially greater than one, highlights the need to develop infrared diagnostics of the luminosity in dusty, luminous galaxies. We have obtained low spectral resolution ($\lambda/\Delta\lambda \sim 50$) mid-infrared observations from 8 – 12.5 μm of a sample of infrared luminous galaxies with 0.3–0.5'' spatial resolution using the Long Wavelength Spectrometer (LWS) on the Keck I Telescope. With this spatial resolution we have been able to isolate individual compact sources that are emitting copiously in the infrared and are our best local examples of ULIRGs.

Spectroscopy of some of the sources observed here has been reported by Smith, Aitken and Roche (1989), Roche et al. (1991) and Dudley (1999). The data reported here are obtained with substantially higher spatial resolution that has allowed us to resolve the separate nuclei in the multiple nuclei sources as well as to explicitly detect spatially extended PAH emission associated with the nuclei.

2. The Sample

The objects observed were selected to be high luminosity galaxies that are bright at 12 μm . VV 114, Markarian 273, IRAS 08572+3915, and Arp 220 were all selected from the IRAS Bright Galaxy Sample (Soifer, et al. 1987), while Markarian 463E is included in the Ultraluminous Warm Galaxy Sample (Sanders, et al. 1988a). The total infrared luminosities of the systems range from $4 \times 10^{11} L_{\odot}$ for VV 114 (Soifer et al.) to $1.5 \times 10^{12} L_{\odot}$ for Arp 220 (Sanders et al. 1988b). Mid-infrared imaging with resolution of 0.3''–0.5'' has been previously reported for Arp 220, Markarian 273 and IRAS 08572+3915, and VV 114 (Soifer, et al. 1999, 2000, 2001). In VV 114, Arp 220, and Markarian 273, two compact sources were seen at $12.5\mu\text{m}$, while in IRAS 08572+3915 a single unresolved source was detected that contains nearly all the bolometric luminosity of the source. No mid - infrared imaging of Markarian 463 has been reported in the literature; as shown below, the present observations show a compact core which emits essentially all the mid-infrared luminosity of the galaxy. Table 1 lists the basic properties of the sources that were observed.

3. Observations and Data Reduction

The observations were made using the low resolution spectroscopic mode of the LWS (Jones & Puetter, 1993) at the f/25 forward Cassegrain focus of the Keck I 10-m Telescope. Briefly, LWS includes a grating spectrometer which contains a 128×128 pixel Si:As array. The spectral dispersion

is $0.0375 \mu\text{m pixel}^{-1}$, and the spatial scale is $0.08'' \text{ pixel}^{-1}$. For the present spectroscopy, a filter with bandpass from 8.1 to $13.0 \mu\text{m}$ was used for order selection; 128×95 pixels (dispersion \times cross dispersion) were un-vignetted, so a wavelength coverage of $4.8 \mu\text{m}$ was available over a $7.6''$ slit length.

The present observations were obtained in May, September, and December of 2000. A log of the observations is presented in Table 2. The observations were made at air masses between 1.1 and 1.5. The atmospheric absorption in the observed spectra was monitored by observing HR=BS 5340 in May, 2000 and BS 8775 in September, 2000 and December, 2000 at similar air masses. For each source an image at $12.5 \mu\text{m}$ or $11.7 \mu\text{m}$ was obtained using the imaging mode of the LWS before spectra were taken as part of the procedure of setting up the target for spectroscopic observations. Observations of stars indicated the seeing had a full width at half maximum (FWHM) between $0.3''$ and $0.4''$. The FWHM and the total on-source integration times for the objects observed are listed in Table 2.

The observations used chopping at a frequency of ~ 1.7 Hz and nodding of the telescope every ~ 30 seconds to suppress sky emission. The telescope was nodded in the same direction as the chopping and the nodding amplitude was the same as the chopping amplitude which is given in Table 2. The chopping/nod direction was set parallel to the slit so that, if the source structure allowed a sufficiently small chopping amplitude, three dispersed images of the objects were on the array. Observations were divided into runs of ~ 6 minutes each. During the observations of the objects, the telescope tracking was controlled using an offset guider with a visible guide star.

For all these observations the slit was six pixels ($0.48''$) wide corresponding to a spectral resolution of $0.22\mu\text{m}$ or $\lambda/\Delta\lambda \sim 50$ for a source uniformly filling the slit. Because the seeing was typically less than the slit width, the spectral resolution was set by the image size, and not the slit width. The seeing disk is close to the diffraction limit, which results in a variable image size; hence the spectral resolution varies with wavelength. In general, the slit position angle on the sky was determined by the location of an appropriately bright offset guide star. This limited the observations to only one infrared component at a time in VV 114 and Markarian 273, even though there were two distinct source components. In the case of Arp 220 a guide star could be used that allowed the slit to be oriented such that both nuclei, separated by $\sim 1''$ (Soifer et al. 1999), could be observed in a single spectrum.

The spectra were reduced by first combining the individual images to subtract the sky contribution. The resultant images were then co-added after appropriately shifting the images (a) parallel to the slit to co-add the rows containing the object and (b) in the dispersion direction to align the ozone emission present in the raw un-sky-subtracted frames. One-dimensional spectra were obtained by extracting five rows ($0.40''$) centered on the maximum emission, and subtracting from this the spectrum of the night sky extracted in the two dimensional spectral image well away from the object. In order to increase the signal to noise ratios, three pixels (half the slit width) throughout the wavelength range of the spectra were averaged in a running average. Many of the

spectra showed a deep absorption band and consequently had locally extremely low signal to noise ratios. For some of these spectra a running average of several more pixels over the wavelength range of low signal was taken, reducing the spectral resolution but increasing the signal to noise ratio. The resultant spectral resolution is indicated in Table 2. The noise per pixel at each wavelength was calculated from the “sky” well away from the object.

Atmospheric and instrumental features, most notably the deep atmospheric ozone absorption at $9.6 \mu\text{m}$, were removed by dividing the object spectrum by the spectrum of BS 5340 and multiplying by a blackbody spectrum at the star’s effective temperature. Since the stellar image was generally smaller than the slit width, the star set both the spectral resolution and wavelength scale of the spectrum, and was often at a different wavelength than that of the associated galaxy spectrum, as evidenced by sharp discontinuities at the edges of the ozone absorption band. After extensive experimentation, it was found better to use an average spectrum of 15 observations of BS 5340 than a single spectrum of a near-by (in time) stellar observation.

The wavelengths of the stellar spectrum were established by comparing the observed stellar spectrum of BS 5340 with models of the earth’s transmission over this wavelength range calculated by Lord (1992). The final wavelength solution for each object was refined, within the bounds set by the ozone emission, by identifying different astrophysical or terrestrial atmosphere features in each object. In VV 114E_{NE}, Markarian 273N, and Arp 220 it was possible to use the emission of the PAH band at $11.25 \mu\text{m}$ (hereafter referred to as the $11.3\mu\text{m}$ feature) in the rest frame to set the wavelengths. In Markarian 463E the continuum was strong enough so that the atmospheric ozone absorption was detectable in individual spectra and was used to establish the wavelength scale. For the remaining three objects, an attempt was made to match the deep atmospheric absorption at $9.6 \mu\text{m}$ before dividing by the stellar spectrum.

4. Results

The mid-infrared spectra of the galaxy nuclei are presented in Figure 1. The individual spectra are described in the following sections.

4.1. VV 114

The structure of VV 114 is dominated at infrared wavelengths by two compact sources (Knop et al. 1994, Doyon et al. 1995, Soifer et al. 2001), both within the highly obscured eastern component of the source, referred to by Soifer et al. as VV 114E_{NE} and VV 114E_{SW}. $2.2\mu\text{m}$ imaging of VV 114E with NICMOS on HST (Scoville et al. 2000) showed that VV 114E_{NE} is slightly extended while VV 114E_{SW} is unresolved. Mid-infrared photometry of these sources (Soifer et al. 2001) reveals a deeper depression in the mid-infrared SED in the brighter northeast component.

Figure 1 shows the spectra of VV 114E_{NE} and VV 114E_{SW}. The two peaks are separated by 1.8'' at 12.5 μ m (Soifer et al. 2001). With seeing of 0.4'' the slit width of 0.5'' isolates the separate peaks. The spectra show that indeed the 10 μ m depression of VV 114E_{NE} is significantly deeper than in VV 114E_{SW}. The spectrum of VV 114E_{NE} shows the characteristic feature of aromatics, i.e. a peak at 11.3 μ m, a shoulder at 8.6 μ m and the continued rise to the shortest observed wavelengths. The minimum flux in the spectrum is at about 10.2 μ m, consistent with the aromatic spectrum of normal galaxies as seen by ISO (Helou et al. 2000).

By comparison the spectrum of VV 114E_{SW} shows a shallower rise to longer wavelengths and a weak 11.3 μ m feature. The equivalent width of the 11.3 μ m feature in VV 114E_{SW} is less than half that in VV 114E_{NE}. In addition, the minimum of the flux appears to occur at shorter wavelengths, closer to 9.8 μ m in the rest frame of the galaxy (although this might be due to a slight mismatch in the correction for the terrestrial ozone absorption at 9.6 μ m.)

4.2. IRAS 08572+3915

IRAS 08572+3915 was found by Soifer et al (2000) to be a single very compact source (<0.3'') at 12.5 μ m that contained nearly all the mid-infrared luminosity detected in the \sim 1' IRAS beam measurements. The mid-infrared spectrum of IRAS 08572+3915 is shown in Figure 1. The spectrum shows a strong depression at 10 μ m, much greater than expected from the photometry reported by Soifer et al., but consistent with that seen by Dudley and Wynn-Williams (1997). This is a result of the redshift of this object, that puts the deep depression outside the sampling of the photometric filters used by Soifer et al.

There is no evidence for PAH features in the spectrum. Rather the spectrum is characteristic of strong absorption by cold silicate dust overlying a warmer background source (e.g. Gillett et al. 1975b), showing a deep minimum at 9.7 μ m.

4.3. Markarian 273

Soifer et al.(2000) showed that this galaxy is dominated by two compact sources separated by 1'' at mid-infrared wavelengths. Markarian 273NE is slightly extended, mostly in the east-west direction in the NICMOS 2.2 μ m image of Scoville et al. (2000), while Markarian 273SW is unresolved in the same NICMOS 2.2 μ m image. Soifer et al. showed that the northern source is generally brighter in the mid-infrared, but with a stronger depression at 10 μ m.

The mid-infrared spectra of the separate nuclei of Markarian 273 are shown in Figure 1. With seeing of \sim 0.3'' the 0.5'' slit adequately separates the spectra of the two nuclei. Markarian 273NE shows a broad depression centered shortward of 10 μ m, rising steeply to shorter and longer wavelengths. The spectrum shows a clear peak at 11.3 μ m and shoulder at 8.6 μ m showing the presence

of the aromatic PAH features.

The spectrum of Markarian 273SW is significantly different from that of Markarian 273NE, i.e. much less depression at $10\ \mu\text{m}$ and little evidence for an $11.3\ \mu\text{m}$ feature. The rise in flux to shorter wavelengths coincides with that seen in the northern source. The flattening at $\lambda < 8.6\ \mu\text{m}$ is suggestive of PAH emission.

4.4. Markarian 463E

Markarian 463E was found by Sanders et al. (1988a) to be a high luminosity galaxy with a “warm” mid-infrared color, i.e. larger $25/60\ \mu\text{m}$ flux density ratio than most ULIRGs in the IRAS Bright Galaxy Sample (Soifer et al. 1987, Sanders et al. 1988b). The optical spectroscopic classification of Markarian 463E is that of a Seyfert galaxy (Miller & Goodrich, 1990).

Imaging at $12.5\ \mu\text{m}$ done in conjunction with the mid-infrared spectroscopy shows Markarian 463E to be compact, with a source of angular diameter $< 0.5''$, or 500 pc for a redshift of $z=0.05$, containing all the $12\ \mu\text{m}$ flux measured by IRAS. The mid-infrared spectrum is shown in Figure 1. The spectrum shows a drop from 8.0 to $9.6\ \mu\text{m}$, a minimum at $\sim 10.0\ \mu\text{m}$ and then a slightly rising continuum to longer wavelengths. There is structure in the spectrum at about $9.2\ \mu\text{m}$ which is most likely associated with imperfectly corrected ozone absorption in the observations. There is a peak at $10.55\ \mu\text{m}$ and no evidence for peaks at 8.6 or $11.3\ \mu\text{m}$. The peak at $10.55\ \mu\text{m}$ could represent [SIV] emission, which is strong in ISO-SWS spectra of comparable sources (Sturm et al. 1999, Lutz et al. 2000).

4.5. Arp 220

Arp 220 is the closest ULIRG (Soifer et al. 1984, Sanders et al. 1988b), at a redshift $z=0.018$. The two nuclei seen at $12.5\ \mu\text{m}$ (Soifer et al. 1999) are separated by $1''$ or 360 pc. The slit position angle was 92° so that both nuclei were on the slit at the same time. The seeing was $\sim 0.3''$ for the observations, so that the spectra of the nuclei are well separated.

The spectra of the separate nuclei are shown in Figure 1. The spectra of both nuclei show strong minima at $\sim 10\ \mu\text{m}$ with roughly the same depression compared to the flux density at $8\ \mu\text{m}$. The spectra of the nuclei are quite similar, the fainter eastern component shows somewhat stronger PAH emission, with a clear peak at $11.3\ \mu\text{m}$ and a shoulder at $8.6\ \mu\text{m}$. In the brighter western source the PAH features are present but not as prominent.

4.6. Diffuse PAH Emission

The continuum sources are spatially compact, consistent with the sizes measured in previous imaging observations (Soifer et al. 1999, 2000, 2001). In addition to the compact continuum structure, there is extended emission in the $11.3\mu\text{m}$ PAH emission feature in some galaxy nuclei in this sample. In the three sources where this feature is prominent – VV 114_{NE}, Markarian 273NE and Arp 220 – the PAH emission is clearly extended. This is revealed in the two-dimensional spectra of these sources shown in Figure 2.

Figure 2a displays a gray scale image of the two-dimensional spectrum in the region of the $11.3\mu\text{m}$ PAH feature in Arp 220 with a contour plot of the intensity overlaid. The continuum emission from the two compact sources in Arp 220 is clearly seen along the spectral dimension, while at $11.3\mu\text{m}$ a band is seen bridging the $1.0''$ (360 pc) gap between the two continuum sources. There is weak PAH emission extending beyond the eastern source (see below). In Figure 2b, spatially extended PAH emission is seen extending to one side of the continuum source in Markarian 273NE by about $0.7''$ (500pc).

In VV114_{NE} (Figure 2c) there is clear $11.3\mu\text{m}$ emission extending in the spatial domain in both directions from the continuum source. The PAH emission extends $\sim 1.3''$ (500 pc) south and $0.7''$ (300 pc) north of the continuum source. An artifact of the observations, which is most clearly seen in the contour plot/grayscale of Figure 2c, is the apparent shift of the wavelength of the PAH feature along the spatial dimension. The shift is probably a result of the seeing disk being small compared to the slit width ($0.5''$), so that shifts in the centroid of the emission within the slit translate in the spectra to apparent shifts in the wavelength along the slit.

To show the spatial distribution of the PAH emission in Arp 220 in more detail, we have constructed a PAH-only spectral image by subtracting a modeled continuum emission. The results are shown in Figure 3. The spatial profile of the continuum was derived by summing the 2-D spectral image (Figure 3a) over wavelengths longward of $12\mu\text{m}$, where the continuum is strong and there is no strong emission line. Then, the continuum spectrum was constructed in two stages. First, seven rows (i.e. pixels in the spatial direction) centered on the maximum emission of the western nucleus were summed to create an average spectrum of the western source. Second, the PAH contaminated spectral regions were masked and a 5th order polynomial was fit to the average spectrum to produce a 1-D pure continuum spectrum. A 2-D continuum spectral image was then created by replicating the spatial profile in the wavelength direction with an amplitude determined by the 1-D continuum fit.

Figure 3b shows the continuum-subtracted PAH only spectral image. It clearly indicates the diffuse nature of the PAH emission. It can also be seen that the peak of the PAH emission is slightly displaced toward the eastern nucleus.

Figure 3c compares the spatial distribution of the continuum and PAH emission. To produce these profiles, the flux over $0.187\mu\text{m}$ (five columns) centered on the peak of the PAH emission

was summed along the wavelength direction in the PAH only image (Figure 3b) and the modeled continuum image. This shows a striking difference between the two components. Unlike the double-peaked continuum emission, the PAH emission has a single peak $\sim 0.25''$ east of the western nucleus, and is nearly uniformly distributed from this peak toward the eastern nucleus. The PAH emission drops markedly at the center of the western nucleus.

5. Discussion

The spectra presented in Figure 1 show a variety of shapes and features, but are quite similar to those seen previously in lower spatial resolution observations (cf. Roche, et al. 1991, Dudley 1999). The overall spectra are a combination of a smooth featureless continuum, absorption due to intervening cold silicate material, and PAH emission features such as seen in the nearby starburst galaxy M82 (c.f. Gillett et al. 1975a, Willner et al. 1977, Roche et al. 1991, Dudley, 1999, Sturm, et al. 2000). In addition, the high spatial resolution of the spectra, seen in Figure 2, resolves the spectra of the individual nuclei and reveals the extended nature of the PAH emission as compared to the compact continuum sources. The substantially higher spatial resolution ($0.3\text{--}0.5''$) of the present observations over previous observations permits the separation of the spectra at different spatial locations. In VV 114E_{SW} there is a hint of extended PAH emission in the two-dimensional spectrum but excess pattern noise in the spectrum precludes determining with any confidence its contribution in the extracted spectrum. In IRAS 08572+3915, Markarian 273SW and Markarian 463E there is no evidence for PAH emission in the spectrum of the compact source or in the two-dimensional spectrum from which it was extracted.

5.1. Spectra of The Compact Sources

The spectra of Arp 220 E & W, VV 114E_{NE} and Markarian 273NE, corrected for the extended PAH emission, are shown in Figure 4. To correct for the extended PAH emission, the strength of the PAH emission adjacent to the compact source was measured in the two-dimensional spectrum, and a spectrum of M82, normalized to this measured PAH strength, was subtracted from the spectrum of the continuum source of Figure 1.

A substantial uncertainty exists in the spectrum of the diffuse emission that is subtracted from the compact sources. We *assume* that this spectrum is universal and like that of M82. Because of the bright compact sources and the faint diffuse emission except in the $11.3\mu\text{m}$ PAH band, we could only measure the $11.3\mu\text{m}$ PAH strength off the nuclei. We could not independently determine the full spectrum off the nuclei. While the smoothness of the resulting spectra as displayed in Figure 4 suggests the basic validity of our procedure, potential variation of PAH to continuum strengths (e.g. Tran et al. 2001) lead to a substantial uncertainty.

Sturm et al. (2000) argue that the mid-infrared spectrum of M82 suffers negligible extinction

($A_V < 5$ mag) based, among other arguments, on model fitting of its spectrum to the observed spectrum of the reflection nebula NGC 7023. However, Willner et al (1977) estimated the extinction to the infrared continuum in M82 to be $A_V \sim 25$ mag from the measured ratio of the Br α and Br γ emission lines at 2.16 and 4.05 μm . If this latter determination of the extinction applies to the PAH emitting region, then presumably the M82 spectrum suffers a corresponding silicate absorption of $\tau_{9.7\mu\text{m}} \sim 2$ in the observed spectrum. The effect of larger extinction on the 10 μm spectrum of M82 is illustrated in Rigopoulou et al (1999). Increasing the silicate absorption over that of M82 in the subtracted spectrum would have the effect of significantly reducing the 9–11 μm continuum that is subtracted from the observed spectrum, compared to the 11.3 μm strength. In turn, this would decrease the inferred silicate absorption in the continuum sources, by preserving a detectable continuum from 9–11 μm .

In Figure 1, VV 114E_{NE} is the source with the strongest PAH emission. As seen in Figure 4, after the extended PAH emission is subtracted from the initial spectrum, little flux remains from 9 – 11 μm . There is a peak close to 11 μm that may be residual PAH emission. The residual continuum is consistent with zero flux in the wavelength range from 9 – 11 μm , suggesting that most of the apparent continuum over these wavelengths in the spectrum of Figure 1 is due to an extended, overlying PAH spectrum. The compact continuum source apparently suffers strong absorption by intervening cold silicate material.

In Markarian 273NE a significant PAH feature is seen in Figure 1. Figure 4 shows a weak PAH shoulder feature remaining after subtraction of the extended PAH emission suggesting that there is a residual PAH band associated with the compact source. This is consistent with the observation of continuum detected in the subtracted spectrum over the entire 9–11 μm range.

In Arp 220E the spectrum of Figure 1 shows a distinct PAH emission peak at 11.3 μm . When the diffuse PAH emission is subtracted from the observed spectrum, there is no evidence for residual PAH emission in the compact source, and the continuum becomes consistent with zero flux from 8.8 – 11.5 μm (Figure 4). In Arp 220W, where the spectrum of Figure 1 shows a shoulder of PAH emission on a steeply rising continuum, after subtraction of the diffuse PAH emission, a weak shoulder remains at 11.3 μm , as does a measurable continuum in the 9–11 μm band.

The spectra of Figure 4 show that the underlying compact sources suffer substantially greater foreground absorption at $\sim 10\mu\text{m}$ than would be inferred from the spectra of Figure 1. Smith, Aitken and Roche (1991) have attempted to correct the 10 μm absorption apparent in the spectrum of Arp 220 for overlying PAH emission and derive a peak optical depth of $\tau_{9.7\mu\text{m}} > 5$ which implies $A_V > 50$ mag. The spectra shown in Figure 4 suggest even greater absorption in the depth of the silicate band. From the spectra of Figure 4 we infer peak optical depths $\tau_{9.7\mu\text{m}}$ (see below) in the range 8–15, which corresponds to optical extinctions A_V of 80–150 mag.

5.2. Detailed Comparison with ISO results for Arp 220

Because it is the closest ULIRG, the results presented here for Arp 220 warrant special discussion. A major finding from these observations is that the two nuclei in Arp 220 are not luminous sources of PAH emission. As seen in Figures 2 and 3, most of the PAH emission in Arp 220 originates in the off-nuclear regions, and a significant fraction actually comes from the region between the two nuclei. Furthermore, the PAH emission drops significantly near the center of the western nucleus, which dominates the mid-infrared continuum luminosity.

The region producing the PAH emission is clearly distinct from the compact sources producing the bulk of the mid-infrared luminosity and most likely the far-infrared luminosity as well. This argues that the extinction toward the PAH emitting regions is not likely to be as large as that inferred from the ISO data. If the extinction toward the PAH emitting region were as large as previously suggested (i.e. 50 magnitudes more than to the corresponding regions in M82), star-forming regions directly associated with the PAH emitting regions would make a dominant contribution to the total continuum luminosity, which is apparently not the case, as seen in Figures 2 and 3c. This is in contrast to the picture developed from the ISO data, which suggests that the strong PAH emission seen in ULIRGs directly traces star formation that dominates the luminosity output in these galaxies (Genzel et al. 1998, Lutz et al. 1998, Rigopoulou et al. 1999, Tran et al. 2001).

The peak of the PAH emission, $\sim 0.25''$ east of the western nucleus, corresponds to the peak of the warm molecular hydrogen detected by Larkin et al. (1995). This suggests that the exciting source of the molecular hydrogen may also be responsible for the PAH emission.

5.3. The Compact Nuclei and the Diffuse PAH emission

The excitation mechanism for PAH emission is generally believed to be single UV/optical photon heating of aromatic molecules (see e.g. Sellgren, 1984, Draine & Anderson, 1985, Leger, D’Hendecourt and Defourneau, 1989). The presence of substantial diffuse PAH emission associated with the luminous compact sources shows that there is a significant optical/UV photon intensity associated with the outer parts of the sources. The spectra of the underlying compact sources show large $10\mu\text{m}$ optical depths. Based on the interstellar extinction curve (e.g. Mathis, 1990, Li & Draine, 2001) this corresponds to an order of magnitude greater extinction in the visible, and a factor of ~ 40 greater optical depth in the UV.

To roughly estimate the silicate optical depths for the sources we assumed an underlying continuum that is constant (in f_λ), and matched the apparent continuum with a silicate absorption profile as a function of wavelength from Gillett et al. (1975b). In the case of the most heavily absorbed sources, where the continuum was not detected from $9\text{--}11\mu\text{m}$, we matched the observed continuum slope, corrected for PAH emission in Figure 4, between 12 and $12.5\mu\text{m}$ (rest frame), and extrapolated the inferred optical depth to the peak optical depth at $9.7\mu\text{m}$. Because of the

uncertainties in the shape of the continuum and the simple technique employed for estimating $\tau_{9.7\mu m}$ these are crude estimates of the silicate optical depth.

The range of silicate optical depths and corresponding A_V in these sources is quite large. With $\tau_{9.7\mu m} \sim 1$ in Markarian 463E, A_V is ~ 10 mag, while in the most highly obscured sources like Arp 220E, the silicate optical depths are as great as ~ 15 , corresponding to $A_V \sim 150$ mag. Given the much higher spatial resolution of the present observations, it is not surprising that the extinction derived for the highly embedded sources in Arp 220 are larger by a factor of 2-3 than those determined from large beam ISO spectroscopic studies (e.g. Sturm et al. 1996). The extinction to the continuum sources in Arp 220 is roughly an order of magnitude greater than that derived by Larkin et al. (1995) from the $P\beta/Br\gamma$ line ratios in these same nuclei. It is common to find increased extinction determined at wavelengths that probe deeper into the regions; this suggests that we are still probing to $\tau \sim 1$ at the observed wavelengths.

The extinctions derived here are so large that it is most unlikely that the UV/optical photons that excite the extended PAH emission arise internally in the compact sources. Much more likely is a large UV/optical radiation field generated due to hot, young stars in the periphery of the compact sources. The circumnuclear regions indeed have internal dust that implies extinction of the ionizing starlight, but not in the huge columns implied from the large silicate optical depths derived above. The presence of such a circumnuclear environment is not surprising, since powerful circumnuclear starbursts have been suggested for Arp 220 and Markarian 273 from the distribution of CO gas (Sakamoto et al. 1999, Downs & Solomon, 1998).

We can crudely estimate the total luminosity associated with the diffuse PAH emission by determining the total flux in the diffuse $11.3\mu m$ PAH band and applying a bolometric correction based on an assumed ratio of the PAH band to total luminosity. If we assume that M82 has a typical PAH to bolometric luminosity ratio we derive a bolometric correction $\frac{L(PAH11.3\mu m)}{L(bol)} = 0.0014$ from the spectrum (Sturm et al. 2000) and total far infrared luminosity of M82 (Soifer et al. 1987). This correction factor is uncertain by at least a factor of two, and depends critically on the amount of additional extinction of the PAH spectrum (above that suffered in M82) in the circumnuclear environments of these sources. To decrease the ratio $\frac{L(PAH11.3\mu m)}{L(bol)}$ by an order of magnitude from that observed in M82 as a result of silicate absorption would require, for the extinction curve of Li & Draine (2001), an additional overlying silicate optical depth at $9.7\mu m$ of 3.8, or $A_V = 45$ mag above that affecting the M82 spectrum.

We have estimated the strength of the extended PAH emission (a) coincident with the continuum source and (b) integrated over the full extent of the PAH emission. We first measured the strength of the PAH band at a position adjacent to the continuum sources of Figure 2. To derive the PAH strength over the continuum source, we extrapolated this value to the spatial location of the continuum source. To determine the total PAH emitting luminosity we integrated the flux in the PAH band over its visible area in the two-dimensional spectra of Figure 2. The PAH band strengths (as measured above) were scaled to the measured fluxes of the continuum sources

(matching bandpasses and spatial locations) from the imaging studies of these objects (Soifer et al. 1999, 2000, 2001). The uncertainty in converting PAH emission to flux is at least 30%, due to uncertainties in the location of the object in the slit.

The results of these estimates for the luminosity corresponding to the PAH emission are given in Table 3 for Arp 220 E&W, VV 114E_{NE} and Markarian 273N. The luminosities attributed to PAH generating sources, i.e. circumnuclear starbursts, lie in the range from a few percent of the total bolometric luminosity in the Arp 220 sources, to more than half of the total luminosity in the compact source in VV 114E_{NE}.

If the bolometric correction that we have adopted based on the PAH emission in M82 is an underestimate because of lower extinction to the PAH emitting region in M82 than is appropriate for these galaxies, the circumnuclear luminosities associated with extended PAH emission in these systems would increase accordingly. In the case where the PAH to bolometric luminosity ratio is $\sim 10^{-4}$, i.e. corresponding to $A_V \sim 50$ mag more than to M82, the extended PAH emitting regions could account for roughly half the total bolometric luminosity of the sources. As discussed above for Arp 220, this seems extreme, since the continuum sources clearly dominate the mid-infrared flux in these observations and presumably dominate the far-infrared continuum as well.

5.4. Mid-Infrared Spectra As Diagnostics Of What Powers Compact Sources?

The spectra of the compact sources corrected for overlaying PAH emission, show a wide range of silicate optical depths, from ~ 1 to ~ 15 , and PAH strengths ranging from no detectable PAH bands to modest PAH bands. Where the detectable silicate absorptions are small, i.e. Markarian 463E, Markarian 273SW and VV 114E_{SW}, there is at most only weak evidence for PAH emission and in two of these cases strong evidence from optical spectroscopy for non-stellar (AGN) ionizing sources dominating the luminosity (Koski, 1978, Miller & Goodrich 1990) . In the other sources where silicate absorption is much greater, there is at best only weak PAH emission in the mid-infrared spectra.

Table 4 compiles the spectral classifications of these systems from a variety of wavelength regions. The last column of Table 4, from this work, is based on the strength of the $11.3\mu\text{m}$ PAH band in the spectrum. The change in classification when correcting for the overlying PAH emission shows the importance of utilizing the highest possible spatial resolution.

Interpreting the mid-infrared spectra in terms of underlying sources is difficult at best. The present observations demonstrate again that the central regions of ULIRGs are quite complex. Continuum emitting regions obscured by many tens of magnitudes of extinction and less obscured diffuse PAH emitting regions fall within the central few hundred parsecs of these sources. Resolving these components in the mid-infrared requires the high spatial resolution afforded by the largest groundbased telescopes.

In the majority of nuclei, the $10\mu\text{m}$ optical depth to the continuum sources is very large, so it is difficult to infer the nature of the underlying power source. The circumnuclear luminosities that can be attributed to starbursts, from the diffuse PAH emission, are substantial, and further highlights the picture of heavily dust/gas enshrouded environments, powered by a highly obscured source, with an overlying substantial starburst region that significantly affects the emergent spectra. The extent of the circumnuclear starburst region, as determined from the spatial extent of the PAH emission, is in the range $100 - 500$ pc, a size that is resolvable at mid-infrared wavelengths only in the closest of these systems and only by the largest telescopes. From the spectra presented here, the large optical depths to the compact $10\mu\text{m}$ sources suggest that even at these wavelengths the opacities are too large to probe the true centers of these regions. Whether the longer wavelength diagnostics of SIRTf or HERSCHEL, with their comparatively poor spatial resolution, can probe the cores of these systems is unclear.

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Fig. 1.—

The mid-infrared spectra of the separate nuclei plotted vs. rest wavelength. The logarithms of the flux densities per wavelength interval in relative units are plotted. Arrows indicate limits. The spectrum of M82, binned to the spectral resolution of the present data, is taken from Sturm et al. (2000).

Fig. 2.—

Contour plots overlaid on gray-scale plots of the two-dimensional spectra of Arp 220 (top), Markarian 273NE (middle) and VV 114E_{NE} (bottom). In all cases, rest wavelength is plotted along the abscissa and spatial dimension is along the ordinate. In each case the strong continuum source is readily seen, while at the wavelength of the PAH emission (11.25 μ m) extended emission along the spatial dimension is also seen. Slight wavelength shifts appear as a result of the shifts of the centroid of the PAH band emission (in the x spatial dimension) within the slit along the y spatial dimension. In Arp 220 the PAH emission is seen between the two continuum sources, in VV 114E_{NE}, PAH emission is seen to both sides of the continuum source, while in Markarian 273NE the PAH emission extends only to one side of the continuum source.

Fig. 3.—

The spatial distribution of the 11.3 μ m PAH feature in Arp 220. Panel a (top) is the observed two-dimensional spectrum, reproduced from the top panel of Figure 2. Panel b (middle) is the continuum subtracted two-dimensional spectrum that shows only the PAH band. The details of how the continuum was removed are described in the text. Panel c (bottom) shows a one dimensional slice of the spatial distribution of the PAH band (from Panel b) and the continuum.

Fig. 4.—

The mid-infrared spectra of the nuclei, plotted vs. rest wavelength, and corrected for the strength of the extended PAH emission as displayed in Figure 2. The correction was applied by normalizing the spectrum of M82 (Sturm et al. 2000) to the strength of the PAH band adjoining the continuum source, and subtracting this spectrum from the corresponding spectrum of Figure 1; see the text. In each panel the top line is the spectrum from Figure 1, the bottom line is the spectrum corrected for the overlying extended PAH emission.

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Table 1: Basic Properties of Observed Galaxies

Name	z	log L $L_{bol}[L_{\odot}]$	Spectrum OPT	linear scale Kpc/''
VV 114=IC 1623	0.020	11.62	HII	400
IRAS 08572+3915	0.058	12.10	LINER	1200
Markarian 463E	0.050	12.03	Sey 1	1000
Markarian 273	0.037	12.13	Sey	800
Arp 220	0.018	12.17	LINER	360

Table 2: Observing Log

Object	Date	FWHM ^a	Obs ^b Time	Chop Amp	P.A. ^c	Averaging	
						Range ^d	Width ^e
	2000	"	s	"	°	μm	μm
VV 114E _{SW}	Sep	0.30	1200	5.0	69	8.91 – 9.64	0.26
VV 114E _{NE}	Dec	0.35	400	10.0	166	8.98 – 10.34	0.26
IRAS 08572+3915	Dec	0.42	200	10.0	157	9.37 – 9.72	0.26
Markarian 463E	May	0.36	800	3.0	61
Markarian 273NE	May	0.35	2600	3.0	83	8.98 – 10.79	0.26
Markarian 273SW	May	0.39	4800	3.0	83
Arp 220W	May	0.30	3000	3.0	92	9.11 – 10.29	0.19
Arp 220E	May	0.30	3000	3.0	92	9.00 – 10.11	0.34

^afull width at half maximum of nearby PSF star

^bincludes time of negative images on array; see text

^cposition angle of slit measured east of north

^dwavelength range in rest frame over which additional running average greater than 0.11 μm was taken; see text

^ewavelength width of additional running average greater than 0.11 μm ; see text

Table 3: Luminosities of PAH Emitting Regions

Object	$L_{bol}(\text{cont})^a$	$L_{bol}(\text{PAH})^{b,d}$	$L_{bol}(\text{PAH})^{c,d}$
	$10^{10}[L_{\odot}]$		
VV 114E _{NE}	5	2.5	12
VV 114E _{SW}	12	<1.2	–
IRAS 08572+3915	150	<15	–
Markarian 273NE	110	7	14
Markarian 273SW	25	<4	–
Markarian 463E	110	<11	–
Arp 220W	120	2	6 ^e
Arp 220E	30	2	6 ^e

^aContinuum luminosities from Soifer et al. 1999,2000, 2001

^bBolometric luminosities from diffuse PAH emission overlaying compact source determined from the strength of the extended PAH band and applying the bolometric correction appropriate to M82 as described in the text. The uncertainty in this bolometric correction is at least a factor of 2

^cTotal PAH-based bolometric luminosity from total 11.3 μm PAH emission as measured in two-dimensional spectrum of Figure 2.

^dThe luminosity cited here should be considered a lower limit because no correction has been applied for extinction to the PAH region beyond that suffered in the M82 spectrum

^eTotal PAH luminosity is measured for the extended region associated with both nuclei Arp 220E & W

Table 4: Spectral Classifications of Compact Nuclei

Object	Spectral Class				
	Optical	Near IR	Mid-IR/ISO	X-ray	Keck-Mid IR ^a
VV 114E _{NE}	HII ¹	SB ⁴	AGN ⁷	–	SB → ?
VV 114E _{SW}	HII ¹	SB ⁴	AGN ⁷	–	SB?
IRAS 08572+3915	LINER ¹	SB ⁵	–	SB ⁹	AGN
Markarian 273NE	Sey2 ²	SB ⁶	AGN ⁸	AGN ^{10,12}	SB → ?
Markarian 273SW	Sey2 ²	SB ⁶	AGN ⁸	AGN ^{10,12}	AGN?
Markarian 463E	Sey1 ³	–	–	AGN ¹¹	AGN
Arp 220E	LINER ¹	SB ⁶	SB ⁸	SB? ¹⁰	SB → ?
Arp 220W	LINER ¹	SB ⁶	SB ⁸	SB? ¹⁰	SB → ?

^aclassifications are from strength of PAH band at 11.3 μ m, first entry is from spectrum of Figure 1, second entry (where appropriate) is from spectrum of Figure 3

SB= PAH feature clearly visible

SB? = PAH feature marginally visible

AGN = PAH feature not detected

References: ¹Veilleux et al. 1995, ²Koski 1978, ³Miller & Goodrich 1990, ⁴Doyon et al. 1995, ⁵Murphy et al. 2001, ⁶Goldader et al. 1995, ⁷Laurent et al. 2000, ⁸Genzel et al. 1998, ⁹Risaliti et al.2000, ¹⁰Iwasawa 1999, ¹¹Ueno et al. 1996,¹²Xia et al. 2001







