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Mid-infrared and optical spectroscopy of ultraluminous infrared galaxies: A comparison [1]

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ABSTRACT

New tools from Infrared Space Observatory (ISO) mid-infrared spectroscopy have recently become available to determine the power sources of dust-obscured ultraluminous infrared galaxies (ULIRGs). We compare ISO classifications – starburst or active galactic nucleus (AGN) – with classifications from optical spectroscopy, and with optical/near-infrared searches for hidden broad-line regions. The agreement between mid-infrared and optical classification is excellent if optical LINER spectra are assigned to the starburst group. The starburst nature of ULIRG LINERs strongly supports the suggestion that LINER spectra in infrared-selected galaxies, rather than being an expression of the AGN phenomenon, are due to shocks that are probably related to galactic superwinds. Differences between ISO and optical classification provide clues on the evolution of ULIRGs and on the configuration of obscuring dust. We find few ISO AGN with optical H II or LINER identification, suggesting that highly obscured AGN exist but are not typical for the ULIRG phenomenon in general. Rather, our results indicate that strong AGN activity, once triggered, quickly breaks the obscuring screen at least in certain directions, thus becoming detectable over a wide wavelength range.

Subject headings: infrared: galaxies, galaxies: starburst, galaxies: active, galaxies: Seyfert

1. Introduction

Dust obscuration is a significant concern in studies of ultraluminous infrared galaxies (ULIRGs, $L_{IR} > 10^{12}L_{\odot}$, see Sanders & Mirabel 1996 for a review). Evidence for both starburst

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and AGN activity has been found, but the extent to which optical and near-infrared spectroscopy probe the true power sources has remained questionable due to the concentration of dust and gas in the nuclear region of ULIRGs. The underlying problem is highlighted in near-infrared spectra of ULIRGs (e.g. Goldader et al. 1995). Qualitatively, their majority is starburst like, but quantitatively the starburst activity traced tends to be insufficient to power the bolometric luminosity of these ULIRGs. This leaves a large unaccounted power source which might be AGN or starburst.

Mid-infrared spectroscopy with ISO is able of penetrating significantly higher dust columns of the equivalent of a visual screen extinction of $A_V \sim 50$. Using as diagnostics both mid-infrared fine structure lines and the mid-infrared emission features usually ascribed to polycyclic aromatic hydrocarbons (PAHs), Genzel et al. (1998) found that the majority of a sample of 15 ULIRGs is predominantly starburst powered. From these data and after correction of the mid-infrared line fluxes for extinction, the highly obscured star forming regions are found able of powering the bulk of the luminosity. This leaves little room for additional hidden power sources. The recent application of the mid-infrared PAH method to larger ULIRG samples allows a direct comparison of optical and mid-infrared diagnostics which is the aim of this letter.

2. Mid-infrared and optical spectroscopy

The ISO mid-infrared spectroscopy sample of ULIRGs consists mainly of the SWS and ISOPHOT-S spectroscopy of Genzel et al. (1998) and Lutz et al. (1998) and a recent addition of higher luminosity sources observed with ISOCAM-CVF for the ZZULIRG consortium (Tran et al., in prep.). We have added observations of two hyperluminous infrared galaxies (Taniguchi et al. 1997; Aussel et al. 1998). The entire mid-infrared emission from an ULIRG is included in the $24'' \times 24''$ aperture of ISOPHOT-S or the ISOCAM-CVF datacubes of $3' \times 3'$ extent. Our spectral classification relies mainly on the feature-to-continuum ratio of the 7.7μm PAH feature. Groundbased observations first demonstrated that PAH features are strong in starburst galaxies but weak or absent in classical AGNs. ISO spectroscopy further demonstrated the anti-correlation between feature strength relative to the continuum and the ionization state of the gas (Genzel et al. 1998). Following Lutz et al. (1998), we classify mid-infrared spectra as AGN-like if the 7.7μm PAH feature-to-continuum ratio (L/C) is less than 1, and starburst-like ('SB') if it is greater than 1. This is motivated by the fact that, with the exception of the dwarfs NGC 5253 (0.5) and NGC 6764 (1.3) all 11 template starbursts had a L/C of more than 1.9, with a median value of 3. In contrast, 17 template AGN had L/C detections or limits well below one. Here we have excluded Seyferts like NGC 7469, with independent evidence for strong circumnuclear star formation. Those systems can reach starburst-like PAH strength in the integrated spectrum (Table 2 of Genzel et al. 1998). Figure 2 of Lutz et al. (1998) gives an impression of the uncertainties of the L/C ratio due to limited S/N, which may affect the classification in some cases. Several ULIRG spectra are too noisy for classification, we include them as uncertain ('?') in Table 1. For sources with available mid-infrared fine structure line spectroscopy (Genzel et al. 1998) we have considered the excitation of the emission line spectrum as well. Both criteria agree well with the exception of Mrk 273 which has somewhat low but still starburst-like PAH L/C of 1.7 and an AGN-like high excitation fine structure line spectrum. We have chosen to classify it as AGN though it likely represents a mixed case with both AGN and starburst contributing strongly to the total luminosity. *Unique classifications were also assigned to other sources on the border between the two regimes.* While such unique classifications do not represent the fact that ULIRGs may host both phenomena, they are required for a meaningful comparison of infrared and optical results concerning the *dominant* source of luminosity.

High quality optical spectra are available for 48 of 83 ULIRGs and IR-bright AGNs observed with ISO (see notes to Table 1). Following Veilleux and Osterbrock (1987), we use ratios of [O III] λ5007/Hβ, [N II] λ6583/Hα, [S II] $\lambda\lambda$6716,6731/Hα, and [O I] λ6300/Hα to distinguish the different ionization mechanisms of H II, LINER, and Seyfert galaxies. The adopted limits of these three regions in the diagnostic diagrams are those shown in Figure 6 of Veilleux et al. (1995). We used extinction corrected line ratios but note that, despite the typically high reddening of ULIRGs, corrections are small due to the close proximity in wavelength of the lines forming the ratios. When available, we used line ratios corrected for the presence of underlying Balmer stellar absorption features. This consistenly applied classification scheme caused some reclassifications with respect to the original papers. The nuclear optical spectral types, listed in Table 1, were obtained through apertures of typically $\sim 2''$ corresponding to between 700pc for the most nearby ULIRG Arp 220 and ~10kpc for distant ULIRGs at redshift approaching 0.3. Kim et al. (1998) and Veilleux, Kim, & Sanders (1999) used $2''$ slitwidth $\times$ 4kpc along the slit to minimize aperture size effects. These apertures include the major part or all of the active regions of ULIRGs. *Again, we have adopted unique classifications.* For double nucleus sources with optical spectroscopy for both nuclei, we have used average line ratios, since both nuclei will be covered by the large ISO apertures. These sources are labelled (D) in Table 1.

3. Discussion

Our results are presented in Table 1 and Figure 1. ISO and optical classification agree well if optical H II and LINER types are grouped together: All but one of 23 ISO starbursts are optical H II or LINER, whereas 11 of 16 ISO AGNs are optical Seyferts. Reversely, all but one of the optical Seyferts of type 1 and 2 are classified as ISO AGN. Objects with uncertain ISO classifications turn out to be H II galaxies or LINERs, just like the ISO starbursts. This agrees with the previous suggestion that they are starbursts, based on their average ISO spectrum and their infrared spectral energy distributions (Lutz et al. 1998).

The presence of a broad-line region (BLR) is an unambiguous AGN indicator. Infrared spectroscopy and optical polarimetry partly circumvent the extinction problems of optical BLR searches by observing in a less obscured wavelength regime, or by using scattered light. Table 1 includes a comparison to published BLR searches. Sources are labelled yes (no) in the respective columns if near-infrared spectroscopy did (not) show broad components to hydrogen recombination lines, or if optical polarimetry has (not) detected broad components to Balmer lines. Most entries are from the complete far-infrared selected sample of Veilleux, Sanders, & Kim (1997, 1999). We note however that some other BLR searches were biased to ULIRGs already considered AGNs from optical spectroscopy. In our sample, BLRs are found only in sources that are optically classified as Seyfert and ISO classified as AGN, giving further weight to the results from optical/near-infrared spectroscopy alone (Veilleux, Sanders, & Kim 1997, 1999).

3.1. The nature of infrared-selected LINERs

Galaxies optically classified as LINERs are well known to be a mixed population. LINER type ratios are firstly observed for LINERs in the classical sense, i.e. small low ionization nuclear emission regions in often fairly normal galaxies, which may represent the 'lower end' of the AGN phenomenon (e.g. Ho, Filippenko, & Sargent 1997; Maoz et al. 1995; but see Maoz et al. 1998), with photoionization likely dominating the gas excitation. Secondly, LINER type ratios are observed in gas excited by ionizing shocks, as found in galactic winds powered by star formation in starburst galaxies like M 82 (Chevalier & Clegg 1985). In such systems, LINER ratios are often found to large distances from the nucleus. This degeneracy has also affected optical classification of ULIRGs. Sanders et al. (1988), in their definition of the class, assigned LINERs to the AGN group. However, spatially resolved studies in both the optical (Heckman, Armus, & Miley 1987,1990; Veilleux et al. 1995; Kim, Veilleux, & Sanders 1998) and soft X-ray (Heckman et al. 1996) have provided evidence for large scale supernova-driven galactic 'superwinds' being responsible for LINER-type optical spectra of ULIRGs and other infrared-selected galaxies. This suggested that selection by far-infrared flux tends to pick a different, shock-dominated population of LINERs than optical surveys of the nuclei of normal galaxies.

The notion that LINER spectra of infrared-selected galaxies and ULIRGs are due to shocks in galactic outflows, and ultimately related to star formation, is strongly supported by the ISO/optical comparison: 10 of 17 optical LINERs are put in the starburst group by the ISO spectroscopy, and only two into the AGN group. The number of starburst LINERs rises to 15 of 17 if one includes the uncertain ISO classifications, which likely are starbursts. The PAH diagnostic does not directly probe the LINER gas, but determines the relative importance of starburst and AGN activity. Figure 1 demonstrates the close similarity of the PAH properties of optical HII and LINER types - they exhibit equally high levels of star forming activity, and low AGN frequency. By analogy to nearby starbursts with large-scale LINER emission, the strong star formation activity in LINER ULIRGs will be able to power the LINER emission via superwinds. The emerging scenario for LINER ULIRGs is one of starburst activity extending from the outskirts to the obscured layers probed by ISO spectroscopy, with optical LINER emission probing starburst-driven shocks and superwinds in the less obscured outer regions. It would be difficult to explain how an energetically dominant central AGN could photoionize the LINER region and still remain undetected in the mid-infrared which is much better at penetrating the obscuring dust.

There are also quantitative difficulties to explain LINER emission in ULIRGs with AGN photoionization. To obtain the low ionization parameter $logU = log(Q_{Lyc}/4\pi R^2 nc) \sim -4$ required for a LINER spectrum, the emitting clouds have to be either at large radii from a central AGN of ULIRG-like luminosity, or the clouds have to be very dense. The first possibility is strongly constrained by the small sizes of the active regions of ULIRGs. A variety of indicators including radio continuum (Condon et al. 1991), 10μm and mm dust emission (Soifer et al. 1999; Sakamoto et al. 1999), and near-IR line emission (Armus et al. 1995; Genzel et al. 1998) suggest that most of the luminosity and line emission of a ULIRG is produced in a region of only a few hundred parsecs size. Scaling the properties of the Seyfert 2 AGN of the Circinus galaxy as modelled by Moorwood et al. (1996), $Q_{Lyc} \sim 10^{53.3}$ photons/s and $L_{Bol} \sim 5 \times 10^9\,L_\odot$, to a ULIRG luminosity results in a Lyman continuum flux of $Q_{Lyc} \sim 10^{55...56}$ photons/s, the lower end being a conservative estimate including uncertainties of AGN modelling and beaming. Adopting a density of the ionized gas of $\leq$1000 cm^{-3}, characteristic of most of the ionized gas in luminous infrared galaxies, the size of a LINER photoionized region with $logU = -4$ would have to be as large as 5 kpc, clearly incompatible with few hundred pc to 1 kpc scales of the active regions of ULIRGs.

The second possibility – high densities – cannot fit the low measured density-sensitive ratios of the mid-infrared [S III] 18.71μm, 33.48μm lines in ULIRGs (Genzel et al. 1998). These low ratios are interpreted as coming from gas close to the low density limit of the [S III] ratio, i.e. at a few hundred to one thousand electrons cm^{-3}, and in addition slightly decreased by differential extinction. At densities in excess of 10^5 cm^{-3}, the intrinsic ratio is a factor of 20 higher. Matching this to the observations would imply extreme differential extinction between 18.71μm and 33.48μm which would require a highly improbable pure screen extinction and make the extinction-corrected emission incompatible with the ULIRG bolometric luminosity. Very high densities are also incompatible with optical [S II] ratios (e.g. Armus, Heckman, & Miley 1989; Veilleux et al. 1995, Veilleux, Kim, & Sanders 1999; Kim, Veilleux, & Sanders 1998) which, however, may preferentially probe outer regions of the ULIRGs observed. Similar problems to match the observed [S III] ratio will occur in LINER models photoionized by hot stars, which require high densities (Shields 1992; Veilleux et al. 1995; Taniguchi et al. 1999).

A further incompatibility between photoionized LINER models and ULIRG observations arises in the ratio of the [Ne III]15.55μm and [Ne II]12.81μm lines. LINER photoionization models predict this ratio to be high, e.g. 5 in the model of Spinoglio and Malkan (1992). In contrast, ISO-SWS observations of the two starburst-like ULIRGs Arp 220 and NGC 6240 obtain limits or values for this ratio substantially less than 1 (E. Sturm, priv. comm.; Egami et al., in prep.). Only the weak fine structure line emission detected in the Seyfert 1 type ULIRG Mrk 231 may be compatible with such a model (Rigopoulou et al., in prep.).

These quantitative considerations demonstrate the difficulty to explain the bulk of a ULIRG's line emission with a photoionized LINER model. They allow, however, the simultaneous presence of a fainter AGN, especially if it were obscured towards our line of sight. The main result from ISO fine structure line spectroscopy of ULIRGs (Genzel et al. 1998), that most ULIRGs are predominantly starburst powered, implies that any coexisting AGN would produce only a minor part to the bolometric luminosity. Such a minor AGN might still contribute to some of the extended emission if it were less obscured in other directions, in the spirit of a Seyfert 'ionization cone'. While this cannot be ruled out, we note that the observed extended line emission in ULIRGs matches well superwind models and observations but is quite different from the extended narrow line region of an AGN 'ionization cone': While ionization cones tend to be high excitation (e.g. Bergeron et al. 1989; Robinson et al. 1994; Wilson & Tsvetanov 1994), the extended emission in ULIRGs is of low excitation LINER type. Ionization cones also tend to be kinematically little disturbed on larger scales, in contrast to line splitting observed in superwinds.

3.2. Can obscured AGN remain hidden?

The presence of both starburst and AGN activity in ULIRGs naturally raises the question of their evolutionary connection. Sanders et al. (1988) put forward the by now classical evolutionary scenario in which interaction and merging of the parent galaxies trigger starburst activity that later subsides while an AGN increasingly dominates the luminosity and expels the obscuring dust. The large concentrations of gas in the nuclear regions of ULIRGs clearly play an important role in fueling both starburst and AGN activity, but the exact relation between the two phenomena remains difficult to model. Furthermore, the lack of a clear correlation between ISO spectral classification and the nuclear separation (Lutz et al. 1998) indicates a more complex relation than expected for a straightforward evolution from starburst to AGN, with local and short term conditions likely being more important.

Coexistence between a faint AGN and an energetically dominant starburst may lead to optical AGN spectra classified as starburst by ISO. We find only one such source. However, high spatial resolution studies indicate that such systems may be more common than indicated in our spectra which sample a large part of the active regions (optical) or the entire galaxies (ISO). UGC 5101 serves as an example: Both groundbased K band imaging spectroscopy (Genzel et al. 1998) and NICMOS multicolour imaging (Evans 1999) indicate a central compact AGN surrounded by a $\sim$1 kpc radius ring of vigorous star formation. NICMOS images suggest similar morphologies for some other ULIRGs (Evans 1999). These systems are a reminder that power sources in ULIRGs are not exclusive: Both AGN and starburst may be present in a galaxy even if one dominates the total power.

The inverse type of discrepant spectra, namely optical starbursts or LINERs classified as AGN by ISO, are of particular interest. They correspond to buried luminous AGN that have often been invoked as source of the luminosity not accounted for by optical and near-infrared observations.

Such buried AGN naturally fit the classical evolutionary scenario, at a point where the AGN is already dominant but has not yet expelled the obscuring dust. We do find such systems, but their number is not large: only 5 of the 36 optical H II/LINER galaxies in our sample. This is not a trivial result – the gas and dust concentration in ULIRGs is large enough to strongly reduce the mid-infrared and completely block the optical radiation if smoothly distributed as a homogeneous absorber. In such a scenario, galaxies would be common with just recognizable AGN in the mid-infrared, but optical spectra dominated by unimportant 'surface' star formation. The small number of such systems suggests a different picture: Quickly after the onset of AGN activity, radiation and outflow from the AGN will manage to break the clumpy obscuring screen at least in certain directions and become visible, though perhaps still only in attenuated or scattered light, over a wide wavelength range. Superwinds from co-existing starbursts will support this process. More deeply embedded AGN, invisible in the mid-infrared as well as the optical, will not be identifiable by differing mid-infrared and optical classifications. However, with the ULIRG starburst activity probed in the mid-infrared being sufficient to power the bulk of the bolometric luminosity (Genzel et al. 1998), such deeply embedded AGN would not be energetically important, even if they existed.

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Table 1: ISO and optical classifications

Source	z	ISO Type	Optical Type	BLR NIR	BLR Pol
00183−7111	0.327	AGN	LINER[j,*]		
00188−0856	0.129	SB	LINER[c]	no[n]	
00397−1312	0.262	AGN	HII[c]	no[m]	
00509+1225 IZw1	0.061	AGN	Sy1[e]		
01003−2238	0.118	SB	HII[c]	no[m]	
01166−0844	0.118	?	HII[c]		
01199−2307	0.156	?	HII[c]		
01298−0744	0.136	SB	HII[c]		
01355−1814	0.191	?	HII[c]		
01569−2939	0.140	AGN	HII[c]		
01572+0009 Mrk1014	0.163	AGN	Sy1[e]		
02411+0354 (D)	0.144	SB	HII[c]		
03521+0028	0.152	SB	LINER[c]	no[m]	
04103−2838	0.118	?	LINER[c]	no?[n]	no[r]
06035−7102 (D)	0.079	SB	HII[d]		
06206−6315	0.092	SB	Sy2[d]		
09104+4109	0.442	AGN	Sy2[f,i,*]	no[p]	yes[q]
09320+6134 UGC5101	0.040	SB	LINER[c]		
09463+8141	0.155	?	LINER[c]		
12112+0305	0.073	SB	LINER[b,c]	no[n]	
12265+0219 3C273	0.158	AGN	Sy1[e]		
12540+5708 Mrk231	0.042	AGN	Sy1[e]		
13428+5608 Mrk273	0.037	AGN	Sy2[b,c]	no[n]	
13536+1836 Mrk463 (D)	0.050	AGN	Sy2[g]	yes[m]	yes[r]
14348−1447 (D)	0.082	SB	LINER[b,c]	no[m]	
15250+3609	0.053	SB	LINER[a]	no[n]	
15307+3253	0.926	AGN	Sy2[h,i]		yes[s]
15327+2340 Arp220	0.018	SB	LINER[b,c]		
16333+4630	0.191	?	LINER[b,c]	no[m]	
16474+3430	0.111	SB	HII[b,c]		
16487+5447	0.104	SB	LINER[b,c]		
16504+0228 NGC6240	0.024	SB	LINER[a]		
17028+5817 (D)	0.106	SB	HII[b,c]		
17068+4027	0.179	AGN	HII[b,c]	no[m]	
17179+5444	0.147	AGN	Sy2[c]	yes?[m]	
17208−0014	0.043	SB	HII[a]	no[n]	
18470+3233	0.079	?	HII[b]		
19254−7245 (D)	0.062	AGN	Sy2[d]		no[t]
20100−4156	0.129	SB	HII[d]		
20551−4250	0.043	SB	HII[d]		
22491−1808	0.077	SB	HII[a]	no[n]	
23060+0505	0.174	AGN	Sy2[c]	yes[m,o]	
23129+2548	0.179	AGN	LINER[c]		
23128−5919 (D)	0.045	SB	HII[d]		no[r]
23230−6926	0.106	?	LINER[d]		
23327+2913	0.107	?	LINER[c]		
23365+3604	0.064	SB	LINER[a]	no[m]	
23389−6139	0.093	SB	HII[d]		

Unique ISO and optical classifications were assigned even for potentially mixed systems. Optical references: [a]Veilleux et al. 1995, [b]Kim et al. 1998, [c]Veilleux, Kim, & Sanders 1999, [d]Duc et al. 1997, [e]Sanders et al. 1988a, [f]Kleinmann et al. 1988, [g]Shuder & Osterbrock 1981, [h]Cutri et al. 1994, [i]Evans et al. 1998, [j]Armus et al. 1989, [*]using observed ratios

References for broad-line region searches: [m]Veilleux, Sanders, & Kim 1997, [n]Veilleux, Sanders, & Kim 1999, [o]Hines 1991, [p]Soifer et al. 1996, [q]Hines & Wills 1993 (broad MgII), [r]Young et al. 1996, [s]Hines et al. 1995, [t]Heisler et al. 1997

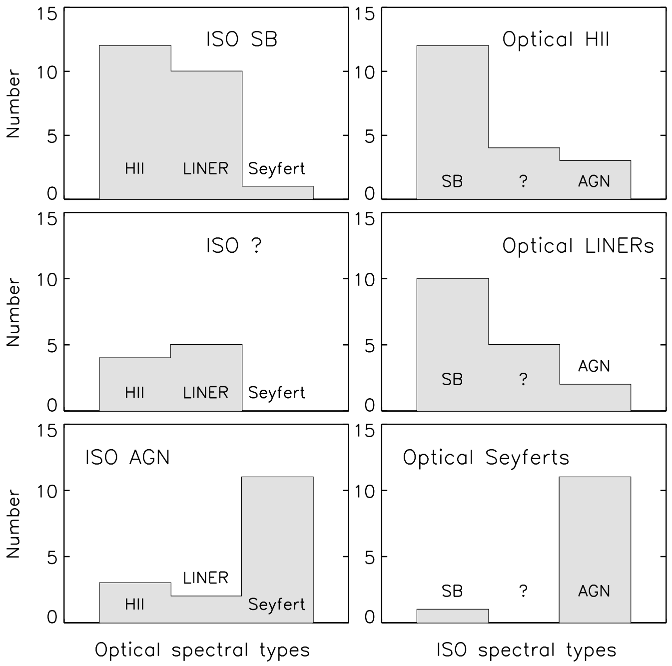

Fig. 1.— Histograms comparing optical and ISO spectral classifications. On the left, the distributions of the optical spectral types are presented for ULIRGs of the different ISO types: From top to bottom starburst, uncertain due to noisy spectra, and AGN. On the right, distributions of the ISO spectral types are presented for ULIRGs of the different optical spectral types.