SPECTROSCOPY OF ULTRALUMINOUS AND INTERACTING GALAXIES

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Abstract

Recent infrared surveys detecting a population of infrared galaxies at high redshift have strengthened the need to characterize their closest local analogues, luminous and ultraluminous infrared galaxies. This paper discusses results from mid- and far-infrared spectroscopy of these, often interacting, galaxies that has become possible for sizeable samples with the advent of ISO, and outlines related projects to be addressed with FIRST.

Key words: galaxies: starburst – galaxies: active – galaxies: ultraluminous

1. A fresh view on the role of infrared galaxies

The detection of cosmic infrared background emission in the COBE data and the first deep infrared and submillimeter surveys have increased the need to understand nature and activity of infrared galaxies. The infrared sources at high and intermediate redshifts detected by SCUBA, MAMBO and ISO apparently are luminous and dusty systems, and understanding their closest local analogues is a prerequisite of progress in determining their contribution to the cosmic star formation history, the role of active galactic nuclei at high z, and the relation between the cosmic infrared and X-ray backgrounds. While our census of the local infrared universe is still essentially based on IRAS, spectroscopy is needed to understand infrared galaxies better than possible from the fairly unspecific continuum measurements that mostly reflect dust reradiation of uncharacterized sources. With future missions like FIRST and SIRTF, spectroscopic methods developped on the local population may even be directly applied to the high redshift universe. From a practical point of view, knowledge of the local infrared galaxy population is crucial for selecting the optimal strategy of large deep surveys with FIRST, for interpreting their results, and for optimization of the difficult follow-up.

2. Continuum, features and ices

With the exception of the brightest lines in the very brightest sources, mid- and far-infrared spectroscopy of galaxies has been impossible to obtain from groundbased or airborne observations. Complete wavelength coverage and high sensitivity of the ISO cryogenic space telescope have changed this situation, providing spectra of unprecedented detail. The spectrum of the Circinus galaxy, which hosts both a type 2 AGN and star formation, collects most of the elements of infrared spectra of galaxies (Figure 1).

The 6-13 μm spectra of star forming galaxies are dominated by strong emission features from transiently heated aromatic carriers which are called PAH features in the following according to one of their most popular identifications. These PAH spectra are very similar among different star forming galaxies (Rigopoulou et al. 1999, Helou et al. 2000). An exception to be noted is the weakness or absence of the PAHs in the spectra of low metallicity starbursting dwarfs, e.g., SBS 0355-052 (Thuan et al. 1999), 30 Dor (Sturm et al. 2000), NGC 5253 (Rigopoulou et al. 1999). While this is of little relevance for studies of nearby dusty starbursts, it may have implications on future mid-infrared observations of lower metallicity galaxies at higher redshift, both for determining their redshifts and for studying their nature. The minimum near 10μm between the two major PAH complexes is difficult to disentangle from silicate absorption, and the latter may have often been overestimated in the past. At longer wavelengths, a rising continuum likely due to very small grains sets in. Close comparison of the M 82 and NGC 253 spectra (Sturm et al. 2000) as well as CAM-CVF spectroscopy of several, partly spatially resolved, starbursts (Laurent et al. 2000) confirms that the PAH feature emission is fairly similar from source to source and likely originates in photodissociation regions (PDRs). Conversely, the rising continuum at longer wavelengths varies with physical conditions in the H II regions of the starburst and is most intense in compact regions like the one in the interaction zone of the Antenna galaxies (Mirabel et al. 1998).

In accordance with previous ground-based results, the aromatic emission features are weaker or absent in many Seyfert spectra. Spatially resolved ISO spectra of NGC 1068, Cen A, and Circinus demonstrate even more convincingly that the PAH features are not AGN related (D. Alexander et al. 1999, Mirabel et al. 1999, Moorwood 1999, Le Floc'h et al. 2001). PAH emission is undetected in the nuclei but seen on larger scales, excited in a starburst or cirrus type situation. In the context of unified scenarios, these observations are related to the finding that

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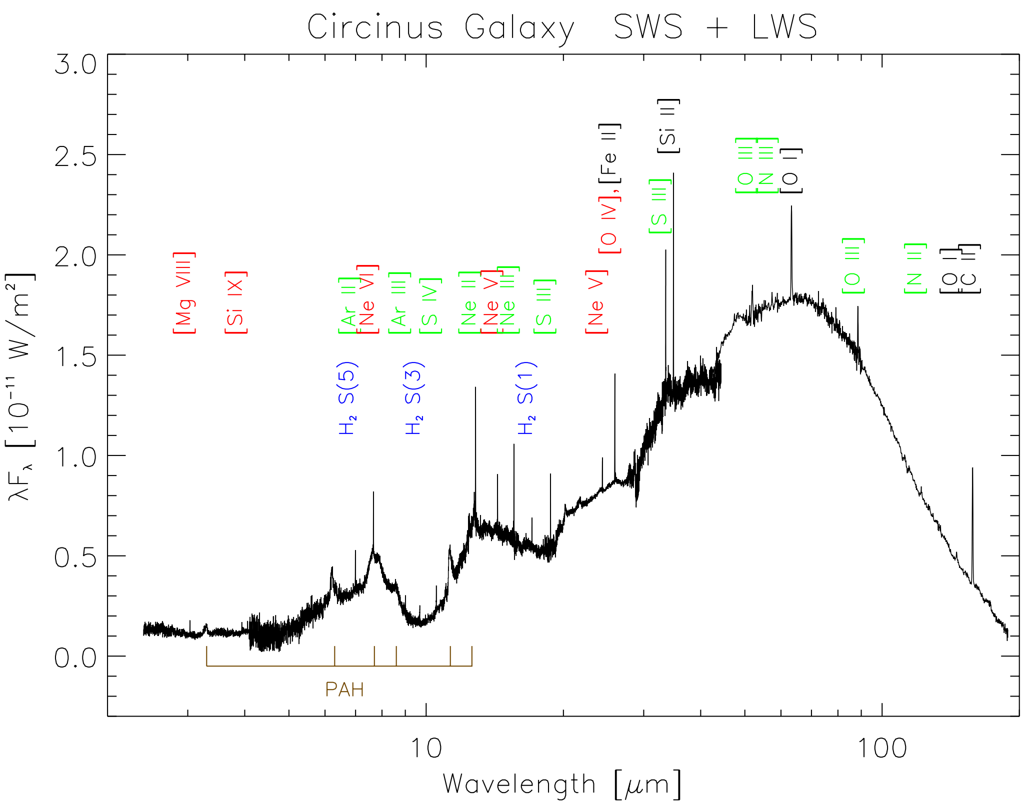

Figure 1. The ISO 2.4-195μm spectrum of the Circinus galaxy collects most elements of infrared spectra of galaxies.

PAH equivalent widths of Seyfert 2's are larger than those of Seyfert 1's while the PAH fluxes of both categories are similar (Clavel et al. 2000). Such a behaviour can be explained if the PAH emission originates on larger scales and is emitted isotropically, while the AGN continuum is emitted anisotropically, changing significantly with angle between line of sight and axis of the putative dust torus.

On detailed inspection of the SWS spectra of galaxies, new fainter features are seen in the 13-25μm range. Analogy to galactic sources suggests that they are most likely due to aromatic carriers just as the stronger ones (Sturm et al. 2000). While the main change from galaxy to galaxy is one of overall strength, there are also some features unique to individual sources e.g. in the 20μm region of Circinus. Given that galaxy spectra average over many different regions, this is surprising and may suggest a transient nature of some of the carriers. The presence of these features leads to ambiguities in the interpretation of low resolution spectra (e.g. CAM-CVF). For example, the [Ne V] line at 14.3μm which is an AGN tracer may be confused with a broader aromatic feature that coincides in wavelength but comes from star forming regions.

Detailed mid-infrared spectroscopy with ISO has considerably widened the observational database of ice features in spectra of Galactic objects. Careful inspection of the ISO database shows them to be present in external galaxies as well. Detections range from moderate

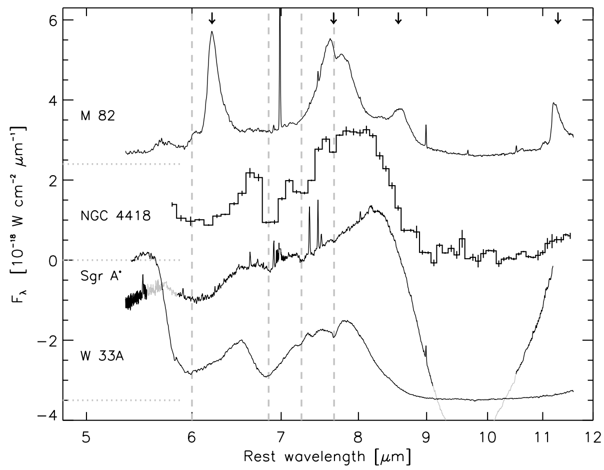

Figure 2. The spectrum of the obscured infrared galaxy NGC 4418 shows strong ice absorptions.

3μm water ice absorption in M82 and NGC 253 (Sturm et al. 2000) to strong water and CO_2 ice absorption in NGC 4945 (Spoon et al. 2000), and to the extreme absorption dominated spectrum of NGC 4418 (Fig. 2, Spoon et al. 2001) that has strong similarities with absorption-dominated spectra of strongly embedded young stellar objects. At first glance, one might expect the cold environment of molecular clouds in starbursts to be more beneficial to the presence of ices than the warm or hot dusty medium close to an AGN, a point of view that is supported by the absence of ices in the spectrum of NGC 1068 (Sturm et al. 2000). The ices in the spectrum of the most likely AGN-dominated NGC 4418, however, caution that more investigations will be needed to elucidate the contributions of starburst molecular clouds, cold regions of circum-AGN molecular material, and the larger scale hosts to the observed extragalactic ice absorptions. Evidence on the strength of ice features in the general galaxy population can be obtained from average ISO spectra of normal galaxies (Helou et al. 2000), starbursts, and ULIRGs (Lutz et al. 1998, Fig. 7). Ices are not strongly detected there, but wavelength limits of the ISO spectra, S/N issues and superposed emission features clearly make these spectra consistent with presence of low to moderate ice obscuration. Systems like NGC 4418 must, however, be the exception. The striking differences in relative strenght of absorption features due to ice and due to carbonaceous material when comparing M 82 and NGC 1068, and even for several lines of sight close to the Galactic center (Chiar et al. 2000) are a further warning that the mid-infrared absorption in galaxies may vary considerably - observations are clearly inconsistent with being due to a unique absorption curve that is just applied at different absolute levels of absorption.

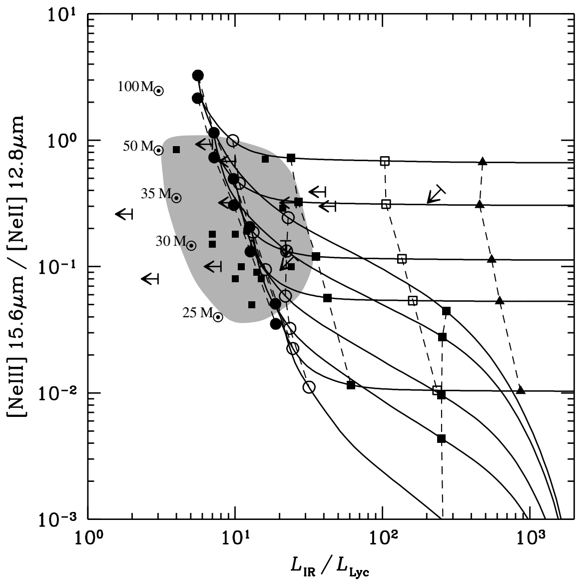

Figure 3. Neon flux ratio and ratio of infrared and Lyman continuum luminosity. Measured values for 27 starbursts mainly populate the shaded area. Modelling results for an ensemble of evolving star clusters are overplotted. Curves are shown for various values in IMF upper mass cutoff and for burst timescales of 1 (lower curves) and 5 MYr (upper curves). Dashed lines connect ages of 1, 5, 10, 20, and 30 Myr.

3. The hot star population in starbursts

A number of key questions are related to the hot star population in starbursts. Is the Initial Mass Function similar to the one in our Galaxy? How do starbursts evolve? Do they continue until they have consumed all their gas fuel or are they stopped in other ways? ISO studied the hot star content by analysis of nebular emission, benefitting from relative insensitivity of the mid infrared lines to extinction and electron temperature. First studies of individual starbursts were obtained in the first months of the ISO mission (Fischer et al. 1996, Kunze et al. 1996, Lutz et al. 1996, Rigopoulou et al. 1996) reaching the 'dark side' of starformation (Mirabel et al. 1998). It should be noted that the large ISO apertures average over large parts and thus physically distinct regions of the galaxies studied (Crowther et al. 1999a). Recently, Thornley et al. (2000) have carried out an SWS survey of [Ne III]/[Ne II] emission in 27 starbursts. The neon line ratio in these starburst galaxies is typically somewhat lower than in individual galactic H II region templates.

Thornley et al. (2000) have carried out a quantitative analysis, modelling a starburst as an ensemble of evolving star clusters photoionizing the surrounding interstellar medium. Spectral energy distributions for each cluster are derived from an evolutionary synthesis using Geneva tracks and recent non-LTE unified stellar atmospheres (Pauldrach et al. 1998). Nebular emission is predicted from these SEDs and photoionization modelling with CLOUDY, adopting an ionization parameter log(U) = -2.3 that is constrained by ISO-measured gas density and high resolution near-infrared observations. The modelling results (Fig. 3) suggest that most of these starbursts are presently deficient in the most massive stars, either because they did not form in an IMF invoking an upper mass cutoff, or because they disappeared due to aging effects. The considerable overlap between excitation of starbursts and Galactic H II regions and direct evidence for the presence of very massive stars in nearby starburst templates suggest aging effects to be dominant while the IMF is likely normal. In that framework and using the ratio of infrared (bolometric) and Lyman continuum luminosity as an additional constraint, most starbursts must be short-lived ($<\sim 10^7$ years), only a few O star lifetimes. The most likely cause for this short lifetimes is a strong negative feedback of star formation. Disruption of the interstellar medium by stellar winds and supernovae will be faster than simple gas consumption. Such short bursts are both consistent with spatially resolved near-infrared studies (e.g. Förster-Schreiber et al. 2001) and with analysis of the far-infrared fine structure line emission of M 82 measured by ISO-LWS (Colbert et al. 1999).

The center of our Galaxy is a well studied environment where direct stellar census suggests a brief star formation event similar to the ones inferred for starburst galaxies. The excitation measured from the neon lines is very low, again resembling starbursts. A quantitative analysis similar to that for the starbursts (Lutz 1999a; Thornley et al. 2000), however, exposes problems both in fitting the observed low nebular excitation, and the large contribution of relatively cool blue supergiants to the ionizing continuum (Najarro et al. 1997). This contribution of about 50% is much higher than expected for a population of the age generally adopted for the Galactic center population, and in fact for any age and star forming history. The most plausible explanation for these discrepancies is an inadequacy of current evolutionary tracks. The observations suggest a revision of weights between hot Wolf-Rayet-like types and cooler blue supergiants. This would imply less stringent constraints from the low excitation on duration of short starbursts. Direct studies of Wolf-Rayet stars suggesting softer ionizing spectra may point in a similar direction (Crowther et al. 1999b; Hillier & Miller 1998).

4. AGN and the big blue bump

In the standard paradigm AGNs contain thin accretion disks that are expected to emit a quasi-thermal radiation of temperature a few times 10^5K. This emission will mainly be in the extreme ultraviolet which cannot be observed even from space, due to Galactic and intrinsic absorption. UV and soft X-ray studies of Seyfert 1s are generally consistent with the presence of an accretion-disk 'Big Blue Bump' in the unobservable EUV but suffer several limitations. A completely independent approach is to use infrared spectra to infer the EUV spectral energy distribution. Ionization energies of line emitting species in the narrow line region and coronal line region cover the EUV range. The emission line spectra will contain a signature of the intrinsic AGN continuum SED which can be reconstructed by photoionization modelling. The emission line spectrum will, however, not only depend on the shape of the ionizing continuum but in addition on other factors like NLR geometry and ionization parameter. SED reconstruction will hence be difficult and possible only with a large number of constraints. The rich mid-infrared fine structure line spectra of the brightest Seyferts are well suited for this task (e.g. Fig. 4). In addition, the fine structure line fluxes are quite insensitive to extinction and electron temperature variations, thus eliminating two additional elements of uncertainty.

Three nearby Seyferts have been analysed using this technique: Circinus (Moorwood et al. 1996,T. Alexander et al. 1999), NGC 4151 (T. Alexander et al. 1999), and NGC 1068 (T. Alexander et al. 2000). The reconstructed EUV spectrum of Circinus is indeed found to exhibit an EUV bump peaking at about 70eV and containing about half of the AGN luminosity. For the small black hole mass of Circinus the AGN must be radiating at high efficiency of greater than 10% of the Eddington luminosity, in accordance with standard expectations.

The SEDs derived for NGC 4151 and NGC 1068 appear quite different (Fig. 5). They fall sharply beyond the

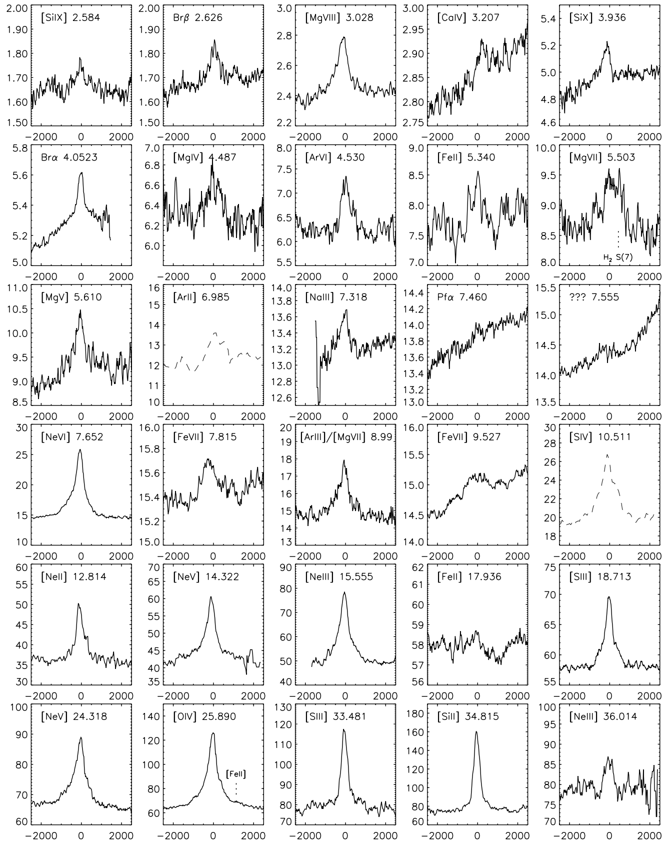

Figure 4. ISO-SWS spectra of lines emerging in the ionized medium of NGC 1068. Flux densities in Jy are shown for a range of ±2500 km/s around systemic velocity

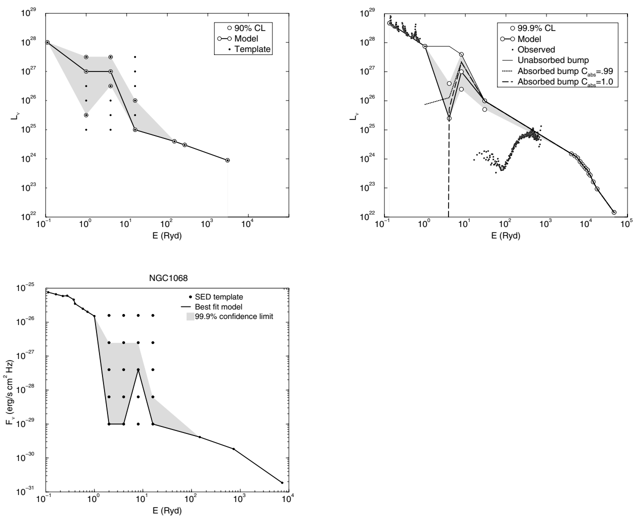

Figure 5. Extreme ultraviolet SEDs of the Seyfert galaxies Circinus (top left), NGC 4151 (top right), and NGC 1068 (bottom) as inferred from photoionization modelling of the infrared and optical line emission. The energy scale is given in Rydberg units (=13.6eV). The gray shaded area indicates the confidence range. The spectra of NGC 4151 and NGC 1068 appear modified by a neutral absorber inside the NLR.

Lyman limit and then rise sharply again toward 100eV. Such a structured SED is not consistent with any accretion disk model and difficult to reconcile with any continuum emission mechanism. Alternatively, the deep minimum might be due to absorption by neutral hydrogen. Then, the narrow line region does not see the intrinsic SED of the AGN which will have a smoother UV continuum and perhaps even a Big Blue Bump. For NGC 4151, this interpretation is corroborated by independent evidence: the reconstructed (absorbed) SED does not contain enough UV photons to photoionize the BLR, i.e. it cannot be the intrinsic SED. Observations of UV Lyman absorption lines similary suggest a neutral absorber (Kriss et al. 1992). While a significant range of SEDs and NLR geometries has been explored to confirm the robustness of the inferred SEDs, it is also possible to get good fits with simple power law continua if introducing significant additional free parameters like a variable ratio of specific matter bounded and radiation bounded clouds (Binette et al. 1997). The reconstructed SEDs that appear very unsual at first glance are again consistent with the standard AGN paradigm of thin accretion disks emitting a Big Blue Bump, assuming that the NLR sees a partially absorbed continuum.

'Unified' models assume that Seyfert 2 galaxies host a Seyfert 1–like BLR which is obscured towards our line of sight by a dusty torus, and have been highly successful in explaining several aspects of Seyfert galaxies. The key observational evidence supporting such models came from the spectropolarimetric detection of broad hydrogen recombination lines, but direct detection of the obscured BLR may be in principle possible at near- and mid-infrared wavelengths and can provide another route to studies of Seyfert unification, independent of the uncertain scattering efficiency entering the quantitative analysis of most spectropolarimetric data. Observations of 2.62μm Brackett β, 4.05μm Brackett α and 7.46μm Pfund α in NGC 1068 were unable to detect broad components (Lutz et al. 2000). The limit of $A_V > 50$mag to the BLR is not yet significant enough to discriminate between different torus models. From a practical point of view, these data favour the use of Brackett α for future infrared BLR searches. 7.46μm Pfund α appears less favourable than assumed pre-ISO, both because the extinction at this wavelengths may be larger than assumed and because of the presence of nearby broad emission features which make continuum definition difficult.

5. The nature of ultraluminous infrared galaxies

Ultraluminous infrared galaxies (ULIRGs) were identified as an important galaxy population in the local universe more than ten years ago after the IRAS mission. Most of their energy output is dust emission which is a calorimeter of the energy relased, with only indirect signatures of the exciting mechanism. The same dust, concentrated in large quantities in fairly small (sub)kpc regions, has hampered attempts to decide from optical and near-infrared spectroscopy whether ULIRGs are powered by starbursts or AGN. Beyond their role in the local universe, ULIRGs are important as the most likely closest analogues of the mid-infrared and (sub)mm sources that were recently discovered as a major contributor to high redshift star formation.

The clear differences between mid-infrared starburst and AGN spectra described above provide two new tools to address this question, at wavelengths that are better able of penetrating the obscuring dust. The first tool is presence of strong high excitation fine structure lines only in the narrow line region of AGN but not in starburst H II regions. Conversely, the mid-infrared PAH emission features are strong in starbursts but weak or absent in AGN. Both tools can be combined in a two-dimensional diagnostic diagram (Fig. 6, Genzel et al. 1998).

From the combined ISO-SWS and ISOPHOT-S diagnostic, most of the 15 ULIRGs studied are found to be predominantly starburst powered. A few examples (Mrk 231, Mrk 273) may be AGN dominated or at least have a significant AGN component (NGC 6240). From the ISO data, significantly higher obscurations towards the starburst region are inferred than previously assumed. This also addresses a key issue in stating that a ULIRG is starburst dominated: Note only is the emission detected by ISO starburst-like, it is also - after correction for extinction - able of powering the bulk of the bolometric luminosity. Little room is thus left for unknown obscured power sources. Dominance of either starburst or AGN activity does not exclude presence of the respective other component. In fact, high resolution near-infrared observations suggest a significant number of composite ULIRG systems.

The fine structure line diagnostics have reached ISO's practical sensitivity limit for this moderate sized sample. Using ISOPHOT-S and ISOCAM-CVF, the PAH diagnostic could be extended to a large sample of about 75 ULIRGs that allows to search for trends and evolutionary effects (Lutz et al. 1998; Rigopoulou et al. 1999; Tran et al. 2001). The average spectrum created from the ISOPHOT-S data (Fig. 7) clearly supports the result that most ULIRGs are predominantly starburst powered. Subtle deviations of ULIRG PAH spectra from starburst ones also support the high level of obscuration inferred from the SWS data. At the highest luminosities in excess of 4×10^{12} solar luminosities, there is a transition towards preferentially AGN dominated systems. Inferring the total contribution of AGN and starburst to a ULIRG's luminosities using the PAH diagnostic implies a bolometric correction from the mid-infrared contributions which are determined fairly reliably using different methods (Tran et al. 2001). At this point, orientation-dependent variations in AGN SEDs (Clavel et al. 2000) introduce an additional uncertainty. Reassuringly, however, ULIRGs classified as starburst-like by the PAH method also turn out to be

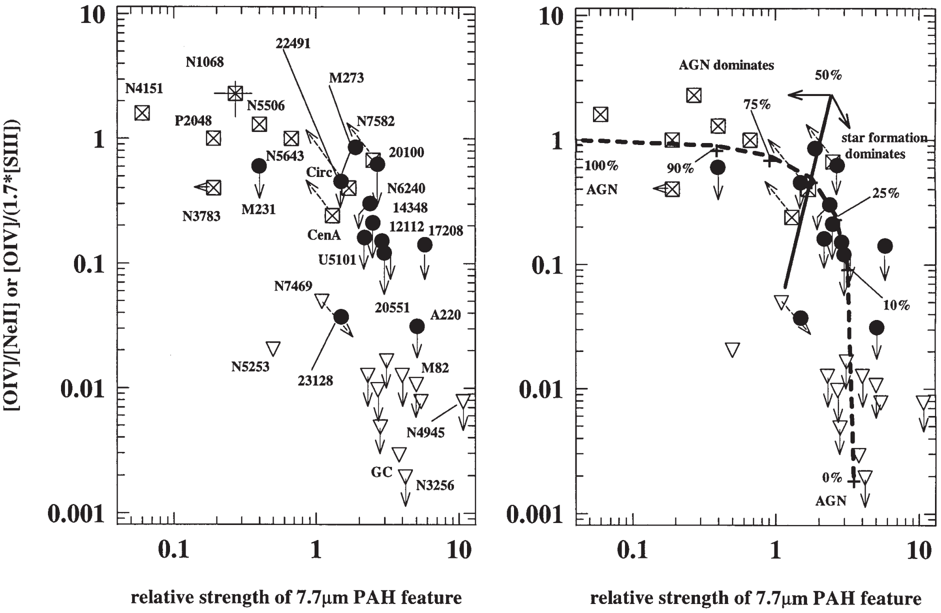

Figure 6. SWS/PHT-S diagnostic diagram for ULIRGs. The vertical axis measures the ratio of low and high excitation mid-infrared emission lines, the horizontal axis the strength of the 7.7μm PAH feature relative to the local continuum. AGN templates are marked by squares, starburst templates by triangles, and ULIRGs by circles. Note that there are upper limits for high excitation line emissin in most ULIRGs. A simple mixing curve is also shown.

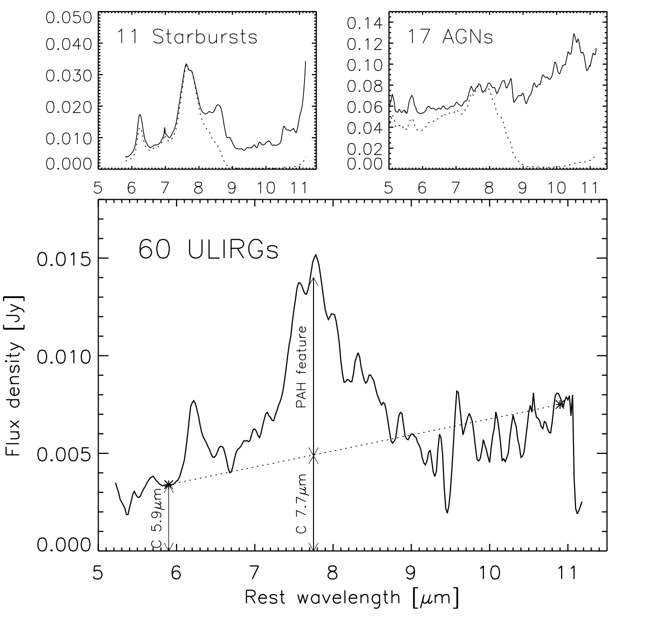

Figure 7. Average ISOPHOT-S spectrum of 60 ULIRGS (z<0.3) along with starburst and AGN comparison spectra. Dotted lines in the comparison spectra indicate the effect of extremely high foreground extinction.

PAH 'ultraluminous' in absolute terms (Rigopoulou et al. 1999), again leaving little room for non-starburst power sources.

ULIRGs are interacting or merging systems. The classical evolutionary scenario (Sanders et al. 1988) postulated increasing AGN dominance during the ULIRG phase, with an energetically dominant AGN later emerging as a QSO. Not only has this scenario to be modified in view of the starburst dominance in most ULIRGs, but also the suggested trend towards AGN dominance at later stages of the interaction is not seen. This observation and a similar lack of a clear correlation of interaction state with gas content (i.e. gas consumption by starburst or AGN) suggest that dominance of starburst or AGN and their feeding may depend on local and shorter term conditions in addition to the global state of the merger.

Despite their high dust content and obscuration the *qualitative* classifications of ULIRGs as starburst or AGN agree surprisingly well from ISO and optical diagnostics (Lutz et al. 1999b). On one hand, this strongly confirms the suggestion that infrared-selected LINERs are not an expression of the AGN phenomenon but characterized by starburst-related shocks and superwinds. On the other hand, the lack of highly obscured AGN that would be only detectable in the IR suggests that a luminous AGN highly obscured in *all* directions is an unlikely scenario. The AGN will manage to break the obscuring screen at least in certain directions and will be visible over a wide wavelength range, though perhaps only in attenuated or scattered light. Similarly satisfactory agreement is found between ISO and hard X-ray results (Genzel & Cesarsky 2000).

6. FIRST SPECTROSCOPY OF LOCAL LUMINOUS GALAXIES

The more than tenfold improvement in far-infrared spectroscopic sensitivity and the improved spatial resolution of FIRST will address a number of key questions left open by ISO. One is clearly related to the origin of the relative weakness of [C II] 157.7μm emission in luminous and FIR-warm galaxies that was somewhat of a surprise early during the ISO mission (Malhotra et al. 1997, Luhman et al. 1998), and has strong implications on the potential use of [C II] as a star formation tracer for high redshift studies. One strong contributor to this effect is most likely a reduced photoelectric heating efficiency in the very intense UV fields of PDRs in these galaxies, but diagnostics to reliably measure the physical conditions in these PDRs or investigate alternative scenarios are largely lacking at this point. Spectroscopy with FIRST will reach the fainter PDR diagnostics, and the higher spectral resolution of PACS and especially HIFI will allow to test the possible role of self-absorption in this effect (Cox et al. 1999). A parameter requiring special attention in view of future high redshift studies is metallicity: Strong [C II] emission observed in local low metallicity systems (e.g. Madden et al. 1997, Hunter et al. 2000) may indicate better prospects for the use of this line.

A related aspect deserving special attention is the far-infrared molecular spectrum. Molecules like OH and H_2O are usually seen in absorption (e.g. Fischer et al. 1999, Harvey et al. 1999) but also in emission (Spinoglio et al. 1999). High sensitivity and spectral resolution are crucial for a better understanding of the far-infrared molecular spectra of galaxies, and their role in megamaser emission. Skinner et al. (1997)) successfully explained the OH megamaser in Arp 220 as infrared pumped in front of a large warm infrared background source.

Finally, the wavelength range of FIRST spectroscopy hosts fine structure lines of [N II], [N III], [O III] that may be used for a starburst diagnose similar to the ISO-SWS [Ne III] vs. [Ne II] one described above, with the additional benefit of yet lower extinction at the longer wavelengths. In that way, absolute level and excitation of star forming activity in highly obscured sources will be charaterized

7. FIRST spectroscopy at high redshift

ISO results demonstrate the power of mid-infrared spectroscopy for determining the power sources of infrared galaxies. Application of those spectroscopic methods to the high z infrared galaxies that will be detected with FIRST or with mid-infrared and (sub)mm surveys is a unique possibility of FIRST spectroscopy, getting beyond the ambiguities remaining in SED-based arguments. For example, the important AGN tracer [O IV] 26μm is shifted into the PACS range just above redshift 1. Sensitivity is an issue, however, (Fig. 8). Spectroscopic studies will be targetted at the brightest objects and lensed targets from FIRST and other (e.g. Planck) surveys, but will provide a unique view on the nature of luminous high z galaxies.

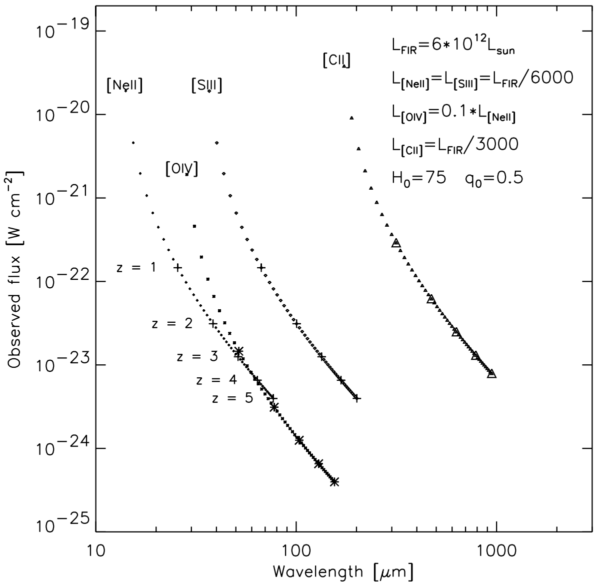

Figure 8. Observed fluxes and wavelengths of fine structure lines from a redshifted ultraluminous galaxy at z = 0.1 to 5.

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