The nature and evolution of Ultraluminous Infrared Galaxies: A mid-infrared spectroscopic survey [1]

D. Lutz[2], H.W.W. Spoon[2], D. Rigopoulou[2], A.F.M. Moorwood[3], R.Genzel[2]

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[2]Max-Planck-Institut für extraterrestrische Physik, Postfach 1603, 85740 Garching, Germany

[3]European Southern Observatory, Karl-Schwarzschild-Straße 1, 85748 Garching, Germany

ABSTRACT

We report the first results of a low resolution mid-infrared spectroscopic survey of an unbiased, far-infrared selected sample of 60 ultraluminous infrared galaxies (ULIRGs, $L_{IR} > 10^{12}L_{\odot}$) using ISOPHOT-S on board ISO, the Infrared Space Observatory.

We use the ratio of the 7.7μm 'PAH' emission feature to the local continuum as a discriminator between starburst and AGN activity. About 80% of all the ULIRGs are found to be predominantly powered by star formation but the fraction of AGN powered objects increases with luminosity. Whereas only about 15% of ULIRGs at luminosities below $2 \times 10^{12}L_{\odot}$ are AGN powered this fraction increases to about half at higher luminosity.

Observed ratios of the PAH features in ULIRGs differ slightly from those in lower luminosity starbursts. This can be plausibly explained by the higher extinction and/or different physical conditions in the interstellar medium of ULIRGs.

The PAH feature-to-continuum ratio is anticorrelated with the ratio of feature-free 5.9μm continuum to the IRAS 60μm continuum, confirming suggestions that strong mid-IR continuum is a prime AGN signature. The location of starburst-dominated ULIRGs in such a diagram is consistent with previous ISO-SWS spectroscopy which implies significant extinction even in the mid-infrared.

We have searched for indications that ULIRGs which are advanced mergers might be more AGN-like, as postulated by the classical evolutionary scenario. No such trend has been found amongst those objects for which near infrared images are available to assess their likely merger status.

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

1. Introduction

The nature of ultraluminous infrared galaxies (ULIRGs, see Sanders & Mirabel 1996 for a recent review) has been the subject of lively debate since their discovery by IRAS more than a decade ago. Although evidence for both starburst and AGN activity in ULIRGs has accumulated during this period, the question as to which generally dominates the luminosity has remained largely unsolved, mainly due to observational difficulties associated with their large dust obscuration.

With the advent of the Infrared Space Observatory (ISO) of the European Space Agency, sensitive mid-infrared spectroscopy became available as a new tool capable of penetrating the obscuring dust. Fine structure line and PAH feature observations with SWS and ISOPHOT-S of a sample of 15 bright ULIRGs suggest that most are starburst-powered (Genzel et al. 1998). However, this sample is too small to search for luminosity or evolutionary effects. Using only PHT-S it has subsequently proved possible to extend to fainter sources and increase to 60 the number of ULIRGs observed over the wavelength range containing the 6.2, 7.7, 8.6, and 11.3μm features commonly attributed to polycyclic aromatic hydrocarbons (PAH). Groundbased observations of these and a companion at 3.3μm first demonstrated that these features are strong in starburst galaxies but weak or absent in classical AGNs (Moorwood 1986, Roche et al. 1991). ISO spectroscopy has further strengthened this link by demonstrating the anti-correlation between feature strength relative to the continuum and the ionization state of the gas (Genzel et al. 1998). In the analysis of the larger sample presented here, therefore, it is considered reasonable to use the line to continuum ratio of the most prominent, 7.7μm, feature as our primary discriminator between starburst and AGN activity.

The sample is drawn from the 1.2 Jy survey (Fisher et al. 1995, Strauss et al. 1992).

We selected ULIRGs with $L_{FIR} > 10^{11.7} L_{\odot}$ (approximately equivalent to $L_{IR} > 10^{12} L_{\odot}$)[4], $S_{60} > 1.3 Jy$; good visibility for ISO; redshift below 0.3 and a clear optical identification. No infrared color criteria were applied to avoid biasing the sample in AGN content. Our sample includes the ULIRGs of Genzel et al. (1998) except NGC 6240 and IRAS 23060+0505 which do not meet the selection criteria. We have adopted IRAS FSC fluxes for all our sources to compute total (8-1000μm) IR luminosities L_{IR} (H_0=75, q_0=0.5), replacing flux upper limits by estimates based on the 60 μm flux and average far-infrared colors of the ULIRGs of Sanders et al. (1988) where necessary. Sources meeting our basic luminosity and flux criteria may be missing because of poor ISO visibility, lack of good optical identifications or because they were not scheduled during the ISO mission. These effects do not, however, affect the unbiased nature of the sample for studying the power sources and evolution of ULIRGs.

2. Observations and Data Analysis

ISOPHOT-S 3-11.6μm spectra of the ULIRGs were obtained in chopped mode, using pure on-source integration times between 512 and 2048 seconds. ISOPHOT-S comprises two simultaneously operating grating spectrometers. Here, we only make use of the long wavelength section covering the wavelength range 5.84 to 11.62μm because the S/N ratio for the faint ULIRGs is too low in the short wavelength section. The data processing was performed using standard procedures of the PHT Interactive Analysis (PIA[5]) software versions 6 and 7. The detector drift modelling available in the most recent versions of PIA

[4]See e.g. Sanders & Mirabel (1996) for the definition of the commonly used 40-120μm (L_{FIR}) and 8-1000μm (L_{IR}) luminosities

[5]PIA is a joint development by the ESA Astrophysics Division and the ISOPHOT Consortium led by the Max-Planck-Institut für Astronomie (MPIA) Heidelberg.

is problematic for extremely faint sources and was therefore not used. Instead an upward flux correction of 40% to the not drift corrected data was made to approximately take into account the drift effects (U. Klaas, private communication).

EDITOR: PLACE FIGURE 1 HERE.

The average of all 60 ULIRG spectra, individually scaled to S_{60}=1Jy to give all sources equal weight (Fig. 1), clearly shows the PAH features at 6.2, 7.7, and 8.6μm but relatively weak continuum. Comparison with the starburst and AGN templates provides a first and direct indication that ULIRGs are, on average, starburst-like. Fig. 1 also illustrates our method for extracting PAH and continuum data from the individual spectra. Two pivots were used to determine the continuum by linear interpolation - a feature-free continuum point at 5.9μm rest wavelength, shortward of the 6.2-8.6μm PAH complex and the underlying emission plateau, and a continuum point at 10.9μm rest wavelength in the long wavelength flank of the silicate absorption, but short of the 11.3μm PAH emission feature. In the relatively frequent cases where the 10.9μm point is redshifted out of the ISOPHOT-S range we adopted $S_{10.9} = (2.5 \pm 0.5) \times S_{5.9}$ which was found adequate for low redshift sources. In a few cases, the linear continuum was estimated by eye because application of the standard method gave unphysical results, e.g. interpolated 7μm continuum above the observed spectrum.

Since ULIRGs are heavily obscured, silicate absorption may strongly influence the spectra beyond 8μm and affect the continuum placement. Because of flanking emission features and the ISOPHOT-S long wavelength cutoff, the silicate optical depth is poorly constrained from our ISOPHOT data alone. To illustrate the effect of extinction, we

Contributing ISOPHOT Consortium Institutes are DIAS, RAL, AIP, MPIK, and MPIA have added as dashed lines in the top panels of Fig. 1 the starburst and AGN templates additionally obscured by A_V=50 assuming the ISO-derived extinction law of Lutz et al. (1996,1997). Obscured starbursts can still be separated from obscured AGNs by presence of the 7.7 and 6.2μm PAH features. Both normal and obscured spectra demonstrate that the ratio between narrow-band fluxes at 7.7μm (feature plus continuum) to 5.9μm (continuum) is a valuable discriminator between starbursts (high ratios) and AGNs, with little sensitivity to extinction since both points are outside the silicate feature. Analysing this ratio for our sample gives AGN/starburst discrimination closely similar to that obtained from the line-to-continuum method. Below, we only present results of the line-to-continuum method which places firmer limits on PAHs on a rising AGN continuum. Due to the proximity of 7.7μm to the reliable 5.9μm continuum point, errors in continuum placement are overall small enough not to affect the discrimination between starbursts and AGNs. Heavily obscured AGN continua can mimick a 7.7μm PAH peak in this method but stay at L/C$\lesssim$1. In addition, obscured AGN would not show the 6.2μm feature that is clearly seen in the average ULIRG spectrum.

Because the shape of PAH features is known to vary with physical conditions (e.g. Roelfsema et al. 1998), we did not attempt to fit a (fixed) PAH shape to the data to measure the PAH features in our low S/N data. The peak strength of the 7.7μm feature was measured by simply taking the average of all data within a window covering the rest wavelengths 7.57–7.94μm. Errors or limits on all these quantities are based on the noise measured shortward of 5.9μm rest wavelength and the increase in noise towards longer wavelengths corresponding to the decrease of the ISOPHOT-S spectral response.

3. Starbursts vs. AGNs

EDITOR: PLACE FIGURE 2 HERE.

Figure 2 shows the measured line-to-continuum ratios (L/C) of the 7.7μm PAH feature plotted as a function of integrated infrared luminosity. For reference, our average starburst and AGN template spectra yield L/C=3 and 0.2 respectively. In the following discussion we have therefore classified ULIRGs with L/C below 1 (plus some with upper limits slightly above 1) as AGNs and the rest as starbursts. Only the average has been plotted for 14 ULIRGs which were not individually detected reliably in either the feature or continuum. The fact that these sources have weak 5.9μm continua compared to those at 60μm (see below) indicates that these are also powered by starbursts. This is supported by the average of their spectra which, although noisy, shows a clear 7.7μm feature. Note also that a selection effect in favour of detecting AGNs is caused by the fact that, for the same 60μm continuum, an average AGN will exhibit a 7.7μm continuum flux density which is higher than the peak PAH flux density of a starburst (Fig 1). The noisy spectra will hence preferentially correspond to starburst-like ULIRGs.

The distribution seen in Fig. 2 suggests that the AGN fraction rises towards high ULIRG luminosities. Dividing the sample into two bins separated at log (L_{IR})=12.3 and using the above criteria we find most probable and (firm upper limit) AGN fractions of 8/51 (21/51) for the low luminosity bin, 5/9 (6/9) for the high and 13/60 (27/60) in total. The most probable values assume that the 14 individually undetected sources are starburst powered, for the reasons given above, while the firm upper limits assume that they are all AGNs.

The above results provide both (i) a better statistical basis for the conclusion, based on SWS and ISOPHOT-S spectroscopy of a smaller sample, that most ULIRGs are predominantly starburst powered (Genzel et al. 1998) and (ii) support for the increase in AGN powered fraction with luminosity inferred from optical spectroscopy (Veilleux 1997). With regard to the latter, however, the AGN fraction at log (L_{IR})<12.3 estimated with the extinction-insensitive PAH method is still lower and, together with more detailed case studies such as that for UGC 5101 (Genzel et al. 1998), cautions that some ULIRGs exhibiting optical Seyfert spectra may still be predominantly starburst-powered.

3.1. Ratios of PAH features

Our average ULIRG spectrum (Fig. 1) exhibits a ratio of the 6.2/7.7μm features which is slightly lower than in typical starbursts. The measured ratio of the integrated feature fluxes is 0.25 compared to 0.30 for the average of the reference starburst galaxies. This behaviour is more pronounced in some individual spectra, e.g. for Arp 220 where the ratio is 0.18. One possibility is that the weakness of the 6.2μm feature reflects the unusual conditions of the ULIRG interstellar medium. ISO observations of galactic sources may provide clues on such trends. For compact H II regions, Roelfsema et al. (1996, 1998) find a 6.2/7.7 ratio which on average is lower than for 'typical' H II regions. Very low 6.2/7.7 ratios, lower than for the ULIRGs, are observed in some of these compact H II regions (Fig. 5 of Roelfsema et al. 1998), as well as high 8.6/7.7 ratios in others which might be linked to an intense radiation field. A decrease of the 6.2/7.7μm ratio is also observed going from the disk to the central starburst of M 82 (Tran 1998).

A second effect which could be responsible for unusual PAH ratios is the influence of strong extinction which is already suggested by the similarity of the average ULIRG spectrum and the obscured starburst spectrum of Figure 1. Extinction suppresses the 6.2, 8.6, and 11.3 features in comparison to the one at 7.7μm. This effect will be even stronger than for a standard extinction curve if the material obscuring the ULIRGs contains icy grains. Absorption features due to water ice and other ices are observed with ISO in the 6μm region and between the two silicate features in galactic sources such as young stellar objects (e.g. Whittet et al. 1996) and, to a lesser degree, towards the center of our Galaxy

(Lutz et al. 1996) which samples a more normal line of sight containing some molecular material. Of the starburst templates with ISOPHOT-S PAH spectra and for which Genzel et al. (1998) estimated extinction from independent ISO-SWS spectroscopy, extinction approaches ULIRG levels only for NGC 4945 and the molecular ring encircling the center of our Galaxy. Interestingly, these are the only spectra in that group which also show low 6.2/7.7μm flux ratios. Further, as in our average ULIRG spectrum, their 8.6μm features appear as a shoulder to the 7.7μm rather than as a separate feature, due to suppression by silicate absorption. Attempts to estimate the strength of the PAH emission from the 11.3μm feature (e.g. Dudley & Wynn-Williams 1997 for Arp220) may underestimate the importance of PAHs in highly obscured sources. This, in consequence, will lead to an overestimate of the depth of the silicate feature and problems in interpretation of the mid-infrared spectrum in general.

3.2. Dust, Destruction and Dilution?

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More insight into the properties of ULIRGs can be gained from a diagnostic diagram which combines the PAH line-to-continuum ratio with the ratio of feature-free 5.9μm continuum (from our spectra) to IRAS 60μm continuum (Fig. 3). Strong 5.9μm continuum appears in the case of AGNs due to the presence of hot dust in the NLR or torus. We also show in this diagram the median location of the small sample of known starbursts observed in addition to the ULIRGs. Seyfert galaxies and QSOs scatter over a wider range of the diagram, possibly due to varying contributions of star formation and are less easily condensed into a median location. The AGN location plotted is meant to represent 'pure' AGNs and QSOs but note that most of the PAH L/C ratios are only upper limits.

We have also plotted the change vectors expected due to various effects. Dust extinction suppresses the 5.9μm continuum with respect to the far-infrared but does not affect the PAH L/C ratio. Destruction of the PAH carriers shifts a source vertically while dilution by an AGN-powered hot dust continuum moves a source along a diagonal, provided the PAH flux and the far-infrared continuum are unaffected.

A first result is the clear anticorrelation between PAH L/C ratio and 5.9 to 60μm flux ratio. A similar anticorrelation is found when the 25 to 60μm ratio is used instead. Our ISO PAH-spectrophotometry thus strongly indicates that 'warm' ULIRGs (in the sense of 5.9/60 or 25/60 flux ratios) are AGN dominated, while 'cold' ULIRGs are starburst dominated, in agreement with earlier continuum-based conclusions (Sanders et al. 1988a).

A second result is that those ULIRGs which are starburst-like in their PAH L/C tend to have lower $S_{5.9}/S_{60}$ than the template starbursts. We interpret this as the result of very high extinction in the dust-rich ULIRGs, in agreement with our conclusion from the PAH feature ratios. The corresponding 6μm extinctions of up to 2.5 magnitudes (for a foreground screen) are consistent with ULIRG 25μm screen extinctions of $\lesssim$1 mag derived from H II region emission lines (Genzel et al. 1998) and the mid-IR extinction curve of Lutz et al. (1996,1997). Also, the corresponding silicate feature optical depths of up to $\sim$5 agree with significant silicate optical depth indicated in Arp220 (Smith et al. 1989, Charmandaris et al. 1997) which interestingly is the source of lowest $\mathrm{S}_{5.9}/\mathrm{S}_{60}$ in Figure 3. Even higher obscuration, that would hide the center completely in the mid-infrared, has been inferred by Fischer et al. (1997) from a fit to the shape of the ISO-LWS far-infrared continuum of Arp 220. Adopting a fully mixed, single temperature emitting slab model they obtain optical depth one (through the complete slab) at 150μm, while optical depth one occurs near 40-50μm in mixed models equivalent to the screen extinctions we derive above. Excellent fits to the Arp 220 SED can also be achieved by assuming $\tau = 1$ in the 30-50μm region and a mix of dust temperatures. CO fluxes and size limits, and FIR/submm continuum size limits (Scoville et al. 1997) have been used to infer that ULIRGS may be optically thick in the far-infrared (e.g. Solomon et al. 1997). Differences between high CO-estimated optical depth and actual optical depth to the starburst are also observed, however, to the central regions of starburst galaxies like M82 and are attributed to a separation between the bulk of the gas and star forming regions. A similar separation may occur in Arp 220 where much of the gas appears to be concentrated into a thin disk (Scoville et al. 1997).

Third, no clear correlation or anticorrelation between the ratio of PAH to FIR continuum flux and the 5.9/60μm flux ratio can be seen in close inspection of Fig. 3. Our ULIRG data are therefore consistent with a model in which the PAH to far infrared emission is constant, mid-infrared extinction is a few magnitudes and the AGNs simply contribute a diluting hot dust continuum. This interpretation may, however, not be unique since some template AGN which are not highly obscured (e.g. NGC 4151) are similarly offset from the dotted line in Fig. 3 representing pure dilution by hot dust. This indicates *less* PAH compared to the 60μm continuum than starbursts resulting e.g. from destruction of their carriers. It is hence equally possible that the extinction to at least some AGN-like ULIRGs is substantially lower, and that the PAH emission is not only diluted by continuum but indeed also suppressed to some degree. Due to the diluting continuum, it is difficult to lower the limits on PAH flux sufficiently to confirm this destruction, even for bright sources with high S/N spectra. For illustration, Fig. 3 also contains a mixing line between starburst and AGN templates, labeled by varying starburst contribution to the 60μm flux. Note that this also indicates that choosing PAH L/C=1 to separate starbursts from AGN is conservative in the sense of not misclassifying AGN as starbursts.

4. Evolution of ULIRGs

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The classical evolutionary scenario of Sanders et al. (1988) postulates that interaction and merging of the ULIRG parent galaxies triggers starburst activity which later subsides while the AGN increasingly dominates the luminosity and expels the obscuring dust. An implication of this scenario would be that advanced mergers should, on average, be more AGN-like than earlier stages of interacting galaxies which are still well separated. To test this, we have plotted in Fig. 4 the PAH line-to-continuum ratio as a function of the nuclear separations estimated from various near-infrared imaging studies (Armus et al. 1994, Carico et al. 1990, Duc et al. 1997, Graham et al. 1990, Majewski et al. 1993, Murphy et al. 1996). Although near infrared imaging of our sample is incomplete, it is already evident in this figure that starbursts are found to the smallest nuclear separations and that there is no obvious trend towards AGN dominance with decreasing separation. This suggests that the dominance of AGN or starburst may depend on local and shorter term conditions determining the fuelling of the AGN in addition to the global state of the merger.

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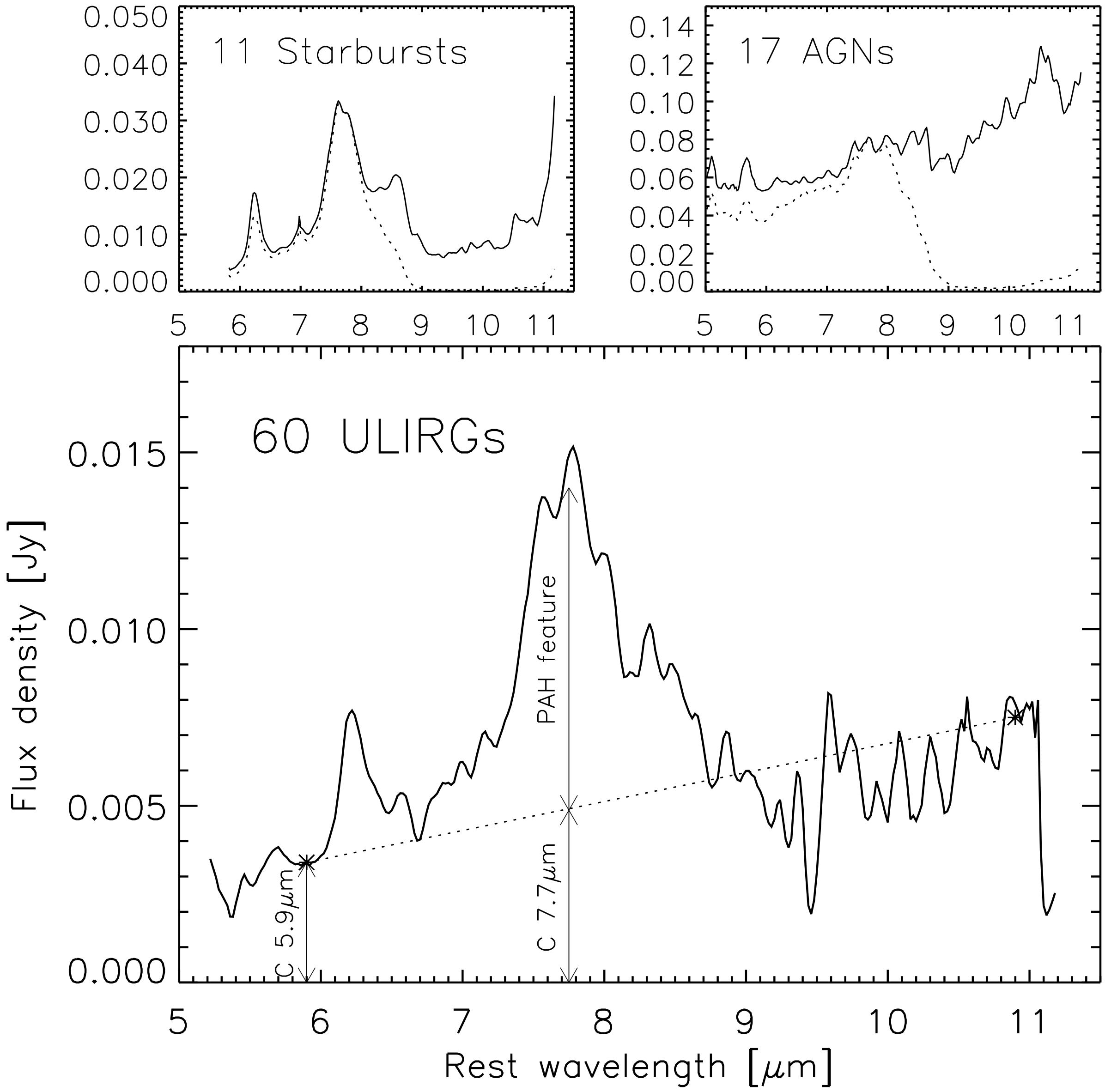
Fig. 1.— Average ISOPHOT-S spectrum of all ULIRGs observed, individually scaled to S_{60}=1Jy. The method used to derive the line-to-continuum for the 7.7μm PAH feature, and the feature-free 5.9μm continuum is indicated (see also text). Average spectra of starburst galaxies and AGNs are added for comparison. The dashed lines represent these spectra after applying an additional A_V=50 foreground extinction and re-scaling for display purposes.

Fig. 2.— Line-to-continuum ratio for the 7.7μm PAH feature as a function of infrared luminosity. Thick symbols refer to PAH detections or 3σ limits with reliable ($> 2\sigma$) continuum detections. Thin symbols represent galaxies with significant PAH but continuum detected at less than 2σ. The filled circle gives the location of the *average* spectrum of 14 ULIRGs that were too faint to be analysed individually. The dotted line indicates the adopted separation between starbursts and AGNs at L/C=1.

Fig. 3.— Line-to-continuum ratio for the 7.7μm PAH feature as a function of the 5.9μm/60μm continuum flux ratios. The filled circle represents the average spectrum of the 14 faint sources with noisy spectra. Pure dilution of a starburst spectrum by 5.9μm continuum (dotted) is indicated, as well as a mixing line (dashed) for the case of a starburst ('SB') and AGN contributing different fractions of the 60μm flux.

Fig. 4.— Line-to-continuum ratio for the 7.7μm PAH feature as a function of nuclear separation of the interacting components of an ULIRG. We have placed faint sources with noisy spectra (small symbols) at L/C=3 derived from their average spectrum. The dotted line indicates the adopted separation between starbursts and AGNs at L/C=1.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60 ULIRGs
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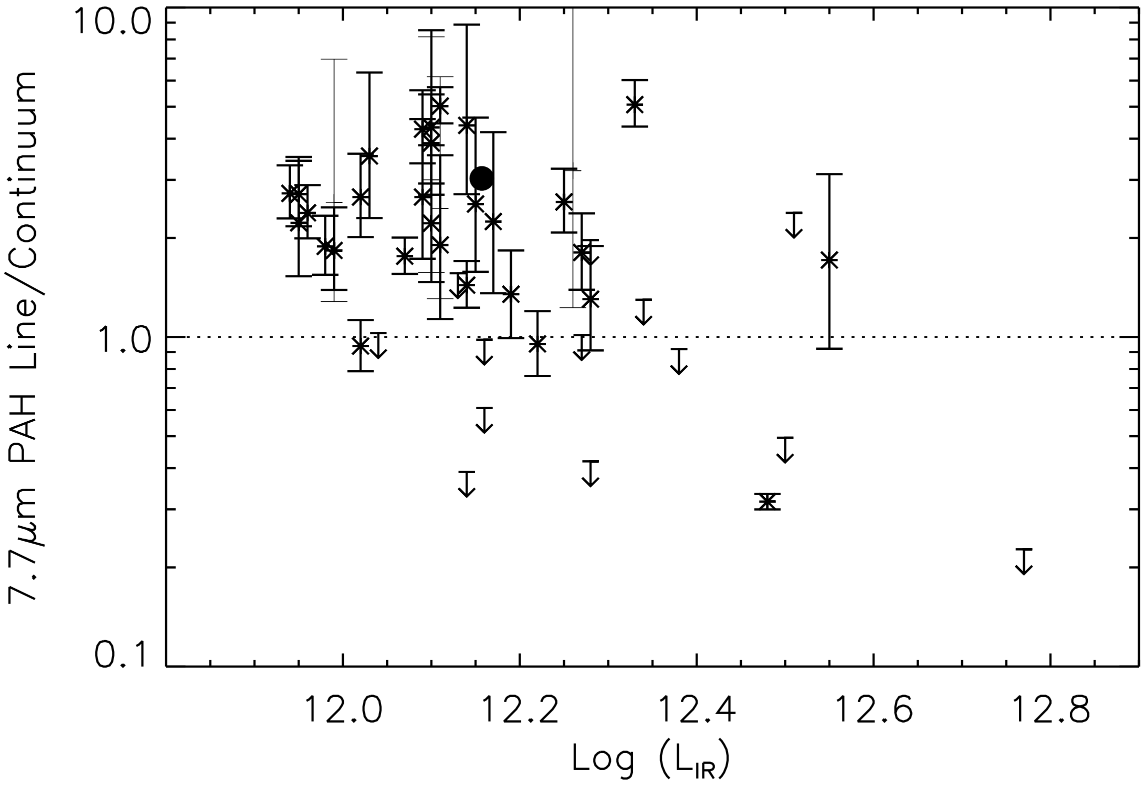
C 7.7μm



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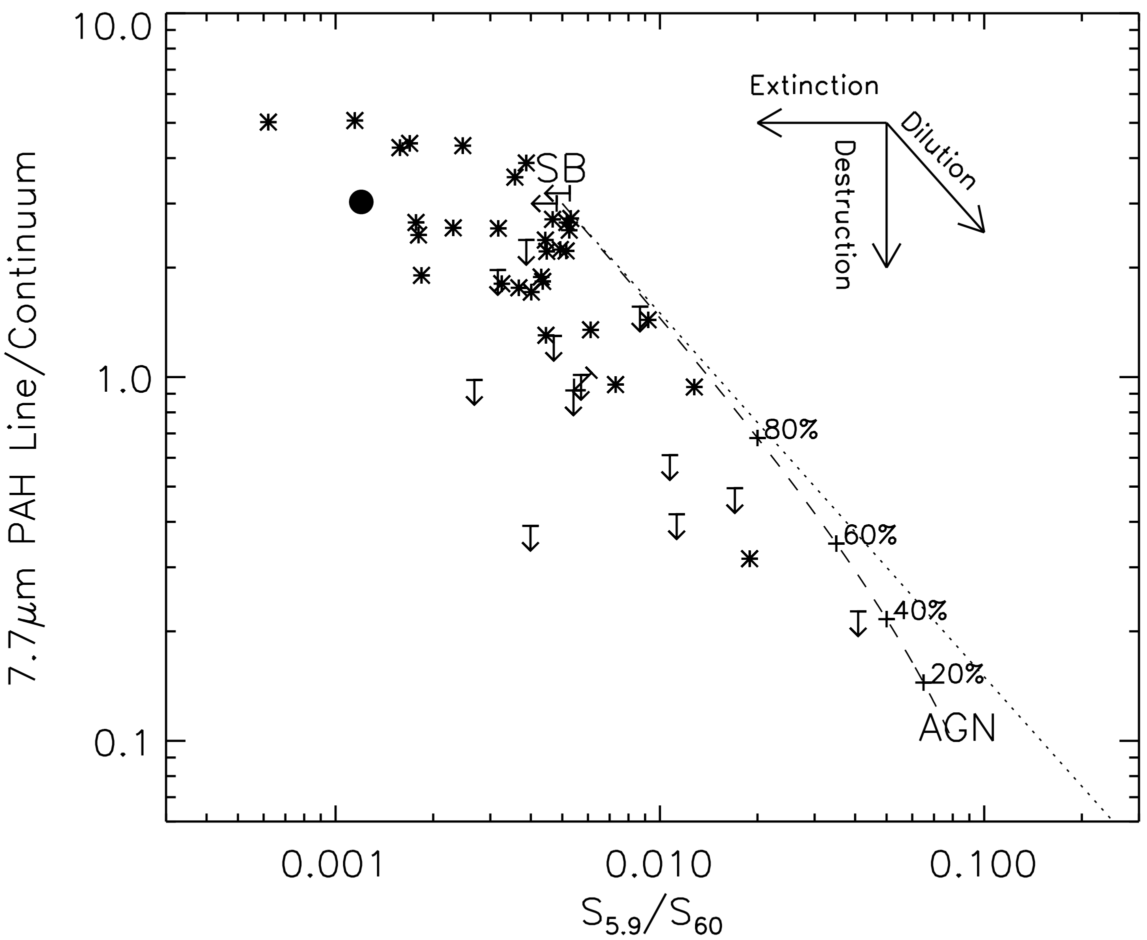

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7.7μm PAH Line/Continuum
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SB
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40%
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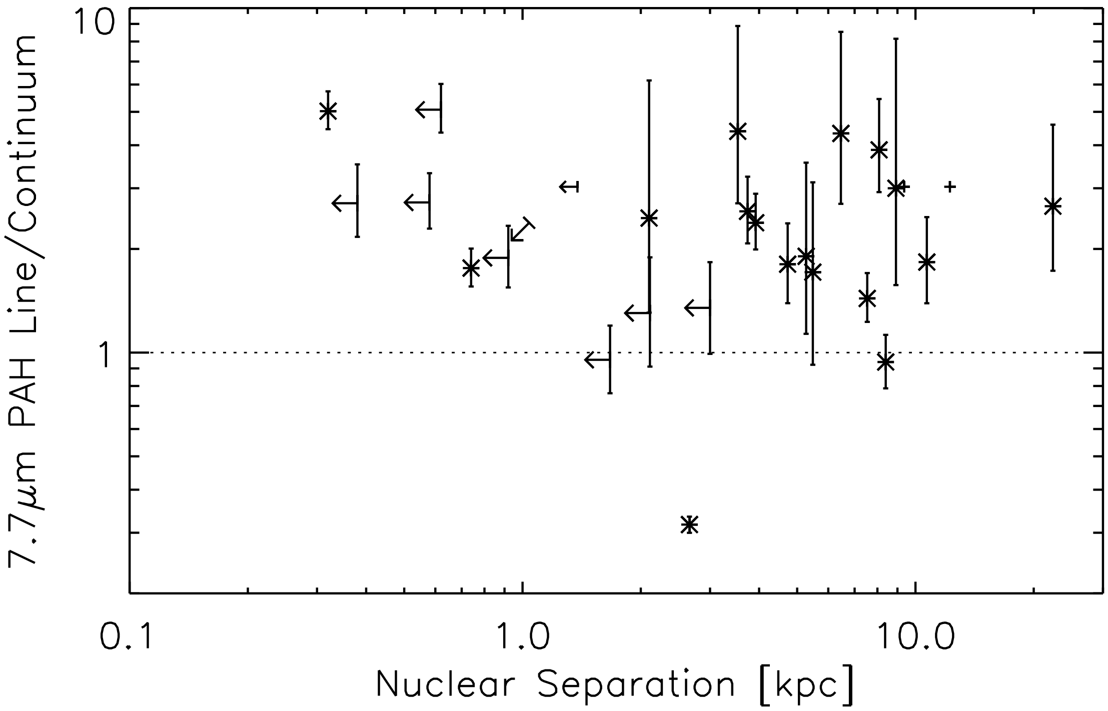
7.7μm PAH Line/Continuum
10
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