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A New MIR/submm Diagnostic for Dust-Enshrouded AGN

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Abstract. We show that the PAH 7.7μm to continuum 850μm flux ratio can be used to reveal high mid-infrared extinction in ultraluminous infrared galaxies (ULIRGs). While the submm radiation is optically thin and represents the emission from essentially all dust grains, the PAH strength (measured by the peak height of the Polycyclic Aromatic Hydocarbonates at 7.7μm) is sensitive to dust extinction in the mid-infrared (MIR). As an application of the new diagnostic, after dereddening of the central MIR continuum and with the assumption of a disk-like dust distribution seen under a tilted angle, we find increasing evidence for a hidden quasar in the archetypal ULIRG Arp220.

1. Introduction

The IR 1-1000μm spectral energy distributions (SEDs) of ULIRGs show two basic types as illustrated in Fig. 1:

1. *Warm* ULIRGs: They have a steep flux rise from the NIR (around 2-5μm) to the MIR (around 10-25μm), a high $F_{25\mu m}$ to $F_{60\mu m}$ ratio (>0.2) and most of them show optical Seyfert spectra.

2. *Cool* ULIRGs: They have a flat NIR flux plateau followed by a sudden jump-like flux rise around 10μm, a low $F_{25\mu m}$ to $F_{60\mu m}$ ratio (<0.2) and most of them show LINER or HII type optical spectra.

The open question is whether the NIR-MIR continuum in cool ULIRGs could be suppressed by extinction on the order of $A_V > 100$. If "yes", then cool ULIRGs could also house a powerful AGN.

Standard methods for the MIR extinction use the Si 9.7μm absorption feature or the S[III] 18.7μm/33.5μm line ratios. These methods are based exclusively on a wavelength regime, the extinction of which is a priori unknown. The limitations could be that they probe only the shallow surface, but not the full dust column.

Therefore a new method is proposed which uses not only the MIR range alone, but also the submm regime at 850μm which is optically thin and traces the full dust column. The PAH (Polycyclic Aromatic Hydrocarbonates) are presumably mixed with the submm emitting grains. The submm emission serves as normalizer, while the PAH 7.7μm line strength is sensitive to extinction.

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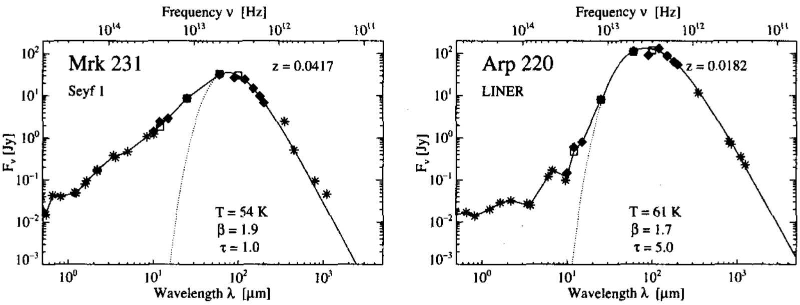

Figure 1. IR SED of Mrk 231 and Arp 220, a warm and a cool ULIRG (from Klaas et al. 2001)

2. Brief Outline of the Diagnosis

First results on the PAH 7.7μm/850μm ratio in ULIRGs have been published by Haas, Klaas, Müller et al. (2001). Also, a comprehensive study of this topic is presented by Haas (2001), and the reader can obtain a copy of this manuscript (just send an email to haas@mpia.de). Here, we restrict the discussion to a brief outline of the diagnosis:

2.1. The Data

We analyse a sample of 15 ULIRGs for which both the PAH spectra (from Rigopoulou et al. 1999) and the submm fluxes are available (from Rigopoulou, Lawrence & Rowan-Robinson 1996, Lisenfeld, Isaak & Hills 2000, Klaas et al. 2001). Also the FIR fluxes at 100μm are considered (from IRAS and from Klaas et al. 2001). These data are compared with those of a sample of 20 "normal" starforming galaxies (submm fluxes from Dunne et al. 2000, PAH spectra from the ISO archive). The PAH spectra refer to an aperture of 24″ (with FWHM of the ISOPHOT-S point spread function ≈ 3″); the submm fluxes are derived assuming unresolved sources (FWHM of SCUBA beam at 850μm ≈ 15″, FWHM of SEST beam at 1.3mm ≈ 24″).

Fig. 2 shows the PAH spectra for two examples, and how the PAH 7.7μm line strength is derived.

2.2. The PAH/Submm Flux Ratio: A Tracer for High MIR Extinction

Fig. 3 shows the PAH 7.7μm to 850μm flux versus PAH 7.7μm to 100μm flux:

1. The y-axis shows the PAH 7.7μm/850μm distribution of the ULIRGs and the reference sample. Strikingly, all ULIRGs except Arp220 and UGC5101 lie in a confined range (around 5 ± 2), which is also the same as for the

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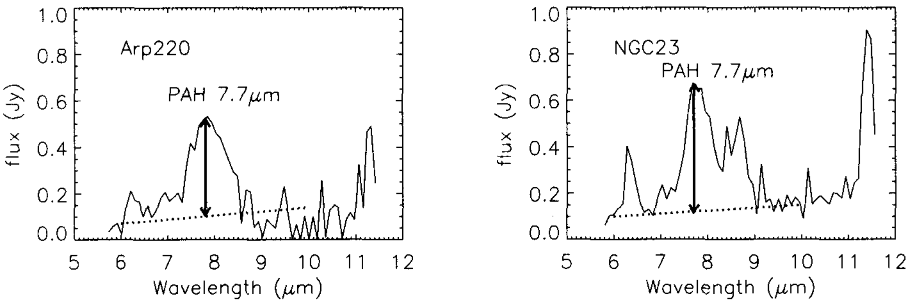

Figure 2. Examples of ISOPHOT-S 5-12 μm spectra (24″ aperture) for the ULIRG Arp220, and the comparison galaxy NGC 23. The dotted line indicates the continuum subtracted for the estimate of the PAH 7.7 μm strength. Note that adopting a lower continuum can increase the determined PAH strength by at most 20%.

normal galaxies. This suggests that for both samples the PAH and the submm emission are related, and that no extraordinary excitation conditions are needed.

UGC5101 has a high mixed case extinction $A_V \approx 50$ derived from NIR-MIR spectroscopy (Genzel, Lutz, Sturm et al. 1998). Dereddening shifts it clearly into the range of the other ULIRGs.

2. The PAH 7.7μm/100μm ratio (x-axis) is lower for the ULIRGs than for the reference sample by a factor of about three. ULIRGs have warmer dust (30K<T<50K) than normal galaxies (20K<T<30K), and therefore their 100μm flux relative to that at 850μm is higher. Again, along the PAH 7.7μm/100μm distribution Arp220 lies below the other obviously more "typical ULIRGs" which populate a confined range.

In principle, the exceptional position of Arp220 could be due to PAH destruction (either by a quasar-like hard UV radiation field or strong collisions) or to an unusually high submm flux excess. Since both of these explanations remain unsatisfatory, as a most likely scenario we conclude that the low PAH 7.7μm/850μm flux ratio of Arp220 is mainly caused by extinction. A comparison with UGC5101 immediately suggests that the MIR extinction is about a factor of three higher in Arp 220.

Note that the precise value for the extinction at 7.7μm depends on the dust properties and extinction curves assumed. Here we consider two "extreme" cases: the interstellar one by Mathis, Rumpl & Nordsieck (MRN 1977, see Mathis, Mezger & Panagia 1983), and the one of dense protostellar clouds by Krügel & Siebenmorgen (1994).

It is reasonable to assume that the PAH carriers are not an isolated component in the interstellar medium (ISM), rather they are mixed with other constituents of the ISM. Thus we consider an ensemble of dust clouds which emit

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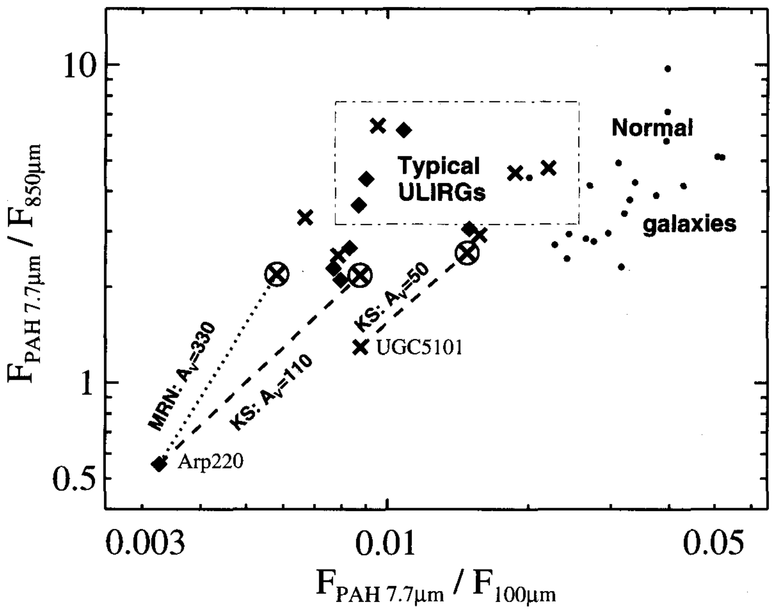

Figure 3. Two-colour diagram PAH 7.7μm to 850μm flux versus PAH 7.7μm to 100μm. The symbols are: crosses = Seyfert-ULIRGs, diamonds = LINER- and HII/SB-ULIRGs, points = normal galaxies. The errors are less than 30%. The positions of Arp220 and UGC5101 after dereddening are marked with the encircled crosses. For Arp220 two mixed case extinction curves are considered: interstellar dust (dotted line: MRN, Mathis, Rumpl & Nordsieck 1977), and protostellar dust (dashed line: KS, Krügel & Siebenmorgen 1994). The dash-dotted box indicates the min-to-max range of the typical ULIRGs after dereddenening the A_V values from Genzel, Lutz, Sturm et al. (1998) with the KS model; note that dereddening reduces the PAH 7.7μm/850μm dispersion.

the FIR and submm luminosity, and the PAH carriers are located preferentially at the borders of these clouds in the photodissociation regions. In this picture the PAH carriers are mixed with the dust clouds – at least on the spatial scale of several pc, which applies to our data. Consequently, for the PAHs we adopt not the commonly used "screen case" extinction, rather the "mixed case" extinction, which results in higher dust column densities.

To summarize, 13 out of 15 ULIRGs as well as 20 comparison galaxies populate the same confined range of the PAH 7.7μm/850μm flux ratio. Their MIR extinction may be moderate ($A_V \lesssim$3-10), so that NIR-MIR spectroscopy can yield proper results. Also, it is not likely that they contain a hidden powerful AGN which has not yet been identified as such. Two ULIRGs, however, lie significantly below this range and their offsets are mainly due to extinction. The new PAH 7.7μm/850μm diagnostics is a promising tool to reveal high MIR extinction in ULIRGs.

2.3. Signatures Favoring a Hidden Quasar in Arp 220

The best signatures for an AGN are broad emission lines. Actually in Arp 220 a broad Br_α line has been discovered (Depoy, Becklin & Geballe 1987). The strength of this NIR line, however, was found to be too faint to account for the ultrahigh bolometric (FIR) luminosity (Depoy, Becklin & Geballe 1987). In order to do so, the extinction towards the region emitting this line would be required to exceed the incredibly high amount of $A_V \approx 130$, but at that time, other extinction estimates were by far lower ($A_V \approx 50$). An extinction of $A_V \approx 110$ is so high that even hard X-rays might be blocked (see also the excellent contribution by Iwasawa in this volumne). The supernova remnants resolved using VLBI at 18 cm (Smith et al. 1998), provide evidence for powerful starbursts whose extent is larger than the 100 pc diameter found for the bulk of the MIR emission (Soifer et al. 1999). They do not exclude the presence of a deeply hidden AGN.

As outlined in the introduction, an alternative tracer for an AGN is a powerful MIR continuum as well as a high MIR/FIR luminosity ratio. Thus our task is to find out the extinction for the MIR continuum, which may differ from that derived for the PAHs, depending on the geometry of the absorbing/reemitting dust. For example, imagine a central AGN as strong MIR continuum source, which (along our line of sight) is hidden by dust clouds emitting in the PAH 7.7μm line as well as the submm continuum. Then the PAH/submm diagnosis yields a *mixed* case extinction for the dust clouds, but the central source suffers from *screen* extinction by these dust clouds. (Actually the screen consists of half of the dust column, if the central source lies in its middle). The crucial point is that the dust column derived for the mixed case extinction is huge, and that the screen extinction of even half of this dust column is still very high. (In order to provide a given reddening curve by mixed case extinction with a dust column of homogeneous density, the emitters located deeply inside need to be extremely reddened, since the emitters at the shallow surface towards the observer are nearly unextincted.)

The presence of CO disks already indicates a *non-spherical axisymmetric geometry* tilted about 45° with respect to our line of sight (Downes & Solomon 1998, Sakamoto et al. 1999). The question is to decide between the two alternatives:

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1. the line of sight towards the two nuclei of Arp 220 is relatively free of extinction, or

2. the two nuclei of Arp 220 are hidden by the disks.

High spatial resolution Keck telescope images between 3.4 and 24.5μm reveal that the colors of the two nuclear regions are similar to those for the extranuclear areas and do not show much lower extinction (Soifer et al. 1999). Furthermore, on NICMOS images between 1.1 and 2.2μm the NIR maximum is offset from the actual western nuclear position as traced by the radio continuum peak, and the eastern nucleus belongs to the most reddened regions (Scoville et al. 1998). These findings argue against the first alternative, hence the nuclei might be hidden by the disks.

It is reasonable to assume that the observed MIR continuum is a mixture of contributions from from (extranuclear) starbursts in the disks and from the nuclei. But we do not know their relative contributions. In Tab. 1 we list the values derived assuming purely mixed case extinction for the disks (rows 2 and 3) and purely screen extinction for the nuclei (row 4). The actual dereddened MIR continuum likely lies between the two extremes. Note that for the high extinction values also the FIR emission has to be dereddened, but the effect is moderate, since probably the mixed case extinction applies to the FIR.

Table 1. Observed and dereddened luminosities of Arp220.

	deredd. factor	L_{MIR} $10^{11}L_\odot$	deredd. factor	L_{FIR} $10^{11}L_\odot$	L_{MIR}/L_{FIR}
observed	1.0	2.1	1.0	9.0	0.23
MRN:A_V=330	10 (4...20)	$\approx$ 21.0	3.2	28.8	0.72
KS: A_V=110	4.0	8.4	1.7 (1.3 ... 2.0)	15.3	0.54
KS: $A_V$screen=90*	20.0	42.0	"	"	2.75

* with screen case on central MIR continuum using the half of the dust column derived from the PAH mixed case extinction, whereby the mixed case extinction probably still applies to the FIR emission

Fig. 4 shows the resulting MIR/FIR luminosity ratios for the ULIRGs, and how the dereddening moves Arp220 from the range observed for cool ULIRGs towards that range which is exclusively populated by PG quasars and typical warm ULIRGs housing a strong AGN. In addition, the nuclear regions are very compact (d $<$ 100 pc), hence the MIR luminosity density exceeds that of known starburst (e.g. in M82) by a factor of about 1000. Since the dust (and the gas) is more dissipative than the stars, it tends to be distributed in a more compact area than the stars. Bearing this in mind, it is difficult to imagine, how starbursts alone can create such a high luminosity density, and *simultaneously* how the dust hides them entirely.

Therefore, a more natural explanation would be that – in addition to the prominent starbursts mainly responsible for the FIR luminosity – one (or both) of the nuclei of Arp 220 contains a powerful AGN providing the quasar-like MIR luminosity which is hidden to us.

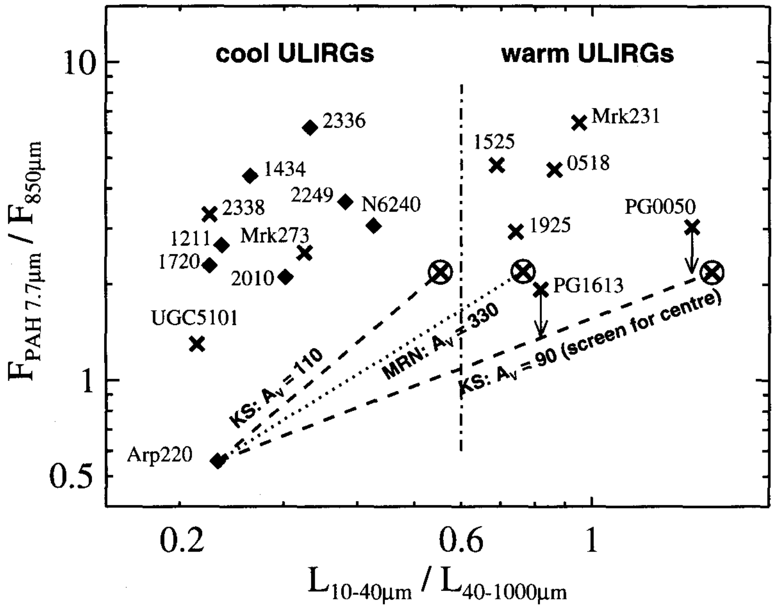

Figure 4. Two-"colour" diagram PAH 7.7μm to 850μm flux versus L_{MIR}/L_{FIR} ($= L_{10-40\mu m}/L_{40-1000\mu m}$). Symbols as in Fig.1. In addition, two PG quasars, where PAH spectra are available, are plotted. The dereddened positions of Arp220 correspond to the KS and MRN cases listed in Tab.1. The vertical dash-dotted line marks the division between warm and cool ULIRGs according to $F_{25\mu m}/F_{60\mu m} \approx 0.2$.

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