ISOCAM-CVF 5–12 MICRON SPECTROSCOPY OF ULTRALUMINOUS INFRARED GALAXIES

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ABSTRACT

We present low-resolution mid-infrared (MIR) spectra of 16 ultraluminous infrared galaxies (ULIRGs) obtained with the circular variable filter (CVF) spectroscopy mode of ISOCAM on board the Infrared Space Observatory (ISO). Our sample completes previous ISO spectroscopy of ultra- and hyperluminous infrared galaxies toward higher luminosities. The combined samples cover an infrared luminosity range of $\sim 10^{12} - 10^{13.1} L_\odot$. To discriminate active galactic nucleus (AGN) and starburst activity, we use the AGN-related MIR continuum and the starburst-related 6.2, 7.7, 8.6, and 11.3 $\mu$m MIR emission bands attributed to aromatic carbonaceous material. For about half of the high-luminosity ULIRGs studied here, strong aromatic emission bands suggest starburst dominance. Other spectra are dominated by a strong AGN-related continuum with weak superposed emission features of uncertain nature. Our sample contains one unusual example, IRAS F00183–7111, of an AGN that is highly obscured even in the MIR. An improved method to characterize quantitatively the relative contribution of star formation and AGN activity to the MIR emission of ULIRGs is presented. The ULIRG spectra are fitted by a superposition of a starburst and an AGN spectrum, both of which may be obscured at different levels. Models in which starburst and AGN obscuration differ are significantly more successful than models with a single extinction. Previous results based on a simpler line-to-continuum measure of aromatic emission strength are confirmed, further supporting the robustness of the aromatic emission feature as a diagnostic of ULIRG power sources. As dominant sources of the bolometric luminosity, starbursts prevail at the lower end and AGNs at the higher end of this range. The transition between mostly starburst and mostly AGN powered occurs at $\sim 10^{12.4} - 10^{12.5} L_\odot$, and individual luminous starbursts are found up to $\sim 10^{12.6} L_\odot$.

Subject headings: galaxies: active — galaxies: starburst — infrared: galaxies

1. INTRODUCTION

Recently, mid-infrared (MIR) spectroscopy has been used increasingly as a tool for studies of ultraluminous infrared galaxies (ULIRGs, $L_{IR} > 10^{12} L_\odot$; see Sanders & Mirabel 1996 for a review). The presence of starbursts and active galactic nuclei (AGNs) in ULIRGs (and coexistence in some of them) has been known for quite some time, but the question of which of the two dominates the luminosity has been difficult to answer because of the large columns of obscuring dust found toward the nuclear regions of these gas- and dust-rich systems. High sensitivity and complete coverage of the infrared spectrum by ESA’s Infrared Space Observatory (ISO; Kessler et al. 1996) have considerably advanced the use of infrared spectroscopy to penetrate this obscuring dust and to probe for the sources of the huge luminosity of ULIRGs.

Fine-structure line and aromatic emission feature observations with ISO-SWS and ISOPHOT-S of a sample of 15 bright ULIRGs suggest that most ULIRGs are predominantly starburst powered (Genzel et al. 1998). The polycyclic aromatic hydrocarbon (PAH) method has been extended to a larger sample (Lutz et al. 1998; Rigopoulou et al. 1999), allowing us to probe for evolutionary effects expected in a scenario in which starburst activity gives way to a quasar-like AGN buried inside the ULIRG (Sanders et al. 1988a). Comparison of optical and MIR spectroscopic diagnostics (Lutz, Veilleux, & Genzel 1999; Taniguchi et al. 1999) demonstrated surprisingly good agreement if optical LINERs are interpreted as starbursts. This finding also suggests that AGNs in ULIRGs usually make their presence known optically at least in certain directions, instead of being fully embedded by large obscuring columns of dust.

This paper presents the result of a solicited program in ISO open time, which addresses two main issues only partly covered by previous work. First, and most important, at which luminosity does the transition from “predominantly starburst powered” to “predominantly AGN powered” occur? On the one hand, the ISO observations of Genzel et al. (1998) and Lutz et al. (1998) suggest that not only luminous infrared galaxies with $L_{IR} < 10^{12} L_\odot$ but also most ULIRGs above this threshold are predominantly starburst powered. On the other hand, optical and MIR observations of hyperluminous infrared galaxies (Hines et al. 1995, 1999; Taniguchi et al. 1997; Aussel et al. 1998) support a previous consensus that AGNs dominate these hyperluminous systems (but note the intriguing possibility that far-infrared

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peaks in some luminous AGNs may trace even higher star formation–related luminosities; e.g., Haas et al. (1998). The luminosity at which local ULIRGs \((z < 0.4)\) on average, switch from starburst to AGN dominated is a quantity with implications for various fields ranging from the interpretation of sources found in recent submillimeter surveys (Hughes et al. 1998; Barger et al. 1998) to explanation of the hard X-ray background (Comastri et al. 1995). Simple arguments based on the free-fall time of the gas mass concentrated in the inner region of ULIRGs and the nucleosynthesis efficiency suggest a maximum luminosity of a starburst event approaching \(10^{13} L_\odot\) (Heckman 1994), the limit depending on gas mass, spatial scale, and initial mass function properties. Observational evidence is clearly needed. Despite its size of \(\sim 60\) sources, the ULIRG sample presented by Lutz et al. (1998) and Rigopoulou et al. (1999) is not optimal for this task: it is selected basically as flux limited at 60 \(\mu m\) and dominated by low to moderate luminosity ULIRGs because of the steep ULIRG luminosity function (Sanders & Mirabel 1996). The preliminary analysis of Lutz et al. (1998) in the MIR and a recent study of Veilleux, Sanders, & Kim (1999) in the optical/near-infrared showed that the presence of AGNs in ULIRGs increases with the luminosity of the object. However, these studies clearly call for improved statistics above \(\sim 10^{12.3} L_\odot\) in order to determine better the transition to AGN-dominated systems.

The second issue addressed by this paper is related to the use of PAH features as an AGN/starburst diagnostic. MIR spectra of most galaxies show the 6.2, 7.7, 8.6, and 11.3 \(\mu m\) features attributed to aromatic carbonaceous material (Duley & Williams 1981; Leger & Puget 1984; Sakata et al. 1987; Papoular et al. 1989). Among several popular designations for these bands will be designated hereafter by the terms PAH or unidentified infrared bands (UIBs, as a result of remaining uncertainties on the precise nature of the aromatic carrier). Ground-based observations of these features and a companion at 3.3 \(\mu m\) first demonstrated that their equivalent width is larger in starburst galaxies than in classical AGNs (Moorwood 1986; Roche et al. 1991). ISO spectroscopy has further strengthened this link by demonstrating the anticorrelation between feature strength relative to the continuum and the ionization state of the gas (Genzel et al. 1998). Spatially resolved ISOCAM-CVF observations of nearby AGNs support this interpretation by showing the equivalent width of PAH features to be weak near the central AGN but strong in the circumnuclear region likely dominated by star formation (e.g., Cen A, NGC 1068, Laurent et al. 2000; Circinus, Moorwood 1999). Despite this solid empirical basis, special care is required in analyzing PAH spectra of ULIRGs for AGN or starburst dominance. All components of the spectrum (continuum and emission features, AGN or starburst) may be unusually obscured, and the limited wavelength coverage of ISOPHOT-SL spectra (5.8–11.6 \(\mu m\) observed wavelength) makes continuum definition difficult. Here the extended wavelength range of ISOCAM-CVF (5–16.5 \(\mu m\)) is beneficial in reaching the long-wavelength side of the broad 9.7 \(\mu m\) silicate absorption feature.

Our paper is organized as follows. We discuss sample selection, observations, and data analysis in \(\S\) 2. Section 3 presents the observational results. Section 4 establishes a new quantitative method to determine the contribution of starburst and AGN activity to the MIR spectra and compares it with the method used by Genzel et al. (1998), Lutz et al. (1998), and Rigopoulou et al. (1999). In \(\S\) 5 we discuss the properties of ULIRGs as a function of luminosity, combining our sample with the results of the ISOPHOT-S sample and with ISOCAM results on hyperluminous infrared galaxies (HYLIRGs). Finally, we conclude in \(\S\) 6.

2. Observations and Data Reduction

2.1. Sample and Observing Strategy

The solicited observing program presented here was defined in the last third of the ISO mission when it had become apparent that low-resolution spectroscopy of ULIRGs was a promising tool and that studies of ULIRGs needed to be extended toward higher luminosities. The sample selection is strongly driven by the visibility constraints of the ISO satellite during the final 6 months of the mission. ULIRGs were selected from the samples of Fisher et al. (1995), Kim (1995), Clements et al. (1996), and Lawrence et al. (1999; the QDOT sample). Six sources were chosen from these catalogs with \(L_{IR} > 10^{12.5} L_\odot\) that had reasonable ISO visibility during the remaining mission, plus an additional 10 slightly lower luminosity sources that could be accommodated within the available observing time. Table 1 lists basic properties of the sample galaxies. Throughout this paper we follow the convention reported by Sanders & Mirabel (1996) to compute the 8–1000 \(\mu m\) luminosity \(L_{IR}\), adopting \(H_\odot = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}\) and \(q_0 = 0.5\), and IRAS Faint Source Catalog (FSC) fluxes (IRAS 03521+0028, IRAS 18030+0705: Point Source Catalog [PSC]). Most of our sources are lacking detections in some of the IRAS photometric bands. In those cases, we replaced the missing fluxes by estimates based on the 60 \(\mu m\) fluxes and average colors of the Sanders et al. (1988a) ULIRGs. The observations included the source IRAS 03452+2320 taken from the sample of Fisher et al. (1995), which is not listed in Table 1. We did not detect a signal at its position. We believe that this reflects an infrared cirrus-related misidentification in the Fisher et al. (1995) sample rather than MIR faintness of a true ULIRG, since Crawford et al. (1996) failed to detect the same source in radio continuum.

Our sample is certainly heterogeneous: it was selected from ULIRG surveys of different limiting 60 \(\mu m\) flux, with a preference for high-luminosity targets but not implementing a strict lower cutoff, and strongly driven by ISO visibilities. None of the selection criteria, however, should significantly bias our sample in MIR spectral properties or AGN content. In particular, no AGN-related IRAS color criteria like the 25/60 \(\mu m\) flux ratio were applied (de Grijp et al. 1985; Sanders et al. 1988b). A slight tendency toward favoring AGNs at higher redshifts/luminosities is induced by the 60 \(\mu m\) selection that is effectively at \(\sim 45 \mu m\) rest wavelength for the most distant targets. We have not attempted to correct for this since detailed far-infrared spectral energy distributions are unavailable for these faint IRAS sources and since the effect will be negligible for our small and still fairly local sample. The sample is hence suited to study the AGN content of ULIRGs, bridging the gap between the lower luminosity ULIRGs studied with ISOPHOT-S (Lutz et al. 1998; Rigopoulou et al. 1999) and the two HYLIRGs observed by ISO (Taniguchi et al. 1997; Aussel et al. 1998). Figure 1 shows the distribution of infrared luminosities for both our sample and the combined ISO database. The observations presented here used the circular vari-
able filter (CVF) mode of the ISOCAM camera (Cesarsky et al. 1999a) rather than the ISOPHOT-S mode with which most other low-resolution ULIRG spectra were obtained and which is efficient in building a large sample of relatively bright sources. The ultimate sensitivity achieved in a long CVF integration time is better, and the need for stabilization overheads was no major concern for our moderate number of very faint sources. In addition, the extended long-wavelength coverage is crucial in targeting objects up to $z \sim 0.4$ and in probing an extended rest wavelength range. Since our sources are expected to be spatially unresolved, we have chosen the most sensitive setting with 6" pixels and a total field of view (FOV) of about 3'. The observed wavelength range varies from source to source, the short end being defined by 5 $\mu$m rest wavelength and the long end either by 12 $\mu$m rest wavelength or, for high-redshift sources, by 16 $\mu$m observed wavelength where the sensitivity of CVF observations starts to decrease quickly.

In order to increase redundancy and to enable correction of the transients of the ISOCAM detector, each CVF scan has been done in up and down direction. To reconcile the need for detector stabilization (10 frames of 5 s exposure at each wavelength) with the total number of wavelength steps and practical limits on observing time, we have executed up- and down-scans with interleaved wavelength steps. The total observing time per source including overheads was typically 2.5 hr. Each final spectrum is composed by about 120 wavelength steps and has an average resolution of $R \approx 35$.

### 2.2. Data Reduction

Reductions have been carried out with the Cam Interactive Analysis (CIA) software. The dark current has been estimated with the dark model described by Biviano & Sauvage (1999). This gives better results than using the two offset observations we have taken before and after the CVF observation. We used the median resolution deglitching method (Starck, Abergel, & Aussel 1999) to remove glitches and then additionally deglitched manually a square of 3 × 3 pixels centered on the source. To correct the transient effect of the detector, the inversion method developed at the Institut d’Astrophysique Spatiale (Coulais & Abergel 1999) was used. The calibration of the flux was performed using the standard spectral response function of CIA.

The Appendix presents a reduction scheme that allows us to quantify the spectrum of a target, with its signal-to-noise ratio (S/N) and the systematic error introduced by the reduction method (the total uncertainty on the flux is about 5 mJy). It also allows us to determine the position of the fairly faint source with subpixel accuracy. The typical uncertainty of the position is 5", including S/N and ISO pointing uncertainty.

One target (IRAS 00406$-$3127) of the set had not been acquired by ISOCAM because of a telemetry drop. For IRAS F02115$+0226$ there was no source detection. The

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**Table 1**

Basic Data of ULIRGs Observed with ISOCAM-CVF

| IRAS Name* | R.A. (2000) | Decl. (2000) | $z$ | $S_{12}$ (Jy) | $S_{25}$ (Jy) | $S_{60}$ (Jy) | $S_{100}$ (Jy) | $\log L_{IR}$ ($L_\odot$) |
|------------|-------------|-------------|----|--------------|--------------|--------------|-------------|-------------------------|
| F00183$-$711 ... | 0 20 35.3 | $-$70 55 22 | 0.327 | <0.06 | 0.13 | 1.20 | 1.19 | 12.77 |
| 00188$-$0856 ... | 0 21 26.6 | $-$83 39 22 | 0.129 | <0.12 | 0.37 | 2.59 | 3.40 | 12.31 |
| 00275$-$2859 ... | 0 30 04.4 | $-$28 42 23 | 0.279 | <0.08 | 0.17 | 0.69 | 0.73 | 12.46 |
| 00406$-$3127 ... | 0 43 03.2 | $-$31 10 50 | 0.342 | <0.06 | <0.09 | 0.72 | 0.99 | 12.64 |
| 02113$-$2937 ... | 2 13 33.0 | $-$29 23 35 | 0.194 | <0.08 | <0.12 | 0.94 | 1.88 | 12.29 |
| F02115$+0226$ ... | 2 14 10.3 | 2.40 00 | 0.400 | <0.11 | <0.16 | 0.32 | 0.64 | 12.48 |
| F02455$-$2220 ... | 2 47 51.3 | $-$22 07 38 | 0.296 | <0.08 | <0.10 | 0.82 | 1.27 | 12.57 |
| 03000$-$2729 ... | 3 02 11.5 | $-$27 07 24 | 0.221 | <0.07 | <0.11 | 0.92 | 2.04 | 12.41 |
| 03538$-$6432 ... | 3 54 25.3 | $-$64 23 39 | 0.310 | <0.06 | 0.06 | 0.99 | 1.30 | 12.65 |
| 03521$+0028$ ... | 3 54 42.4 | 0.152 | <0.25 | 0.23 | 2.64 | 3.83 | 12.46 |
| 04384$-$4848 ... | 4 39 50.8 | $-$48 43 11 | 0.213 | <0.04 | 0.07 | 0.99 | 1.34 | 12.32 |
| 17463$+5806$ ... | 17 47 04.6 | 58 05 24 | 0.309 | <0.04 | <0.04 | 0.65 | 0.95 | 12.48 |
| 18030$+0705$ ... | 18 05 32.5 | 7 06 9 | 0.146 | <0.25 | <0.25 | 0.84 | 4.40 | 12.18 |
| 22192$+3211$ ... | 22 22 09.6 | $-$31 56 34 | 0.231 | <0.12 | 0.19 | 0.89 | 1.42 | 12.43 |
| 23515$+2917$ ... | 23 54 06.7 | $-$29 00 58 | 0.336 | <0.08 | <0.14 | 0.65 | 1.06 | 12.60 |
| F23529$+2919$ ... | 23 55 33.3 | $-$21 03 7 | 0.430 | <0.08 | <0.16 | 0.33 | 0.63 | 12.55 |

* A name starting with an "F" refers to an FSC object name. The others names are taken from the PSC.

**Note.**—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. Positions have been computed from the ISOCAM observations, with an accuracy of 5".

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**Fig. 1.**—Histogram of infrared luminosities for ULIRGs with low-resolution ISO MIR spectroscopy taken from ISOPHOT-S observations (Rigopoulou et al. 1999) and ISOCAM-CVF observations (this paper). Sources with ISOCAM-CVF spectra shown in this paper are shaded. The combined sample shown here is biased toward high-luminosity ULIRGs.
S/N observed for IRAS F02455—2220 is not high enough to determine reliably the point-spread function (PSF) correction described in the Appendix. However, the observed spectrum can be taken as a lower limit, using only the signal from the brightest pixel. For the remaining 13 targets, the data reduction has been applied successfully.

3. RESULTS

The rest-frame spectra for the 13 sources are shown in Figure 2. The shaded confidence area around the spectrum represents the rms plus the systematic error. Table 1 lists the position of the sources as obtained by the PSF fitting method (see the Appendix) and the IRAS fluxes. All targets were found to be pointlike sources at ISOCAM resolution. One target has been found to be significantly offset from the IRAS PSC position: IRAS 18030+0705. The offset is about 1'. We checked the original IRAS data using XSCANPI and found a source with fluxes similar to those listed in the PSC, but centered on the ISOCAM position. The origin of this position discrepancy is unknown. The FSC fluxes were adopted for the ULIRGs detected by ISOCAM except for IRAS 18030+0705 and IRAS 03521+0028, for which we used PSC fluxes.

From previous studies, the following components are expected to be present in ULIRG spectra, but not necessarily together in one spectrum:

1. UIB emission features at 6.2, 7.7, 8.6, and 11.3 μm, mainly originating from star-forming regions of the galaxies. This UIB emission can be also coupled with a continuum of hot dust present in the most energetic H II regions of the starburst.

2. An AGN continuum from the hot dust present in the vicinity of the AGN, e.g., in a dust torus or at larger scale in the narrow-line region.

3. Strong absorption, both continuous and in features like the silicate 9.7 μm one. Absorption may arise in either the surroundings of the AGN or the larger scale interstellar medium (ISM). The amount of absorption may be different for AGNs and for starbursts.

The silicate feature at 9.7 μm that is usually found in absorption may also mimic emission features. In dust configurations as in some torus models (Pier & Krolik 1992), self-absorbed silicate emission can create an emission peak near 8 μm that is superficially similar to a faint UIB emission and may be observed in one HYLIRG (Taniguchi et al. 1997). Discrimination of such a “fake UIB” peak and real UIB emission has to rely on the detailed shape of the 8 μm peak and presence of the other UIB features.

Table 2 summarizes the presence of the UIB bands. About half of the targets exhibit a spectrum with at least the 6.2, 7.7, and 11.3 μm MIR bands clearly visible. The remaining targets do not exhibit all these bands, and for two of them no band is significantly detected. It is striking that almost all the observed ULIRGs show a strong feature at or near 7.7 μm. IRAS F23529—2919 is an exception. Here the continuum might be so strong that it can dominate the emission of the 7.7 μm emission band. In addition, the shape of the 7.7 μm feature is very different in two other galaxies from the typical UIB band. IRAS 22192—3211 and IRAS 00275—2859 have a band that is broader than the one observed in a “normal” starburst galaxy. The S/N for IRAS 23515—2917 is lower, so it is more difficult to draw a definitive conclusion. A strong continuum has been detected in the two former targets, which supports the presence of an AGN in both sources. The change of the shape of the 7.7 μm feature can be explained in two ways. The carriers of the UIB might be processed in the AGN environment, changing the shape of the spectral emission of these carriers. Such changes in the shape of the 7.7/8.6 μm complex have in fact been observed in some ultracompact H II regions (Cesarsky et al. 1996b). Alternatively, a “fake” 7.7 μm feature could arise when one observes a high optical depth source with self-absorbed silicate emission. There is no agreement in detail, however; between the broadish 8 μm features in these ULIRGs and the spectral shapes predicted by torus models (Pier & Krolik 1992). A further problem of a “torus” identification of these 8 μm features is that they are not observed in the spectra of template Seyfert galaxies and QSOs (Rigopoulou et al. 1999; Clavel et al. 2000).

Another source, IRAS F00183—7111, has a maximum near 8 μm that we do not ascribe to UIBs. Its spectrum is remarkably similar to some deeply obscured objects (NGC 7538, d’Hendecourt et al. 1996; IRS 1, D. Cesarsky 2001, 2001).

| IRAS Name       | 6.2 μm | 7.7 μm | 11.3 μm | L/C | Note                  |
|-----------------|--------|--------|---------|-----|----------------------|
| F00183—7111.....| N      | N      | N       | 0.88|                      |
| 00188—0856......| N      | N      | Y       | 1.53|                      |
| 00275—2859......| N      | N      | N       | 0.58|                      |
| 00406—3127......| N      | N      | N       | 2.53|                      |
| 02113—2937......| N      | N      | N       | 1.74|                      |
| 02215—0226......| N      | N      | N       | 1.70|                      |
| 02455—2220......| N      | N      | N       | 3.23|                      |
| 03000—2729......| N      | N      | N       | 2.08|                      |
| 03538—6432......| N      | Y      | N       | 1.85|                      |
| 03521+0028......| N      | N      | N       | 2.53|                      |
| 04384—4848......| N      | N      | N       | 1.88|                      |
| 17463+5806......| N      | N      | N       | 1.85| Large position offset|
| 18030+0705......| N      | N      | N       | 1.85|                      |
| 22192—3211......| N      | N      | N       | 2.53|                      |
| 23515—2917......| N      | N      | N       | 1.88|                      |
| F23529—2919.....| N      | N      | N       | 0.38|                      |

Note: — Y: Feature is significantly present (detected at 3 σ except for F02455—2220). N: Feature is doubtful or undetected. Ellipses: undefined.
Fig. 2.—MIR spectra of sources observed with ISOCAM. Shaded regions represent the sum of rms and systematic error, as described in § 2.2. Positions of the 6.2, 7.7, 8.6, and 11.3 μm features are indicated in each plot. We also plot the uncorrected spectrum of IRAS F02455−2220, which should be considered a lower limit (see text). An upper limit is given for IRAS 02115+0226. Wavelengths are rest-frame wavelengths.
unpublished), showing a strong 5–8 μm continuum and an extremely deep silicate absorption. Even an apparent “6.5 μm emission” is indicated in this object, which is very likely the result of the absorption of water ice at 6 μm and an absorption feature at 6.85 μm that is of unclear origin (Schutte 1998). The spectrum of IRAS F00183 − 7111 is thus dominated by a heavily absorbed (AGN) continuum with a possible weak 7.7 μm emission, which might be due to either a classical UIB or self-absorbed silicate emission. In total, it appears to be the only unambiguous example in our data for a type of source considered typical in the classical Sanders et al. (1988a) scenario: an extremely obscured AGN.

4. Quantitative Diagnostics of the Starburst and AGN Activity in ULIRGs

The use of the line-to-continuum (L/C) ratio of the 7.7 μm band as proposed by Genzel et al. (1998) and Lutz et al. (1998) to distinguish in the MIR between starburst-dominated and AGN-dominated ULIRGs is based on evidence that a starburst galaxy presents strong UIB features while an AGN presents strong continuum with low-contrast emission features in the nuclear part of the galaxy. This is suggested by ground-based observations (Moorwood 1986; Roche et al. 1991; ISO spectroscopy, Genzel et al. 1998; Rigopoulou et al. 1999; ISO spectro-imaging, Moorwood 1999; Laurent et al. 2000). This also implies that the UIB luminosity of a galaxy scales with its star formation. Recent studies tend to reinforce this idea: in spiral galaxies, the global Hα emission of the disk is correlated with the total MIR emission of UIB (Vigroux et al. 1999; Roussel et al. 2001).

When using these features as tracers of the sources of the total ULIRG luminosity, a further assumption is that the MIR actually probes the active regions and not just a surface layer. This is not trivial since the active regions of ULIRGs are small (Condon et al. 1991; Soifer et al. 2000) and dusty. Depending on dust configuration, a major part of the luminosity could be hidden from MIR view. Genzel et al. (1998) have addressed this problem using the starburst-type MIR nebular spectra of ULIRGs. For ULIRGs, the ratio of the inferred starburst ionizing luminosity to the bolometric luminosity approaches that for template starbursts, indicating that more than half of the luminosity has been traced by the MIR observations. Similar analyses can be made using the luminosity of the PAH features. Rigopoulou et al. (1999) and Genzel & Cesarsky (2000) find that observed PAH luminosities of ULIRGs are well above those of lower luminosity sources, the ratio to bolometric luminosity being only a factor of 1.4–2 lower than in starbursts. This factor is plausibly explained by the higher extinction in ULIRGs and perhaps the effect of the more intense radiation field on the PAH emission. We have tentatively repeated this comparison using the extinction correction derived from our fits described below, which, however, give only fairly uncertain extinction for individual noisy spectra. The mean discrepancy narrows down to a factor of 1.2. Thus, the MIR diagnostics are probing the major part of the luminosity.

For a narrow line and emission from a single region, both line and continuum are obscured by the same amount. The width of the PAH feature and the strong wavelength dependence of extinction at the onset of the silicate feature make the PAH L/C less ideal. In some objects the absorption might be so strong that it can mimic a 7.7 band. There are, however, differences in shape, and the L/C will normally stay below the cutoff of 1 adopted in previous papers. IRAS F00183 − 7111 is the only clear example in our sample. Another technical point that has to be verified is the determination of the continuum under the 7.7 μm feature. In the L/C diagnostic, this continuum is deduced from the linear interpolation of the continuum levels at 5.9 and 10.9 μm, i.e., the L/C ratio is affected by the flux uncertainties at these wavelengths. This is also a systematic source of uncertainty since the 10.9 μm point is still within the silicate feature and does not probe a clean continuum.

We have explored alternative methods in order to verify the robustness of the L/C ratio with respect to the systematic error induced in the 7.7 μm continuum determination. First, we constructed the “narrow-band” ratio between the flux density at 7.7 and 6 μm. Strong UIB emission will create a high ratio that is not reached by a pure continuum unless it is unrealistically steep over this small wavelength interval. This diagnostic should hence identify strong UIB emission easily but will face problems discriminating weak UIBs from continuum slope variations. The strength of this diagnostic is to avoid any assumption on the shape of the spectrum in the region obscured by the silicate feature. Figure 3 shows the correlation between the L/C and F7.7 μm/F6 μm diagnostics seen for ULIRGs and template spectra observed by PHOT-S (Rigopoulou et al. 1999), SWS (Sturm et al. 2000), and CAM-CVF (this paper). The dispersion in this plot is explained by the variation in continuum slope and the systematic error of the L/C discussed before. The good correlation of the two diagnostics supports the use of the L/C diagnostic to identify systems that are clearly starburst-like and show strong UIBs. By definition of the F7.7 μm/F6 μm diagnostic, Figure 3 cannot test the effect of continuum placement uncertainty in the L/C method on measurements of faint residual UIBs in AGN-like systems. The line F7.7 μm/F6 μm = L/C + 1 is also overplotted in Figure 3 to indicate the asymptotic case in which the continuum is flat.

![Figure 3](image-url)

**Figure 3**—Comparison between the L/C diagnostic of the 7.7 μm band adopted by Genzel et al. (1998) and subsequent papers and a narrowband diagnostic using just the ratio of fluxes at 7.7 and 6 μm for galaxies observed by PHOT-S (Rigopoulou et al. 1999), SWS (Sturm et al. 2000), and CAM-CVF (this paper). Upper and lower limits have been suppressed in this plot. The overplotted line shows the expected relation if the underlying continuum is flat.
4. The Draine & Lee (1984) law is lower than the Galactic center law. The squares represent the extinction law toward the GC derived from hydrogen lines (Lutz 1999).

To investigate further how the different spectral components influence the MIR spectrum of a galaxy, we created another diagnostic whose basis is a more physical parameterization of the spectrum.

4.1. Presentation of the Model

Our aim is an empirical fitting procedure using the complete MIR low-resolution spectra to derive the contribution of the AGN and starburst components to the MIR spectrum. In a second step, results will be extrapolated to the bolometric luminosities. The fit is based on template spectra of dusty starbursts and AGNs and applied to the whole set of ULIRG and template spectra observed by PHOT-S (Rigopoulou et al. 1999), SWS (Sturm et al. 2000), and CAM-CVF (this paper). Since absorption plays an important role for the spectra of dust-rich ULIRGs, we incorporate the effects of absorption that is higher than in the templates. In principle, explaining the MIR spectra of ULIRGs is a problem of three-dimensional radiative transfer requiring a consistent treatment of dust, ices, and PAH features. Considerable insight can be gained, however, from a simple superposition of a screen-obscured starburst and a screen-obscured AGN. Arguments in favor of this approach are as follows. (1) The MIR diagnostic reaches most of the active region. Unknown, more obscured sources will be minor contributors. (2) The use of an observed AGN template implicitly accounts for warm dust close to the AGN. Screen extinction is a reasonable first approximation for the effect of even more dust around the AGN, since this dust will mostly just absorb in the MIR considered here and reemit in the far-infrared. (3) An aggregate of star-forming regions is in principle better represented by a case in which emission and absorption are well mixed. Mixed case extinctions are difficult to determine, however, unless there are probes measured at high S/N over a large range of optical depths, a requirement not met by our spectra. The screen case adopted here will give similar results for optical depths around 1, fall short at higher optical depth, but be conservative in the sense of not inferring excessive starburst activity in uncertain cases.

4.1.1. The Starburst Component

Genzel et al. (1998), Rigopoulou et al. (1999), and Sturm et al. (2000) showed that in the range of the 6–9 μm UIB bands there is little variation in starburst MIR spectra observed by SWS and PHOT-S. Starburst spectra present some variations at longer wavelength, however. Vigroux et al. (1996) noted that in some regions of NGC 4038/4039 the flux at 15 μm can rise dramatically and dominate the MIR spectrum. It can be shown that the MIR spectrum of starburst galaxies is the superposition of two components: one from photodissociation regions (PDRs) and one from H II regions (Tran 1998). The PDR component is responsible for

Fig. 4.—Comparison of the extinction laws described in § 4. The Draine & Lee (1984) law is lower than the Galactic center law. The squares represent the extinction law toward the GC derived from hydrogen lines (Lutz 1999).

Fig. 5.—Examples of model fits to ULIRG spectra, using model 3a. The figure includes high- and low-S/N spectra and AGN- and starburst-dominated spectra to show the success of the fitting procedure in all those cases. Data are shown by thin lines, while the fitted spectra are shown by thick lines.
the UIB emission and the H II region for the hot dust continuum that becomes important at 12 μm (Cesarsky et al. 1996b; Verstraete et al. 1996; Roelfsema et al. 1996). This hot dust continuum is probably due to very small grains heated to temperatures as high as 200 K in some regions. This continuum is very faint at 7 μm (Cesarsky et al. 1996b; Verstraete et al. 1996; Tran 1998) and is not really noticeable in the spectrum of the majority of starburst galaxies where the PDR contribution (i.e., the UIB contribution) dominates in this part of the spectrum (Sturm et al. 2000). For some dwarf metal-deficient starburst galaxies like NGC 5253 and IIZw40 (Rigopoulou et al. 1999; S. Madden 1999, private communication), UIBs are nearly absent. In such a case a strong featureless continuum will not be an AGN signature. Since ULIRGs are dust-rich and not known to be metal-deficient, this effect is likely not relevant, and we still consider a strong ULIRG continuum with weak UIBs to be an AGN signature.

As the (rest) wavelength range investigated in this paper is between 5 and 12 μm, the contribution of the hot dust continuum from H II regions will not drastically change the spectrum of the starburst contribution. However, one must keep in mind that, strictly speaking, a significant continuum at short wavelengths (5–8 μm) is not necessarily a tracer of an AGN but could reveal a higher weight on H II regions in the ISM with respect to PDRs. To break the degeneracy, one has to look at the continuum at 15 μm since the continuum of an H II region is steeper than the continuum of an AGN (Laurent et al. 2000).

In the present model we assume that the template spectrum of a starburst does not change in a significant way between 5 and 12 μm (see § 4.2 for the self-consistency of this hypothesis). We have used the M82 SWS spectrum as the starburst template spectrum, supposed to represent the standard L/C ratio of the UIB seen in a dusty starburst.

4.1.2. The Continuum Component

Nuclear AGN spectra have low-contrast UIB features and mainly present a continuum emitted by hot dust. Obviously, when looking at the total spectrum of a galaxy hosting an AGN, one naturally observes UIB bands from circumnuclear star formation or from the disk of the AGN host (see, e.g., Mirabel et al. 1999; Clavel et al. 2000; Moorwood 1999; Alexander et al. 1999). The AGN spectrum itself can be described by an intrinsic continuum that can be well fitted by a power law\(^{11}\) of variable index (Clavel et al. 2000) subject to absorption by dust, especially in the region of the 9.7 μm silicate absorption feature.

As discussed in the previous subsection, a continuum seen in the MIR may also be due to H II regions. In the wavelength range considered (5–12 μm), there is a degeneracy between the AGN continuum and a continuum coming from an H II region, although an H II continuum is usually steeper and fainter. Our fit invokes a single “continuum component” including both possibilities of an AGN continuum and an unusually strong H II continuum. We will come back to the degeneracy between these two types of continua when discussing fit results.

4.1.3. Dust Obscuration

Because ULIRGs are gas- and dust-rich galaxies (Solomon et al. 1997), the extinction is expected to play a crucial role in shaping the spectra of these galaxies, even in the MIR (see, e.g., Arp 220; Sturm et al. 1996). It is important to test how dust obscuration can affect both UIB-dominated and featureless spectra (Rigopoulou et al. 1999). One can argue that MIR ULIRG spectra could be completely dominated by absorption and that the 7.7 μm feature, which we identify as a UIB, could result from a deep absorption of a flat continuum (Dudley & Wynn-Williams 1997). This could be the case in the strongly absorbed galaxy F00183−7111. We want to test more generally whether it is possible to produce an emission feature around 8 μm by a power-law continuum affected by an absorption law or whether a simple UIB spectrum affected by absorption is preferred.

We used two absorption laws, the “classical” Draine & Lee (1984) absorption law and one composite absorption law derived from the Galactic center–Sgr A* spectrum (hereafter GC or GC–Sgr A*). The GC extinction law has a higher extinction level between 3 and 7 μm (Lutz et al. 1996; Lutz 1999). Since this law is derived from hydrogen recombination lines and does not sample the silicate feature well, we have supplemented it with points deduced from the GC continuum spectrum itself. They have been computed assuming that the intrinsic GC spectrum is a power-law spectrum absorbed by a dust screen. The extinction law and the exponent of the power law have been adjusted in order to fit the extinction deduced from the hydrogen lines and the GC spectrum itself. This procedure is adequate since we cover only a limited wavelength range and since the dust in front of the Galactic center is close to the ideal screen case. This absorption law has two main peculiarities: a flatter absorption between 3 and 7 μm and a narrower silicate feature than what the Draine & Lee (1984) curve predicts (see Fig. 4).

These two absorption laws have been used to represent variations in dust properties as possible in extreme environments such as close to an AGN. Comparison of the M82 and NGC 1068 SWS spectra (Sturm et al. 2000) suggests such variations at least for absorption features. Because of the possibility of such variations, absolute \(A_V\) values derived from the model are somewhat uncertain. The main emphasis is to test whether the shape of the ULIRG spectra can be reproduced well.

4.1.4. The Different Models

The two spectral components and obscuration have been used to construct four types of models in two classes:

1. The first class is based on the assumption that the starburst component and the continuum component are obscured by the same dust screen. Models of this class vary in extinction properties: the dust extinction law is either a “pure” Draine & Lee (1984) law, a “pure” GC extinction law, or a mixture of the two.

2. The second class allows different obscuration of the two components and is clearly more realistic. The two different contributions (continuum and starburst) are not necessarily located in the same physical region and therefore do not suffer the same extinction.

Table 3 provides the formal description of the different models used. Models 1a, 1b, and 2 refer to the first class, while models 3a–3d and 4 refer to the second class. In two cases (models 2 and 4), the extinction law is a linear combination of the GC extinction law and the Draine & Lee
(1984) one. This combination is not constrained by observations but is included in our modeling as a comparison to other models with different degrees of freedom.

4.2. Testing the Validity of the Model

To validate the model, the fit quality is quantified first. Second, the results from test fits to template starburst and AGN spectra are investigated and compared to observations of “mixed” sources where the AGN and starburst relative contributions are well known from spatially resolved data.

### 4.2.1. Quality of Model Fits

Figure 5 shows some examples of fits to ULIRG spectra using model 3a. The figure includes AGN and starburst-like spectra of both high and low S/N. Fits using other models tend to be slightly worse but still acceptable. The first conclusion is that the models presented in Table 3 can give a reasonable fit for all ULIRG spectra. This implies that the assumptions of these models (e.g., an MIR spectrum of a ULIRG is a superposition of a continuum component and a starburst component extincted by a dust-rich ISM) are not in obvious contradiction with observations.

| Model | Type of Model | Number of Parameters | $\chi^2/N_{\text{data}}$ All ULIRGs | $\chi^2/N_{\text{data}}$ High-S/N ULIRGs |
|-------|---------------|----------------------|-------------------------------------|-----------------------------------------|
| 1a    | $(a_1 F_{\text{sb}} + a_2 F_{\text{AGN}}) \exp (-\beta_1 A_{\text{DL}})$ | 4 | 2.48 | 4.79 |
| 1b    | $(a_1 F_{\text{sb}} + a_2 F_{\text{AGN}}) \exp (-\beta_2 A_{\text{GC}})$ | 4 | 2.24 | 4.30 |
| 2     | $(a_1 F_{\text{sb}} + a_2 F_{\text{AGN}}) \exp (-\beta_1 A_{\text{DL}} - \beta_2 A_{\text{GC}})$ | 5 | 2.23 | 4.31 |
| 3a    | $a_1 F_{\text{sb}} \exp (-\beta_1 A_{\text{DL}}) + a_2 F_{\text{AGN}} \exp (-\beta_2 A_{\text{DL}})$ | 5 | 1.70 | 2.81 |
| 3b    | $a_1 F_{\text{sb}} \exp (-\beta_1 A_{\text{DL}}) + a_2 F_{\text{AGN}} \exp (-\beta_2 A_{\text{GC}})$ | 5 | 1.54 | 2.52 |
| 4     | $a_1 F_{\text{sb}} \exp (-\beta_1 A_{\text{DL}} - \beta_2 A_{\text{GC}})$ | 5 | 1.64 | 2.79 |
| 3c    | $a_1 F_{\text{sb}} \exp (-\beta_1 A_{\text{GC}}) + a_2 F_{\text{AGN}} \exp (-\beta_2 A_{\text{DL}})$ | 5 | 1.72 | 3.05 |
| 3d    | $a_1 F_{\text{sb}} \exp (-\beta_1 A_{\text{GC}}) + a_2 F_{\text{AGN}} \exp (-\beta_2 A_{\text{GC}})$ | 5 | 1.42 | 2.21 |

| Model | Type of Model | Number of Parameters | $\chi^2/N_{\text{data}}$ All ULIRGs | $\chi^2/N_{\text{data}}$ High-S/N ULIRGs |
|-------|---------------|----------------------|-------------------------------------|-----------------------------------------|
| 1a    | $(a_1 F_{\text{sb}} + a_2 F_{\text{AGN}}) \exp (-\beta_1 A_{\text{DL}})$ | 4 | 2.48 | 4.79 |
| 1b    | $(a_1 F_{\text{sb}} + a_2 F_{\text{AGN}}) \exp (-\beta_2 A_{\text{GC}})$ | 4 | 2.24 | 4.30 |
| 2     | $(a_1 F_{\text{sb}} + a_2 F_{\text{AGN}}) \exp (-\beta_1 A_{\text{DL}} - \beta_2 A_{\text{GC}})$ | 5 | 2.23 | 4.31 |
| 3a    | $a_1 F_{\text{sb}} \exp (-\beta_1 A_{\text{DL}}) + a_2 F_{\text{AGN}} \exp (-\beta_2 A_{\text{DL}})$ | 5 | 1.70 | 2.81 |
| 3b    | $a_1 F_{\text{sb}} \exp (-\beta_1 A_{\text{DL}}) + a_2 F_{\text{AGN}} \exp (-\beta_2 A_{\text{GC}})$ | 5 | 1.54 | 2.52 |
| 4     | $a_1 F_{\text{sb}} \exp (-\beta_1 A_{\text{DL}} - \beta_2 A_{\text{GC}})$ | 5 | 1.64 | 2.79 |
| 3c    | $a_1 F_{\text{sb}} \exp (-\beta_1 A_{\text{GC}}) + a_2 F_{\text{AGN}} \exp (-\beta_2 A_{\text{DL}})$ | 5 | 1.72 | 3.05 |
| 3d    | $a_1 F_{\text{sb}} \exp (-\beta_1 A_{\text{GC}}) + a_2 F_{\text{AGN}} \exp (-\beta_2 A_{\text{GC}})$ | 5 | 1.42 | 2.21 |

**Note:** $F_{\text{sb}}$ represents the starburst template spectrum (M82), $F_{\text{AGN}}$ the power-law continuum. $A_{\text{DL}}$ and $A_{\text{GC}}$ are the extinction laws of Draine & Lee 1984 and of the Galactic center, respectively. Comparison of fit quality (see text) for the various models for all ULIRGs and for a high-quality subset.
To quantify better the quality of the various models, we adopt the indicator $\chi^2/N_{\text{free}} = \left( \sum (F_{\text{obs}} - F_{\text{mod}})^2 / \sum (\sigma_{\text{obs}})^2 \right) (1/N_{\text{free}})$, where $F_{\text{obs}}$ is the observed flux density, $F_{\text{mod}}$ is the model flux density, and $\sigma_{\text{obs}}$ is the rms of the observed flux density. The summation is done over all ULIRG spectra, and $N_{\text{free}}$ is the sum of degrees of freedom of modeled spectra. With this indicator the quality of the different models can be compared: the closer to 1, the better. Table 3 presents the mean $\chi^2/N_{\text{free}}$ both for our complete ULIRG sample and for a high-quality subset with observed S/N greater than 3.

### 4.2.2. Comparison with Template Sources

We have obtained model fits for various starburst, AGN, and mixed template sources. A first result can be obtained from a comparison of the two classes of models for the mixed templates Circinus and Centaurus A. Figure 6 shows the obvious superiority of models where the extinction toward the AGN is different from that toward the starburst. Fully equivalent good fits are achieved for models 3a–3c.

Figures 7 and 8 show the observed spectrum and the fitted spectrum computed with model 3a, for several starburst and AGN templates. The Galactic center has been grouped with the AGNs since the very center shown here is also a continuum source devoid of UIBs (Lutz et al. 1996). The absence of these features in the GC–Sgr A* spectrum is due to the presence of an H II region with an intense radiation field that probably destroys the UIB carriers. We overlay the contributions of the starburst component and the contributions of the continuum component. As expected, the starburst component dominates totally the modeled spectrum for the starburst galaxies. Similarly, a quasi-pure continuum contribution is needed to fit the AGN spectra, with extinction being negligible in many cases but significant in others (NGC 5506). The low-metallicity galaxy NGC 5253 (not shown) is well fitted by a strong continuum contribution and weak UIBs. The fits to the starburst templates (Fig. 7) show at their long-wavelength end a varying contribution of a faint steeply rising continuum. Most likely, this is due to variations in the strength of the 15 $\mu$m very small grains (VSG) continuum, a conclusion also reached by Sturm et al. (2000) on the basis of the SWS spectra of M82 and NGC 253.

A further test is to apply the model to objects that are well known to be composite, containing both a starburst and an AGN. In Figure 9 spectra of four such objects are presented, showing plausible decompositions into the starburst and continuum components. A stringent test can be obtained for Centaurus A and Circinus, which have both been observed by ISOCAM/CVF at high spatial resolution (Mirabel et al. 1999; A. F. M. Moorwood et al. 2001, in preparation). These observations allow us to separate the contribution of the nucleus and the surrounding star-forming regions and thus provide a direct test of our model decomposition. The spectrum of the Centaurus A nucleus, extracted from the ISOCAM-CVF observation, is overplotted in Figure 9. The modeled continuum contribution is indeed very similar to the observed spectrum of the nucleus,

![Fig. 7.—Comparison of the fitted spectrum and model 3a with the starburst templates M83, NGC 3256, NGC 6946, and NGC 253. The thin line is the observed spectrum, the thick line is the model spectrum, the dashed line is the continuum contribution, and the dotted line is the starburst contribution.](image-url)
confirming the validity of our approach. We performed the same comparison for the Circinus galaxy (A. F. M. Moorwood 1999, private communication) and found the same good agreement between the observed nuclear continuum and the modeled continuum contribution. At least for these two sources, the separation into two contributions (continuum and starburst) is reliable.

4.3. Results of the Modeling of Starburst and Continuum Contributions

Table 3 shows that the two classes of models do not reproduce the ULIRG spectra equally well. It is obvious that the models of the second class, where extinctions of continuum and starburst are different, are in better agreement with the observations. This better accuracy is not explained trivially by the increasing number of free parameters. Model 2, which has the same number of free parameters as the “good” models 3a–3c, is clearly less successful. This means that more flexibility in the shape of the extinction does not improve the fit significantly, while invoking different extinction toward the starburst and AGN does. This lends support to the plausible idea that two different extinctions are applicable to the physically distinct starburst and AGN parts of a ULIRG. Comparing the continuum and starburst extinction derived by our fit procedure, we find the continuum extinction to be slightly smaller on average. This is plausible if the obscuring dust is not distributed with spherical symmetry. We note, however, that this result should be considered tentative given the considerable uncertainty of individual $A_v$ values.

Figure 10 compares the $L/C$ ratio used in previous papers with the ratio of the integrated 5–10 $\mu$m fluxes contained in the continuum contribution and in the starburst contribution as deduced from model 3a. In this plot we also add the starburst and AGN comparison samples as described by Rigopoulou et al. (1999). The two indicators are well (anti)correlated. This correlation shows a posteriori the consistency of the two indicators. Table 4 displays the individual value of $L/C$ and the ratio of the integrated 5–10 $\mu$m fluxes contained in the continuum contribution and in the starburst contribution.

Genzel et al. (1998) and subsequent papers adopted an $L/C$ threshold of 1 to discriminate between starburst- and AGN-dominated systems. At this threshold, the flux ratio of the continuum and starburst components, each integrated over the 5–10 $\mu$m range, will be larger than 1 simply because the UIBs are relatively narrow features. This is reflected in Figure 10. The purpose of the threshold, however, is to identify the component dominating the bolometric luminosity and not just the 5–10 $\mu$m flux. The MIR contributions have to be extrapolated to the bolometric contributions. Using the spectral energy distributions of M82 and of the central region of NGC 1068 as starburst...
and AGN templates (see Sturm et al. 2000 for M82, including IRAS points and correcting for aperture effects), we find the ratio \( L_{5-10 \mu m}/L_{IR} \) about 2.5 times greater in the case of the AGN than for starbursts. Very similar values are obtained for other AGN templates (NGC 4151, 3C 273), consistent with the notion of stronger MIR continua in Seyfert galaxies than in starbursts (de Grijp et al. 1985). Orientation-related variations in MIR Seyfert continua (Clavel et al. 2000) caution that there will be some scatter in these bolometric corrections for individual AGNs. In the remainder of this paper we will apply the factor of 2.5 wherever total infrared (i.e., bolometric) quantities are discussed. Taking into account the correction factor 2.5,
Figure 10 confirms the \( L/C \) threshold of 1 as a sensible one for differentiating between sources dominated by the starburst component and those dominated by the AGN component.

![Graph](image)

**Fig. 12.** Comparison of the spectra of Arp 220 and the strong star-forming region in the overlap region of NGC 4038/4039 (knot A; Vigroux et al. 1996; Mirabel et al. 1998). The graphical conventions are as described for Fig. 8.

5. DISCUSSION

5.1. Mid-Infrared Spectra and Power Sources of the Highest Luminosity ULIRGs

Determination of the power source of the highest luminosity ULIRGs is a prime goal of our project, extending the ISOPHOT-S sample, which is dominated by lower luminosity sources (Lutz et al. 1998; Rigopoulou et al. 1999). Figure 11 displays the \( L/C \) ratio for the CAM-CVF ULIRGs together with data from Lutz et al. (1998) and the two hyperluminous sources observed by ISO (Tanziguchi et al. 1997; Aussel et al. 1998). The UIB \( L/C \) is used to classify sources as starburst-like if \( L/C > 1 \) or AGN-like if \( L/C < 1 \). From our enlarged database, we confirm that most ULIRGs are starburst dominated in the MIR but that there is a trend toward AGN-like ULIRGs at higher luminosities. In our sample, which contains 17 sources above \( L_{100} = 10^{12.4} L_\odot \), the highest luminosity source classified as starburst is at \( 10^{12.65} L_\odot \) (IRAS 03835—6432). Such a luminosity limit for the “most luminous starburst” is in agreement with the timescale argument given by Heckman (1994). Adopting the bolometric luminosities of our sources and sizes like those derived by Soifer et al. (2000) for the MIR emitting region of ULIRGs, the surface brightness will exceed the limit for starbursts suggested by Meurer et al. (1997). Individual star-forming regions are known to exceed this limit, however, and the huge gas concentration in the centers of ULIRGs provides sufficient fuel. Additionally, Meurer et al. (1997) derived their limit using, for similar sources, Hz-based sizes, which are larger than the MIR ones found by Soifer et al. (2000), thus staying below the actual surface brightness. Even in our sample enriched in luminous ULIRGs, statistics at the highest luminosities are limited, thus maintaining the possibility for higher luminosity starbursts. Given the modest sample size, it is difficult to assign an accurate value for the luminosity at which half of the sources are starburst dominated and half AGN dominated. From Figure 11, this occurs most likely at luminosities \( 10^{12.4} - 10^{12.5} L_\odot \).

The trend from starburst dominance for most “normal” ULIRGs to AGN dominance at the highest luminosities now consistently emerges from a variety of indicators: MIR continuum (Sanders et al. 1988b), MIR spectroscopy (Lutz et al. 1998; this paper), and optical spectroscopy (Veilleux et al. 1999). As noted by Lutz et al. (1999), the good agreement between optical and MIR suggests that AGNs in ULIRGs do not remain fully embedded for long but manage to break the obscuring screen at least in certain directions.

The highest luminosity “starburst-like” systems appear well above our cutoff \( L/C \) of 1 but below the \( L/C \sim 3 \) typical for starbursts and lower luminosity ULIRGs. This can be interpreted in different ways. Either they contain a noticeable though not dominant AGN component, or the increased continuum contribution is due to an increase in the \( \text{H}_\alpha \) region–related continuum, as might be reasonable for sources with very high star formation rates in a small region.

5.2. The Nature of the Mid-Infrared Continuum

The simple \( L/C \) method will not be able to break the degeneracy for the origin of ULIRG MIR continua. Also, the parameterization chosen for our fits (§ 4.1) describes the spectrum of a ULIRG in terms of just two components: a UIB-dominated starburst component and a continuum.
component that is due to either an AGN or extra H II region contributions. If the relative weight of “PDR-like” and “H II region–like” components varies for different starburst conditions, as seen, e.g., for different regions of the Antennae galaxies (Vigroux et al. 1996), assigning the continuum entirely to an AGN may be misleading. The nature of the continuum has to be investigated in more detail to quantify the fraction of energy radiated by the AGN (AGN continuum) and by star formation activity (UIB-dominated component plus H II region continuum).

It is possible to break the continuum degeneracy by using the slope of the continuum (Laurent et al. 1999). The ratio of the fluxes at 6 and 15 μm is different for an H II region and a continuum emitted by the dust (torus) surrounding an AGN. Dust in the inner parts of H II regions emits an MIR spectrum that is steep over our wavelength range. This can be seen both in Galactic H II regions (Verstraete et al. 1996; Cesarsky et al. 1996a) and in extragalactic regions of particularly concentrated star formation, e.g., the star-forming knot A in the Antennae galaxies (Vigroux et al. 1996; Mirabel et al. 1998). In contrast, the continuum emitted by hot AGN dust is much flatter in the MIR, as shown by the examples of Cen A (Mirabel et al. 1999) and NGC 1068 (Lutz et al. 2000).

Because of the presence of the UIB emission and silicate absorption features, the steepness of the continuum can be determined reliably only with sufficient wavelength coverage, ideally from 6 (or less) to 15 μm (rest wavelength). This condition is not met by the ISOPHOT-S spectra, which do not extend to these wavelengths. In contrast, the ISOCAM-CVF spectra presented in this paper, which typically extend to rest wavelengths of 11 μm, are better suited to this purpose. It is partially met for the ISOPHOT-S spectra, which extend to 15 μm in some cases but not in others. The case is less clear for our spectra, which do not extend to rest wavelengths of 15 μm.

### Table 4

| IRAS Name | Continuum/Starburst* | L/C* | IRAS Name | Continuum/Starburst* | L/C* |
|-----------|---------------------|------|-----------|---------------------|------|
| 00153 + 5454 | 0.0 | 3.34 | 17028 + 5817 | 0.47 | 3.58 |
| F00183 - 7111 | 5.31 | 0.88 | 17068 + 4027 | 0.0 | 1.40 |
| 00188 - 0856 | 1.48 | 1.53 | 17179 + 5444 | 1.59 | 1.38 |
| 00199 - 7426 | 6.26 | 1.08 | 17208 - 0004 | 0.07 | 5.54 |
| 00275 - 2859 | 100. | 0.57 | 17463 + 5806 | 2.38 | 1.85 |
| 00397 - 1312 | 100. | 0.22 | 18030 + 0705 | 0.60 | 1.88 |
| 01003 - 2238 | 100. | 1.44 | 18443 + 7433 | 6.09 | 1.70 |
| 01166 - 0844 | 0.00 | 2.16 | 18470 + 3233 | 100. | 0.68 |
| 01199 - 2307 | 0.00 | 0.97 | 18531 - 4616 | 1.59 | 2.59 |
| 01298 - 0744 | 1.79 | 1.50 | 19254 - 7245 | 3.47 | 0.89 |
| 01355 - 1814 | 0.00 | 0.93 | 19420 + 4556 | 0.0 | 3.69 |
| 01388 - 4618 | 0.00 | 3.93 | 19458 + 0944 | 0.0 | 2.44 |
| 01494 - 1845 | 0.00 | 1.95 | 20049 - 7210 | 0.0 | 3.77 |
| 01569 - 2939 | 100. | 1.14 | 20100 + 4156 | 0.0 | 1.92 |
| 02113 - 2937 | 0.64 | 2.53 | 20446 - 6218 | 0.0 | 0.94 |
| 02364 - 4751 | 0.66 | 3.48 | 20551 - 4250 | 0.42 | 2.33 |
| 02411 + 0354 | 0.18 | 3.17 | 21396 + 3623 | 0.0 | 2.31 |
| 03000 - 2719 | 0.88 | 1.73 | 22055 + 3024 | 1.12 | 0.96 |
| 03158 + 4227 | 0.53 | 1.72 | 22192 - 3211 | 100. | 0.84 |
| 03521 + 0028 | 0.21 | 3.23 | 22491 - 1808 | 1.04 | 2.85 |
| 03538 - 6432 | 1.45 | 1.70 | 23060 + 0505 | 100. | 0.08 |
| 04063 - 3236 | 100. | 2.55 | 23128 - 5919 | 0.96 | 2.86 |
| 04103 - 2838 | 100. | 1.37 | 23129 + 2548 | 0.0 | 3.55 |
| 04114 - 5117 | 1.03 | 0.97 | 23230 - 6926 | 0.58 | 1.50 |
| 04384 - 4848 | 0.93 | 2.08 | 23253 - 5415 | 0.79 | 1.58 |
| 06009 - 7716 | 1.64 | 3.63 | 23327 + 2913 | 0.0 | 0.97 |
| 06035 - 7102 | 0.92 | 1.11 | 23365 + 3604 | 0.0 | 4.47 |
| 06206 - 6315 | 0.33 | 3.69 | 23389 - 6139 | 0.0 | 1.33 |
| 06301 - 7934 | 0.48 | 1.02 | 23515 - 2917 | 2.87 | 1.36 |
| 06361 - 6217 | 2.0 | 0.67 | F23529 - 2119 | 15.32 | 0.38 |
| 09104 + 4109 | 100. | 0.48 | Arp 220 | 0.0 | 4.20 |
| 12112 + 0305 | 0.39 | 3.13 | Mrk 1014 | 100. | 0.62 |
| 14348 - 1447 | 0.0 | 3.55 | Mrk 231 | 100. | 0.31 |
| 15250 + 3069 | 0.46 | 2.88 | Mrk 273 | 1.24 | 1.90 |
| 15307 + 3252 | 100. | 0.27 | NGC 6240 | 0.0 | 2.58 |
| 16474 + 3430 | 0.35 | 3.58 | UGC 5101 | 0.33 | 2.12 |
| 16487 + 5447 | 0.52 | 2.19 | ... | ... | ... |

Note.—The table includes the ISOPHOT-S (Rigopoulou et al. 1999) and CAM-CVF (this paper) ULIRGs.

* Ratio of the integrated MIR fluxes contained in the continuum contribution and in the starburst contribution

$F_{\text{6-10\,μm(continuum)}}/F_{\text{3-10\,μm(starburst)}}$ (not dereddened) computed with model 3a.

PAH line-to-continuum ratio.

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The table includes the ISOPHOT-S (Rigopoulou et al. 1999) and CAM-CVF (this paper) ULIRGs.
to 15 μm. Some spectra suggest a strong but steep continuum at the long-wavelength end of a UIB-dominated spectrum (e.g., IRAS 03521 + 0028), while others are fitted by a UIB-dominated spectrum plus a flat continuum (e.g., IRAS 18030 + 0705). At the limited wavelength coverage, the uncertainties are considerable, also taking into account that fits are affected by some 7–8 μm features not showing the typical PAH shape (§ 3).

5.3. Model Results: Contributions of Starburst and AGN Activity

Our model can be used to quantify better the contribution of starburst and AGN activity independent from the L/C criterion used earlier. We measured the MIR fluxes emitted by starburst and continuum contribution (not dereddened) integrated over the wavelength range 5–10 μm (similar to the filter LW2 of ISOCAM). When discussing total infrared (bolometric) contributions instead of 5–10 μm ones, the different AGN and starburst spectral energy distributions (SEDs) are considered by increasing the starburst contribution by the correction factor 2.5 derived in § 4.3.

Since we were not able to break reliably the degeneracy of AGN and H II region continuum for our wavelength coverage and S/N, we explored two extreme cases for the origin of the continuum, reality should probably lie in between.

The first scenario assumes that the continuum is coming entirely from an AGN. The examples of H II region continua discussed above, however, clearly argue for some star formation contribution to the continuum. It is unlikely that an almost pure continuum spectrum is produced in this way. The only star formation-powered galaxies approaching this case are low-metallicity dwarfs like NGC 5253, an unlikely match to the ULIRG situation. We hence have adopted the following second extreme scenario: all faint continua, defined as emitting less than 50% of the total 5–10 μm flux, are assumed to be due to star formation, while all stronger ones are due to an AGN.

Figure 13 shows the median ratio of the energy emitted by the starburst component to the total energy emitted [F_{5–10 μm}(star burst)/F_{5–10 μm}(total)] of ULIRGs presented in Table 4 and two HYLIRGs (Taniguchi et al. 1997; Aussel et al. 1998) versus the total infrared luminosity. A trend toward AGN dominance at high luminosity is again clearly seen. The cutoff between starburst-dominated galaxies and AGN-dominated galaxies lies at L ≈ 10^{12.4–10^{2.5}} L_{⊙}. The significance of this trend can be tested by dividing the luminosity range into the bins L_{FIR} = 10^{11.8–10^{12.4}} L_{⊙} and L_{FIR} = 10^{12.4–10^{13.0}} L_{⊙} and using, respectively, the Kolmogorov-Smirnov test and Student’s t-test to test if the two samples follow the same distribution or have the mean value. The probabilities for such hypotheses are 1.0 × 10^{-4} and 1.3 × 10^{-4}, respectively, demonstrating that the trend is statistically very significant. We also perform the two statistical tests while removing the two most luminous galaxies (L_{FIR} > 10^{13} L_{⊙}). Probabilities are then 9.0 × 10^{-4} and 5.0 × 10^{-4}.

To quantify the AGN contribution at different luminosities, we identified either all or none of the continuum of each source as AGN according to the two scenarios described previously. We then determined the ratio F_{5–10 μm}(star formation)/F_{5–10 μm}(total), with F_{5–10 μm}(star formation) being the sum of UIB-dominated starburst flux and that part of the continuum flux that is ascribed to star formation under the given scenario. For each scenario, we averaged the results for the ULIRGs in each of the two luminosity bins. Table 5 displays the resulting average values along with their uncertainties. The average contribution of star formation to the 5–10 μm flux is 65%–84% for the low-luminosity bin and 24%–33% for the high-luminosity bin, the ranges representing the two extreme scenarios. Extrapolating from MIR fluxes to total far-infrared ones, the average contributions of star formation are 82%–94% for the low-luminosity bin and 44%–55% for the high-luminosity bin. These results from quantitative modeling considerably reinforce the conclusions from the earlier work based on the L/C ratio: low-luminosity ULIRGs are predominantly starburst powered, while AGN powering dominates above ~ 10^{12.4–10^{12.5}} L_{⊙}.

6. Conclusions

We have presented ISOCAM-CVF low-resolution MIR spectroscopy of 16 ultraluminous infrared galaxies obtained within a program targeted at investigating the most luminous ULIRGs. The data are analyzed along with the complete ISO database of low-resolution spectra of ULIRGs/HYLIRGs, totalling 76 sources. We use the presence of the MIR “UIB” aromatic bands as a diagnostic of starburst activity, finding starburst-dominated systems up to a luminosity of L_{IR} = 10^{12.65} L_{⊙}. Other spectra show a strong AGN continuum with weaker features of uncertain origin. We have found one highly obscured AGN.

The MIR spectra can be modeled in terms of a superposition of a UIB-dominated starburst spectrum and a continuum, both potentially strongly obscured. This continuum contains both AGN and additional H II region contributions. The fits prefer a two-zone model in which the extinction to starburst and continuum regions may differ. Results from these fits agree well with previous simpler diagnostics based on the line-to-continuum ratio of the UIB features.

Low-luminosity ULIRGs are mostly starburst dominated, but the AGN fraction increases with luminosity and

| LUMINOSITY | F_{5–10 μm}(star formation)/F_{5–10 μm}(total) | F_{3–1000 μm}(star formation)/F_{3–1000 μm}(total) |
|------------|-----------------------------------------------|--------------------------------------------------|
| L < 10^{12.4} L_{⊙} | 65 ± 4 | 82 ± 10 |
| L > 10^{12.4} L_{⊙} | 24 ± 7 | 44 ± 17 |

NOTE.—Scenario A: Continuum is attributed only to AGNs. Scenario B: Faint continua (less than 50% of the total MIR emission) are attributed to a starburst (see § 5). The uncertainties are uncertainties of the mean value in one luminosity bin. The means of the two luminosity bins of a single scenario differ at 5 σ in the MIR.
most ULIRGs above \( \sim 10^{12.4} - 10^{12.5} \) \( L_\odot \) appear AGN-like. We have separated ULIRGs into two luminosity bins of \( L_{\text{FIR}} = 10^{11.8} - 10^{12.4} \) \( L_\odot \) and \( L_{\text{FIR}} = 10^{12.4} - 10^{13.6} \) \( L_\odot \). We find that the average contributions of star formation to the infrared luminosity are 82\%–94\% for the low-luminosity bin and 44\%–55\% for the high-luminosity bin.

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APPENDIX

REDUCTION SCHEME FOR CVF OBSERVATIONS OF FAINT POINT SOURCES

Aiming for a good CAM-CVF spectrum including a reliable continuum, a main source of uncertainty is due to the PSF. Because the width of the PSF changes with the observed wavelength, it is crucial to determine the observed total flux for each wavelength separately. This is easily done for bright point sources because it is easy to sum the observed flux over a large box (typically 5 \( \times \) 5 pixels) or to fit the PSF profile to the observed image. Since our sources are pointlike at CAM spatial resolution, it is not necessary to consider the complex situation for extended sources. Even for point sources, however, the PSF correction is difficult if they are faint. Then, only a few pixels around the brightest one have a significant S/N (hereafter the brightest pixel will be called the "central pixel"). In such a case, the S/N of the corrected spectrum obtained by summing over a box or fitting the PSF profile is usually very low.

A better S/N can be obtained just using the signal of the central pixel and applying a PSF correction factor that varies slowly with wavelength. The main difficulty in determining this factor is to obtain the position of the source within the central pixel. This could be done by fitting a model of the PSF to the observed images at each wavelength. However, because the S/N is quite low for the pixels around the central pixel, direct application of this method gives uncertain positions and a final spectrum where the S/N is low, comparable to the S/N obtained by summing over a box. In order to improve the S/N, we adopted the following method.

In CIA, theoretical PSFs are available at every half-micron of the ISOCAM-CVF wavelength range, and residual variations over such ranges are small. We divided the observed wavelength range into subranges of 1 \( \mu \text{m} \) centered around the wavelength of a theoretical PSF and summed images corresponding to wavelengths in this range of 1 \( \mu \text{m} \) around the given wavelength (i.e., about 10 images). We then fitted a PSF profile to the resulting image (hereafter the summed image). This method improves the S/N, and the deduced position of the source in the central pixel is known with a better confidence level. We used this position and the PSF to derive the correction factor from flux in the central pixel to total flux, which was applied for each image in the considered wavelength range.

Although this method gives a better position of the source, it is still necessary to compute the systematic error introduced by this correction. The formal way is to compute the S/N for each pixel of the summed image and then to use an inverse Monte Carlo method to compute the S/N of the spectrum. Another equivalent way that avoids a Monte Carlo simulation is to consider the images used to obtain the summed image as guesses of a Monte Carlo simulation. This is equivalent to a simulation with 10 guesses because the S/N of the summed image is deduced from these images. We then used the positions of the source obtained for all these images to correct the flux of the summed image. From the scatter of these measurements, it is then possible to deduce the systematic error introduced by the fitting method of the PSF profile.

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