The Institute of Space and Astronautical Science
Report SP No.14, December 2000

ISO Spectroscopy of ULIRGs and AGN: Lessons for Future Missions

By

Dieter Lutz*

(November 1, 2000)

Abstract: With the advent of ISO, mid-infrared spectroscopy has become sensitive enough for detailed analyses of sizeable samples of galaxies. Mid-infrared aromatic emission features are detected strongly and ubiquitously in star forming galaxies. They are absent close to an active galactic nucleus but can be strong on larger scales of the AGN host, in particular, if there is intense circumnuclear star formation. Through their nebular emission, hot star populations can be studied in dusty environments like starburst galaxies. Starbursts seem to be normal in their hot star initial mass function but short lived due to strong negative feedback. The rich fine structure and coronal line spectrum of active galaxies can be used to reconstruct the otherwise unobservable extreme ultraviolet emission of the AGN. Mid-infrared emission lines and continuum features provide new diagnostics to discriminate between starburst and AGN activity in obscured galaxies. Using these tools, most ultraluminous infrared galaxies are found to be predominantly starburst powered. Trends can be searched for in a larger sample of ULIRGs. The fraction of AGNs increases with luminosity above $\sim 3 \times 10^{12} L_{\odot}$, but there is no obvious trend for ULIRGs to be more AGN-like with more advanced merger phase.

1. INTRODUCTION

The detection of cosmic infrared background emission in the COBE data and the first deep infrared and submillimeter surveys have increased the need to understand the nature and activity of infrared galaxies. The infrared sources at high and intermediate redshifts detected by SCUBA and ISO apparently are luminous and dusty systems, and understanding their closest local analogues is a prerequisite of progress in determining their contribution to the cosmic star formation history, the role of active galactic nuclei at high z, and the relation between the cosmic infrared and X-ray backgrounds. While our census of the local infrared universe is still essentially based on IRAS, spectroscopy is needed to understand it better than possible from the fairly unspecific continuum measurements that mostly reflect dust reradiation of uncharacterized energy sources. With future missions like SIRTF and HII/L2, spectroscopic methods developed on the local population may even be directly applied to the high redshift universe.

* Max-Planck-Institut für extraterrestrische Physik, Postfach 1312, 85741 Garching, Germany; lutz@mpe.mpg.de

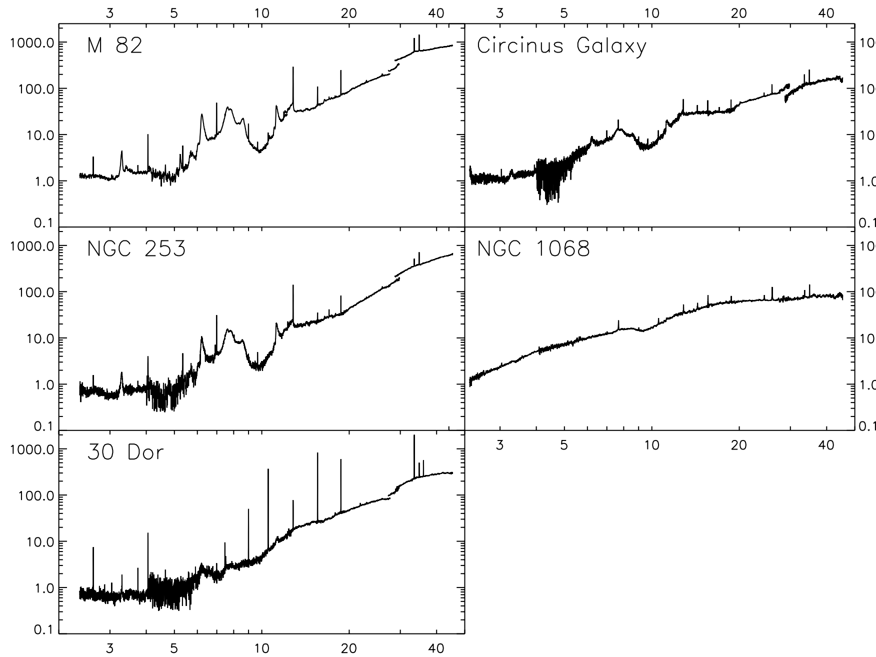

Fig. 1: ISO-SWS 2.4-45μm spectra of template starburst and Seyfert galaxies and part of the 30Dor region in the Large Magellanic Cloud

2. CONTINUUM AND FEATURES

With the exception of the brightest lines in the very brightest sources, mid-infrared spectroscopy of galaxies has been impossible to obtain from groundbased or airborne observations. Full wavelength coverage and high sensitivity of the ISO cryogenic space telescope have changed this situation, providing spectra of unprecedented detail, in particular, for the 2.4-45μm region covered by the short wavelength spectrometer SWS. Figure 1 compares the SWS spectra of prototypical starburst and Seyfert galaxies (Sturm et al. 2000). A first clear difference is the stronger and warmer mid-infrared continuum of the Seyferts, due to dust heated by the AGN.

The 6-13μm spectra of star forming galaxies are dominated by strong emission features due to transiently heated aromatic carriers which we will call PAH features according to one of the most popular identifications. These PAH spectra are very similar among different star forming galaxies (Rigopoulou et al. 1999; Helou et al. 2000). An exception to be noted is the weakness or absence of the PAHs in the spectra of low metallicity starbursting dwarfs (e.g. 30 Dor, Figure 1; NGC 5253, Rigopoulou et al. 1999). While this is of little relevance for studies of nearby dusty starbursts, it may have implications for future mid-infrared observations of lower metallicity galaxies at higher redshift, both for determining their redshifts and for studying their nature. The minimum near 10μm between the two major PAH complexes is difficult to disentangle from silicate absorption, and the latter may have often been overestimated in the past. At longer wavelengths, a rising continuum likely due to very small grains sets in. Close comparison of the M 82 and NGC 253 spectra (Sturm et al. 2000) as well as CAM-CVF spectroscopy of several, spatially partly resolved starbursts (Laurent et al. 1999) confirms that the PAH feature emission is fairly similar from source to source and likely originates in photodissociation regions (PDRs). Conversely, the rising continuum at longer wavelengths varies with physical conditions in the H II regions of the starburst and is most intense in compact regions like the one in the interaction zone of the Antenna galaxies (Mirabel et al. 1998).

In accordance with previous ground-based results, the aromatic emission features are weaker or absent in many Seyfert spectra. Spatially resolved ISO spectra of NGC 1068, Cen A, and Circinus demonstrate even more convincingly that the PAH features are not AGN related (Alexander et al. 1999a; Laurent et al. 1999; Mirabel et al. 1999; Moorwood 1999). PAH emission is undetected in the nuclei but seen on larger scales, excited in a starburst or cirrus type situation. In the context of unified scenarios, these observations are related to the finding that PAH equivalent widths of Seyfert 2's are larger than those of Seyfert 1's while the PAH fluxes of both categories are similar (Clavel et al. 1998). Such a behavior can be explained if the PAH emission originates on larger scales and is emitted isotropically, while the AGN continuum is emitted anisotropically, changing significantly with angle between line of sight and axis of the putative dust torus.

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

3. THE HOT STAR POPULATION IN STARBURSTS

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

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

4. AGN AND THE BIG BLUE BUMP

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

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

The SEDs derived for NGC 4151 and NGC 1068 appear quite different. They fall sharply beyond the Lyman limit and then rise sharply again toward 100eV. Such a structured SED is not consistent with any accretion disk model and difficult to reconcile with any continuum emission mechanism. Alternatively, the deep minimum might be due to absorption by neutral hydrogen. Then, the narrow line region does not see the intrinsic SED of the AGN which will have a smoother UV continuum and perhaps even a Big Blue Bump. For NGC 4151, this interpretation is corroborated by independent evidence: the reconstructed (absorbed) SED does not contain enough UV photons to photoionize the BLR, i.e. it cannot be the intrinsic SED. Observations of UV Lyman absorption lines similarly suggest a neutral absorber (Kriss et al. 1992). While a significant range of SEDs and NLR geometries has been explored to confirm the robustness of the inferred SEDs, it is also possible to get good fits with simple power law continua by

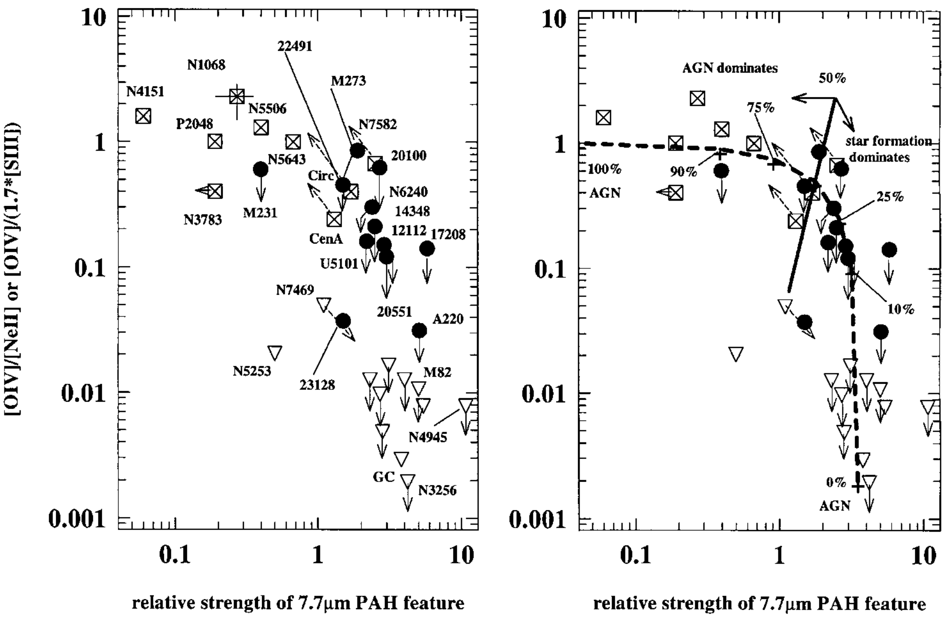

Fig. 2: SWS/PHT-S diagnostic diagram for ULIRGs. The vertical axis measures the ratio of low and high excitation mid-infrared emission lines, the horizontal axis the strength of the 7.7μm PAH feature relative to the local continuum. AGN templates are marked by squares, starburst templates by triangles, and ULIRGs by circles. Note that there are upper limits for high excitation line emission in most ULIRGs. A simple mixing curve is also shown.

introducing significant additional free parameters like a variable ratio of specific matter bounded and radiation bounded clouds (Binette et al. 1997). Our reconstructed SEDs that appear very unusual at first glance are again consistent with the standard AGN paradigm of thin accretion disks emitting a Big Blue Bump, assuming that the NLR sees a partially absorbed continuum.

5. THE NATURE OF ULTRALUMINOUS INFRARED GALAXIES

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

The clear differences between mid-infrared starburst and AGN spectra described above provide two new tools to address this question, at wavelengths that are better able to penetrate the obscuring dust. The first tool is the presence of strong high excitation fine structure lines only in the narrow line region of AGN but not in starburst H II regions. Conversely, the mid-infrared PAH emission features are strong in starbursts but weak or absent in AGN. Both tools can be combined in a two-dimensional diagnostic diagram (Figure 2, Genzel et al. 1998).

From the combined ISO-SWS and ISOPHOT-S diagnostic, most of the 15 ULIRGs studied are found to be predominantly starburst powered. A few examples (Mrk 231, Mrk 273) may

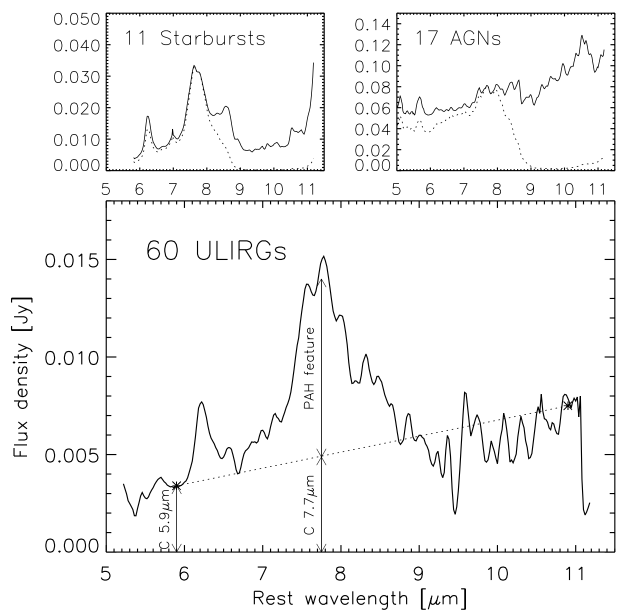

Fig. 3: Average ISOPHOT-S spectrum of 60 ULIRGS (z<0.3) along with starburst and AGN comparison spectra. Dotted lines in the comparison spectra indicate the effect of extremely high foreground extinction.

be AGN dominated or at least have a significant AGN component (NGC 6240). From the ISO data, significantly higher obscurations towards the starburst region are inferred than previously assumed. This also addresses a key issue in stating that a ULIRG is starburst dominated: Not only is the emission detected by ISO starburst-like, it is also - after correction for extinction - enough to provide the bulk of the bolometric luminosity. Little room is thus left for unknown obscured power sources. Dominance of either starburst or AGN activity does not exclude the presence of the respective other component. In fact, high resolution near-infrared observations suggest a significant number of composite ULIRG systems.

The fine structure line diagnostics have reached ISO's practical sensitivity limit for this moderate sized sample. Using ISOPHOT-S and ISOCAM-CVF, the PAH diagnostic could be extended to a large sample of about 75 ULIRGs that allows to search for trends and evolutionary effects (Lutz et al. 1998; Rigopoulou et al. 1999; Tran et al. 2000). The average spectrum created from the ISOPHOT-S data (Figure 3) clearly supports the result that most ULIRGs are predominantly starburst powered. Subtle deviations of ULIRG PAH spectra from starburst ones also support the high level of obscuration inferred from the SWS data. At the highest luminosities in excess of 4×10^{12} solar luminosities, there is a transition towards preferentially AGN dominated systems. Inferring the total contribution of AGN and starburst to a ULIRG's luminosities using the PAH diagnostic implies a bolometric correction from the mid-infrared contributions which are determined fairly reliably using different methods (Tran et al. 2000). At this point, orientation-dependent variations in AGN SEDs (Clavel et al. 1998) introduce an additional uncertainty. Reassuringly, however, ULIRGs classified as starburst-like by the PAH method also turn out to be PAH 'ultraluminous' in absolute terms (Rigopoulou et al. 1999), again leaving little room for non-starburst power sources.

ULIRGs are interacting or merging systems. The classical evolutionary scenario of Sanders et al. (1988) postulated increasing AGN dominance during the ULIRG phase, with an ener-

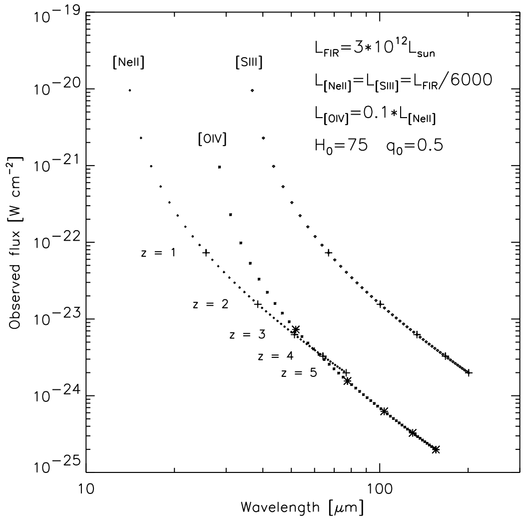

Fig. 4: Expected wavelengths and fluxes for key fine structure lines from a high redshift ultraluminous galaxy

getically dominant AGN later emerging as a QSO. Not only has this scenario to be modified in view of the starburst dominance in most ULIRGs, but also the suggested trend towards AGN dominance at later stages of the interaction is not seen. This observation and a similar lack of a clear correlation of state of interaction with gas content (i.e. gas consumption by starburst or AGN) suggest that dominance of starburst or AGN and their feeding may depend on local and shorter term conditions in addition to the global state of the merger.

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

6. THE FUTURE: INFRARED SPECTROSCOPY OF HIGH-REDSHIFT GALAXIES

New missions will allow us to directly apply the tools developed with ISO data to faint high redshift systems. Results from ISO spectroscopy are used in Figure 4 to estimate at which wavelengths and fluxes, the brightest key fine structure lines may be expected for a high redshift ultraluminous galaxy. The fluxes of the fainter but diagnostically important lines like [O IV] quickly fall below $10^{-23}\,\mathrm{W\,m^{-2}}$. Such measurements will be time consuming even with a cold 3.5m-mirror. A mission like HII/L2 would, however, be ideally suited to exploit the diagnostic power of the mid-infrared features that can be extracted from low resolution spectra. A variety of existing and upcoming missions (SCUBA, FIRST etc.) will detect large numbers of high redshift infrared galaxies with spectral energy distributions typically peaking at a few mJy or more in the far-infrared and submm range. The aromatic emission features of such sources should peak at a few tens of μJy in the 15 to 50μm range. In addition to their diagnostic value, such spectra may also serve for direct redshift determination, a particularly valuable feature given the considerable difficulties of optical identification of faint infrared galaxies detected with large beam instruments.

ACKNOWLEDGMENTS

It is a pleasure to thank all who have contributed to this work, in particular Tal Alexander, Natascha Förster-Schreiber, Reinhard Genzel, Dietmar Kunze, Alan Moorwood, Hagai Netzer, Dimitra Rigopoulou, Henrik Spoon, Amiel Sternberg, Eckhard Sturm, Michele Thornley, and Dan Tran.

REFERENCES

Alexander, D. M. et al. 1999a, MNRAS, 310, 78
Alexander, T. et al. 1999b, ApJ, 512, 204
Alexander, T. et al. 2000, ApJ, 536, 710
Binette, L. et al. 1997, A&A, 327, 909
Clavel, J. et al. 1998, preprint (astro-ph/9806054)
Colbert, J. W. et al. 1999, ApJ, 511, 721
Cox, P. et al. 1999, in: ESA EP-427, The Universe as seen by ISO, ed. P. Cox & M. F. Kessler (Noordwijk: ESA), 631
Crowther, P. A. et al. 1999, MNRAS, 304, 654
Fischer, J. et al. 1996, A&A, 315, L97
Förster-Schreiber, N. et al. 2000, submitted
Genzel, R. et al. 1998, ApJ, 498, 579
Helou, G. et al. 2000, ApJ, 532, L21
Kriss, G. A. et al. 1992, ApJ, 392, 485
Kunze, D. et al. 1996, A&A, 315, L101
Laurent, O. et al. 1999, in: ESA SP-427, The Universe as seen by ISO, ed. P. Cox & M. F. Kessler (Noordwijk: ESA), 913
Lutz, D. et al. 1996, A&A, 315, L269
Lutz, D. et al. 1998, ApJ, 505, L103
Lutz, D. 1999, in: ESA SP-427, The Universe as seen by ISO, ed. P. Cox & M. F. Kessler (Noordwijk: ESA), 623
Lutz, D., Veilleux, S. & Genzel, R. 1999b, ApJ, 517, L13
Mirabel, I. F. et al. 1998, A&A, 331, L1
Mirabel, I. F. et al. 1999, A&A, 341, 667
Moorwood, A. F. M. et al. 1996, A&A, 315, L109
Moorwood, A. F. M. et al. 1999 in: ESA SP-327, The Universe as seen by ISO, ed. P. Cox & M. F. Kessler (Noordwijk; ESA), 825
Pauldrach, A. W. A. et al. 1998, in: ASP Conf. Ser. 131, Boulder-Munich II, Properties of Hot, Luminous Stars, ed. I. Howarth (San Francisco: ASP), 258
Rigopoulou, D. et al. 1996, A&A, 315, L125
Rigopoulou, D. et al. 1999, AJ, 118, 2625
Sanders, D. B. et al. 1988, ApJ, 325, 74
Sturm, E. et al. 2000, A&A, 358, 481
Thornley, M. D. et al. 2000, ApJ, in press
Tran, D. et al., 2000, ApJ, submitted