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MID-INFRARED OBSERVATIONS OF GALAXIES

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RESUMEN

Los avances recientes en la tecnología de detectores infrarrojos y la misión espacial ISO han propiciado el uso de imagen y espectroscopía en el infrarrojo medio para el estudio de las galaxias y su evolución. El énfasis de estos estudios se pone en la naturaleza de las regiones oscuras, inaccesibles en otras longitudes de onda. Esta contribución versa sobre un conjunto de resultados recientes obtenidos de observaciones con alta resolución espacial con telescopios de tierra similares al GTC.

ABSTRACT

Advances in detector technology and the *ISO* space mission have recently boosted the use of mid-infrared imaging and spectroscopy for the study of galaxies and their evolution. An emphasis of such studies is on the nature of obscured regions that are inaccessible at other wavelengths. This contribution discusses a selection of recent results and highlights topics for high spatial resolution observations with large ground-based telescopes like the GTC.

Key Words: **GALAXIES: ACTIVE — GALAXIES: ISM — GALAXIES: STARBURST — INFRARED: ISM: LINES AND BANDS**

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1. MID-INFRARED OBSERVATIONS FROM THE GROUND AND SPACE

Ten years ago, the field of extragalactic mid-infrared astronomy was mainly defined by the *IRAS* database and ground-based 4 m class telescopes, equipped with instruments with only few detector pixels. This situation has changed dramatically with ESA's *Infrared Space Observatory* (*ISO*) and with large format mid-infrared detectors appearing in instruments of 4 m and 10 m class telescopes on the ground. Technological progress will continue with more sophisticated ground-based instruments for large telescopes and with the upcoming *SIRTF* mission. In this context it is important to note the dichotomy and complementarity between mid-infrared astronomy from ground and from space. Space observations excel in complete wavelength coverage and sensitivity: in point source photometry, *SIRTF* is more than an order of magnitude more sensitive than a 10 m class ground-based instrument, and this advantage increases for extended sources. Conversely, the spatial resolution of the small cryogenic space telescopes is more than ten times poorer than that of a 10 m telescope like the GTC at similar wavelengths. Even more than in other fields, this complementarity is important for extragalactic observations that tend to be sensitivity-starved. When trying to give an overview of recent results, this paper deemphasizes some exciting and productive fields like deep extragalactic surveys or mapping of the relatively low surface brightness mid-IR emission in normal galaxies. These are mainly in the "space" domain, with ground-based mid-IR instruments in a targeted follow-up role. Rather, we will emphasize issues more directly related to GTC-type science.

2. MID-INFRARED DIAGNOSTICS

The *ISO* 2.5–200 μm spectrum of the Circinus galaxy, which hosts both a type 2 AGN and star formation, collects most of the elements of infrared spectra of galaxies that can be used as spectroscopic or photometric diagnostics (Figure 1). A rich spectrum of ionic fine-structure lines, hydrogen recombination lines and molecular hydrogen rotational lines is superposed on the far-infrared dust emission and the mid-infrared emission and absorption features.

The 6–13 μm spectra of star forming galaxies are dominated by strong emission features from transiently heated aromatic carriers called PAH (polycyclic aromatic hydrocarbon) features in the following according to one of their most popular identifications. These PAH spectra are very similar among different star forming galaxies (Rigopoulou et al. 1999; Helou et al. 2000). An exception to be noted is the weakness or absence of the PAHs in the spectra of low metallicity starbursting dwarfs, e.g., SBS 0355-052 (Thuan et al. 1999), 30 Dor (Sturm et al. 2000), and NGC 5253 (Rigopoulou et al. 1999). While

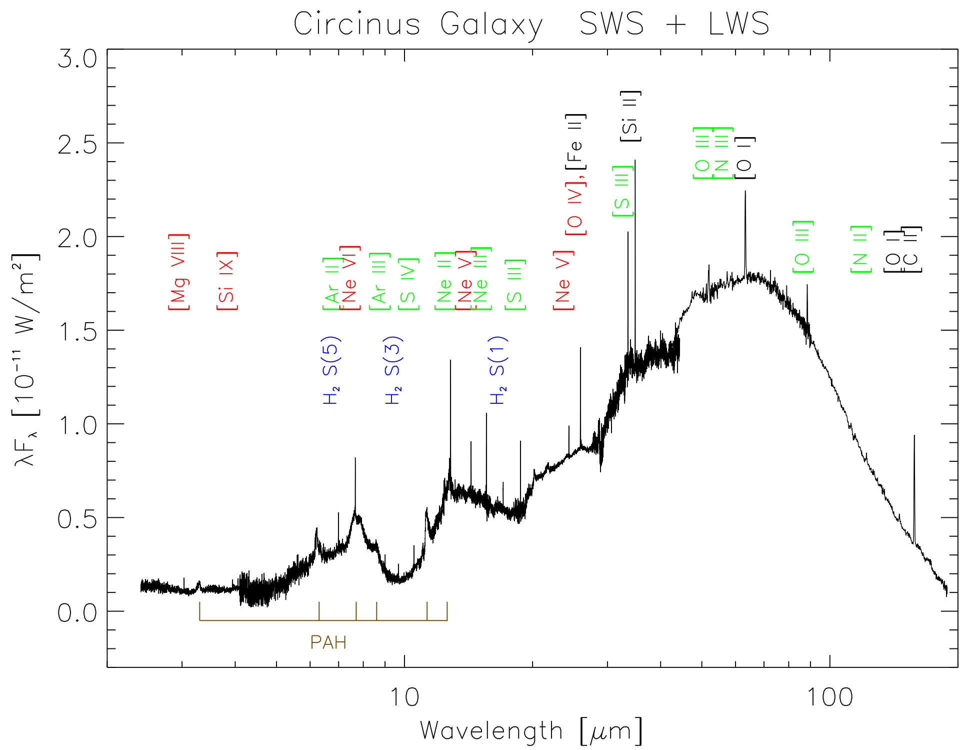

Fig. 1. The *ISO* 2.4–195 μm spectrum of the Circinus galaxy collects most elements of infrared spectra of galaxies.

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this is of little relevance for studies of nearby dusty starbursts, it may have implications on future mid-infrared observations of lower metallicity galaxies at higher redshift, both for determining their redshifts and for studying their nature. The minimum near 10 μm 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 probably due to very small grains sets in. Close comparison of the M82 and NGC 253 spectra (Sturm et al. 2000), as well as CAM-CVF spectroscopy of several partly spatially resolved starbursts (Laurent et al. 2000), confirms that the PAH feature emission is fairly similar from source to source and probably 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. 1999; Mirabel et al. 1999; Moorwood 1999; Le Floc'h et al. 2001). PAH emission is undetected in the nuclei but seen on larger scales, excited in a starburst or cirrus-type situation. In the context of unified scenarios, these observations are related to the finding that PAH equivalent widths of Seyfert 2s are larger than those of Seyfert 1s while the PAH fluxes of both categories are similar (Clavel et al. 2000). Such 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 the line of sight and the axis of the putative dust torus.

2.1. *Application to ultraluminous infrared galaxies*

Ultraluminous infrared galaxies (ULIRGs) were identified as an important galaxy population in the local Universe more than ten years ago after the *IRAS* mission. Most of their energy output is dust emission, which is a calorimeter of the energy 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

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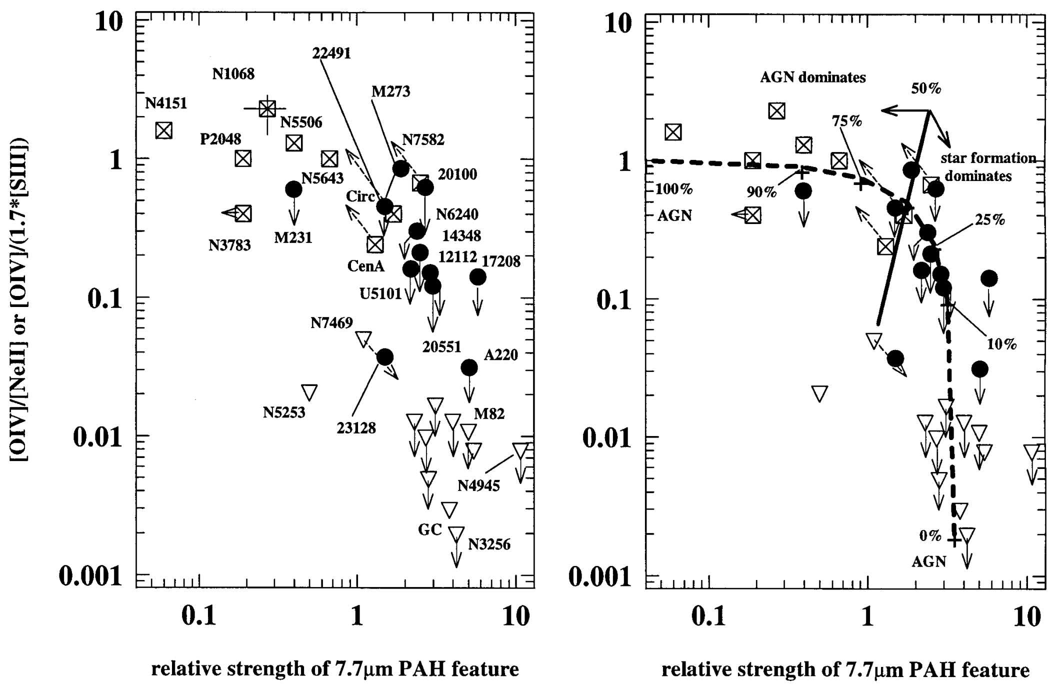

Fig. 2. SWS/PHT-S diagnostic diagram for ULIRGs. The vertical axis measures the ratio of low and high excitation mid-infrared emission lines, and the horizontal axis gives the strength of the 7.7 μm PAH feature relative to the local continuum. AGN templates are marked by squares, starburst templates 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.

Universe, ULIRGs are important as the most likely closest analogues of the mid-infrared and (sub)mm sources that were recently discovered as major contributors to high redshift star formation.

The clear differences between mid-infrared starburst and AGN spectra described above provide two new tools to address this question at wavelengths that are better able of penetrating the obscuring dust. The first tool is 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 this combined ISO-SWS and ISOPHOT-S diagnostic, most of the fifteen ULIRGs studied are found to be predominantly starburst-powered. The fine-structure line diagnostics reach *ISO*'s practical sensitivity limit for this moderately sized sample. Using ISOPHOT-S and ISOCAM-CVF, the PAH diagnostic could be extended to a large sample of about 75 ULIRGs that allows us to search for trends and evolutionary effects (Lutz et al. 1998; Rigopoulou et al. 1999; Tran et al. 2001).

2.2. *Ices*

Detailed mid-infrared spectroscopy with *ISO* has considerably widened the observational database of ice features in spectra of Galactic objects. Careful inspection of the *ISO* database shows them to be present in external galaxies as well. Detections range from moderate 3 μm water ice absorption in M82 and NGC 253 (Sturm et al. 2000) to strong water and CO_2 ice absorption in NGC 4945 (Spoon et al. 2000), and to the extreme absorption-dominated spectrum of NGC 4418 (Figure 3; Spoon et al. 2001) that has similarities with absorption-dominated spectra of strongly embedded young stellar objects. At first glance, one might expect the cold environment of molecular clouds in starbursts to be more beneficial to the presence of ices than the warm or hot dusty medium close to an AGN, a point of view that is supported by the absence of ices in the spectrum of NGC 1068 (Sturm et al. 2000). The ices in the spectrum of the most likely AGN-dominated NGC 4418, however, caution that more investigations will be needed to elucidate the contributions of starburst molecular clouds, cold regions of circum-AGN molecular material, and the larger scale hosts to the observed extragalactic ice absorptions.

Spoon et al. (2002) have recently searched all

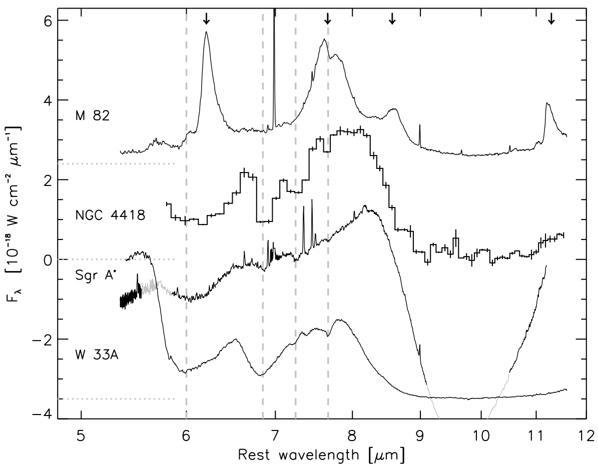

Fig. 3. The spectrum of the obscured infrared galaxy NGC 4418 shows strong ice absorptions.

ISOPHOT-S and ISOCAM-CVF spectra of galaxies for indications of ice features. At the detection limits of the *ISO* data, ices are detected in a moderate fraction (∼20%) of objects in this heterogeneous sample. Systems like NGC 4418 must be the exception. The highest detection rate is in ULIRGs, consistent with the presence of large quantities of molecular material in these objects. The striking differences in relative strength of absorption features due to ice and carbonaceous material when comparing M82 and NGC 1068, and even for several lines of sight close to the Galactic Center (Chiar et al. 2000) are a further warning that the mid-infrared absorption in galaxies may vary considerably—observations are clearly inconsistent with its being caused by a unique absorption curve that is just applied at different absolute levels of absorption.

Ice absorption adds another complication to the interpretation of mid-IR low resolution spectra. The *ISO* experience clearly demonstrates that good S/N and wavelength coverage are needed to reliably disentangle the various components. Ground-based *N* band spectra and ISOPHOT-S spectra both have their shortcomings; ISOCAM-CVF with its larger wavelength coverage does better. Successful models for future low resolution spectroscopy with, for example, SIRTF-IRS will have to extend the three components of PAHs, H II region continuum and AGN continuum (Laurent et al. 2000) with a more sophisticated treatment of absorption for each of these components.

3. AGN SEARCHES

IRAS-based studies established that Seyferts and QSOs differ from non-AGN galaxies by their stronger mid-IR dust emission (e.g., de Grijp et al 1985; de Grijp et al 1987). The strong mid-IR emission probably originates both in the putative torus (Pier & Krolik 1993) and in dust mixed with the narrow line region gas (Cameron et al. 1993). *ISO* photometric and spectrophotometric studies have further completed this picture (Rodriguez Espinosa et al. 1996; Clavel et al. 2000; Pérez García & Rodriguez Espinosa 2001). This well-established AGN signature is, of course, difficult to identify if the AGN is a minor contributor to the galaxy's luminosity, rather than being dominant. High spatial resolution ground-based observations in the mid-IR (or in the near-IR *L* and *M* bands assisted by adaptive optics) will be key to extending such studies to lower luminosity AGN. Krabbe et al. (2001) present a first attempt of this type based on observations with the ESO 2.2 m telescope, claiming an excellent correlation between the mid-IR AGN emission and extinction corrected hard X-rays. Sensitivity and angular resolution of a large telescope like the GTC will vastly improve the ability to separate AGN and background emission, for example, from circumnuclear starbursts, allowing better detections of faint or obscured AGN. Similarly, measurements of orientation effects and their comparison with unified AGN scenarios will be much more efficient than in earlier data (Heckman 1995; Maiolino et al. 1995; Clavel et al. 2000; Pérez García & Rodriguez Espinosa 2001).

4. STARBURSTS AND THE OBSCURED PHASES OF STAR CLUSTER DEVELOPMENT

The importance of infrared observations for the study of dusty starbursts from the *IRAS* database has long been recognized. In contrast, less obscured starbursts and blue compact dwarfs have been mainly studied in the optical and UV, and simple "foreground screen" approximations of dust effects on their spectra are in wide use, in particular in the interpretation of high redshift galaxy data. In this context, the discovery of compact, extremely obscured regions of star formation in a number of mostly low metallicity galaxies comes as a warning, questioning at least the physical interpretation of these simple approximations.

Compact (from a few parsecs to a few tens of parsecs), highly obscured regions in a number of nearby starbursts have been detected in both the radio (e.g., Kobulnicky & Johnson 1999; Turner et al. 2000) and the infrared (Thuan et al. 1999; Gorjian et al. 2001; Hunt et al. 2001; Dale et al. 2001; Vacca et al. 2002). Even in those low metallicity objects, heavily obscured regions contribute a major fraction of

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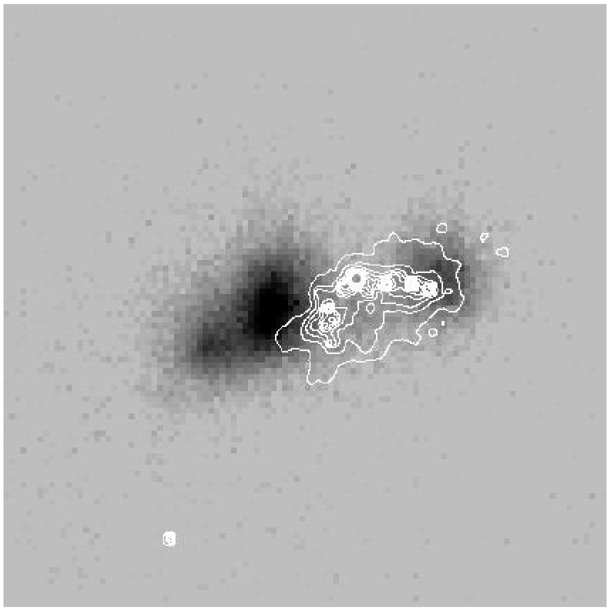

Fig. 4. *N* band image of the dwarf galaxy He2-10 overlaid with optical *V* band contours from the *HST*. The mid-IR morphology is not correlated with the regions of star formation apparent in the ultraviolet and optical bands. The obscured mid-IR sources contribute ∼60% of the mid-IR and probably a similar fraction of the far-IR emission (Vacca et al. 2002).

the bolometric luminosity. Further high spatial resolution imaging and spectroscopic studies of these objects can provide insight into the star formation process in galaxies in general, and most probably into the early evolution of "super star clusters" that are commonly found in high resolution *HST* images of starbursts. What is the contribution of these obscured clusters to the bolometric luminosity? What fraction of star formation occurs in clusters? What are their luminosity functions in continuum and line emission? What is their nebular excitation? A further interesting link may exist between individual obscured H II regions and the absorbed components seen in integrated spectra of galaxies (Spoon et al. 2002), in particular ULIRGs. On large scales, high resolution mid-IR imaging is a key tool to determine the spatial structure of dusty starbursts (Soifer et al. 1999; Soifer et al. 2000; Soifer et al. 2001).

Spectroscopic diagnostics have rarely been applied to individual obscured clusters (see, however, Crowther et al. 1999), but to a considerable number of integrated *ISO* starburst spectra. A number of key questions are related to the hot star population in starbursts. Is the initial mass function (IMF) similar to that in our Galaxy? How do starbursts evolve? Do they continue until they have consumed all their gas fuel or are they stopped in other ways? *ISO* studied the hot star content by analysis of nebular emission, benefiting from the relative insensitivity of the mid-infrared lines to extinction and electron temperature. Thornley et al. (2000) have carried out an SWS survey of the [Ne III] 15.55 μm and [Ne II] 12.81 μm lines 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, modeling 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. Nebular emission is predicted from these SEDs and photoionization modeling with CLOUDY. The modeling results suggest that most of these starbursts are presently deficient in the most massive stars, either because they did not form in an IMF invoking an upper mass cut-off, or because they disappeared because of aging effects. The considerable overlap between excitation of starbursts and Galactic H II regions and direct evidence for the presence of very massive stars in nearby starburst templates suggest aging effects to be dominant while the IMF is probably 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 ($<\sim 10^7$ yr), 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 (Förster-Schreiber et al. 2001).

A number of studies are applying similar methods to Galactic H II regions (Giveon et al. 2002; Martin-Hernandez et al. 2002). In addition to analysis of our Galaxy, they can provide important tests of the methods and assumptions of starburst studies. The adequacy of most recent hot star model atmospheres by the Munich group, for example, appears to be good (Giveon et al. 2002). In addition, comparison to galactic H II regions can constrain the role of metallicity in determining the starburst spectra.

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