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EXTRAGALACTIC SPECTROSCOPY WITH THE INFRARED SPACE OBSERVATORY

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RESUMEN

El satélite Infrared Space Observatory está abriendo la ventana de 2.5 a 200 μm para el estudio de galaxias. Basados en los primeros resultados sobre las líneas emisión obtenidas con el Short-Wavelength-Spectrometer, discutimos la naturaleza de las galaxias infrarrojas ultraluminosas.

ABSTRACT

The Infrared Space Observatory is opening the 2.5 to 200 μm band for detailed studies of galaxies. Based on the first results on ionic emission lines obtained with the Short-Wavelength-Spectrometer we discuss the nature of ultra-luminous IR, galaxies.

Key words: **GALAXIES: STARBURST — INFRARED: GALAXIES**

1. INTRODUCTION

The infrared waveband (1 to a few hundred μm) is a very interesting new window for the exploration of galaxies. At these wavelengths it is possible to probe regions that are heavily obscured by dust. Across the waveband there are a host of spectral lines of key ions, atoms, and molecules and characteristic signatures of various types of dust particles. It is therefore possible to probe the spatial distribution, composition and dynamics of interstellar matter (ISM) in the immediate vicinity of the nucleus or obscured disk star forming regions, in particular of the neutral ISM that cannot be observed at any other wavelength. With the successful launch and operation of the Infrared Space Observatory (ISO) of the European Space Agency (ESA) a new era has begun in sensitive photometry, imaging, and spectroscopy across the 2.5–200 μm band. In the following, we will discuss the first extragalactic spectroscopy we have undertaken with ISO.

2. WHAT POWERS (ULTRA-) LUMINOUS IR, GALAXIES?

One of the key discoveries of the *Infrared Astronomical Satellite (IRAS)* survey in the mid 80s was the identification of a class of very luminous ($L \sim 10^{11.5-12.5}\ L_\odot$) galaxies emitting most of their energy in the far-IR, (30 to 300 μm) wavelength band (for reviews see Soifer et al. 1987; Sanders & Mirabel 1996). While these galaxies are relatively rare compared to normal galaxies their local volume density is similar to or even exceeds that of optically selected QSOs of the same luminosity (Soifer et al. 1987). Most of them appear to be interacting galaxies, or advanced mergers (Soifer et al. 1987; Sanders et al. 1988; Solomon et al. 1996). They are very gas- and dust-rich (e.g., Sanders & Mirabel 1985; Sanders et al. 1988; Rigopoulou et al. 1996b) with typical gas masses of $\sim 10^{10}\ M_\odot$. Millimeter interferometry of some of the prototypical sources, such as Arp 220 (Wang et al. 1991), Mkn 273 (Yun & Scoville 1995), Mkn 231 (Bryant & Scoville 1996) and F10214+4724 (Downes et al. 1995; Scoville et al. 1995) shows that this gas is typically concentrated in the central kiloparsec or less. This translates to average hydrogen column densities exceeding 10^{24} cm^{-2} or visual extinction exceeding

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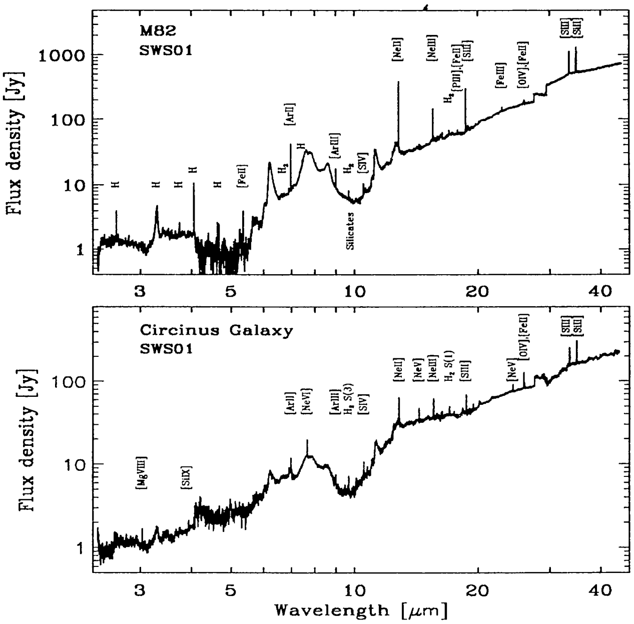

Fig. 1. Full 2.5–45 μm SWS spectra of the starburst galaxy M82 (upper panel) and the Seyfert 2/starburst galaxy Circinus (Moorwood et al. 1996). The jumps at ~ 30 μm are due to a change in aperture.

500. A key open question about these IR, luminous galaxies is the source(s) of their luminosity. Based on their far-IR, millimeter and radio properties many authors have argued that they are powered by active star formation (e.g., Rieke et al. 1985; Rowan-Robinson & Efstathiou 1993; Condon et al. 1991). Their optical properties, on the other hand, resemble narrow line active galactic nuclei (LINER or Seyfert 2), with a few broad line examples (e.g., Mrk 231) (Sanders et al. 1998; Veilleux et al. 1995). Some of them have compact radio nuclei (Lonsdale et al. 1993) or highly absorbed hard X-ray sources again indicative of hidden AGNs.

With the advent of ISO, sensitive mid- and far-IR, spectroscopy has now become available as a new, very specific tool for investigating the physical processes at the nuclei of obscured galaxies. The data discussed below were taken with the short wavelength spectrometer (SWS: de Graauw et al. 1996) during the calibration-verification (PV) phase and the first three months of the central program (CP) phase. The results are discussed in more detail in the special issue of A&A dedicated to ISO (Lutz et al. 1996; Rigopoulou et al. 1996; Sturm et al. 1996; Kunze et al. 1996; Moorwood et al. 1996). The ionic IR, emission lines toward galactic nuclei arise, like optical emission lines, predominantly from photoionized gas. Hence a powerful tool for investigating whether star formation or a central AGN dominates in obscured nuclei is to study the excitation state of the mid- and far-IR, emission line spectrum. Of particular interest are high excitation ('coronal') lines that require a much harder radiation field than can be delivered by stars, and thus are signposts for a (hidden) AGN. As a demonstration of SWS's capabilities in this regard, Figure 1 shows two full scans of the entire 2.5 μm to 45 μm spectrum in the classical starburst galaxy, M82, and in the nearby Seyfert 2 galaxy, Circinus (A1409-65). The qualitative and quantitative differences in the emission line spectra of the two galaxies are obvious. M82 is dominated by fairly low ionization species ([Ne II], [S III], [Si II], [Ar II]) while Circinus also shows very intense high excitation lines ([O IV], [Ne V], [Ne VI], [Mg VIII], [Si IX]) with ionization potential up to 320 eV (see Moorwood et al. 1996 and Oliva et al. 1994). In addition to the ionic fine structure lines, both galaxies (and most others we have observed so far) show a number of H_2 rotational emission lines. The molecular hydrogen emitting in the mid-IR, has temperatures of a few hundred K and typically makes up a few percent of the total (cold) molecular ISM. M82 and Circinus also show pronounced 3.2 μm, 6 to 8.5 μm and 11/12 μm emission features arising from UV-heated very small dust grains and PAHs.

Figure 2 is a plot of the (dereddened) [Ne V]/[Ne II] and [O IV]/[Ne II] line ratios (or 3σ upper limits) for 11 galaxies observed so far with SWS (Lutz et al. 1996). This includes several starburst and AGN templates, as well as three typical (ultra-) luminous *IRAS* galaxies (Arp 220, NGC 6240, NGC 3256). In all sources known to be powered by stars alone, the [Ne V]/[Ne II] and [O IV]/[Ne II] ratios range are ≤ 0.1, while these ratios are between 0.13 and 1.5 in the two AGNs. All three luminous *IRAS* galaxies also have line ratios $\leq$0.1, strongly

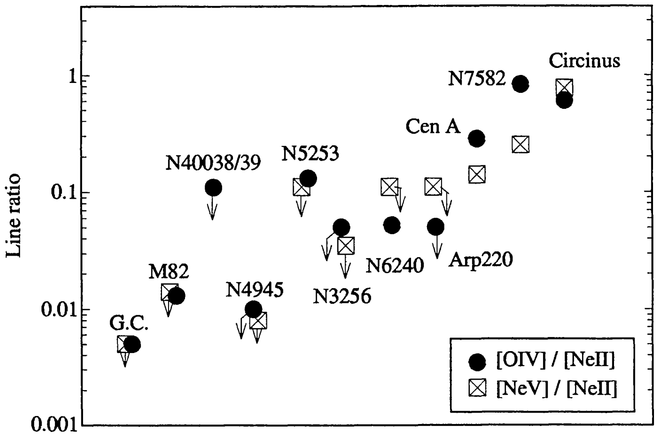

Fig. 2. Dereddened 14.3 μm [Ne V] (excitation potential 97 eV)/12.8 μm [Ne II] and 25.9 μm [O IV] (excitation potential 55 eV)/12.8 μm [Ne II] ratios (or 3σ upper limits) for 11 galaxies observed so far by ISO SWS (Lutz et al. 1996). To the left are the starburst template galaxies, to the right three active galactic nuclei. The three (ultra-)luminous *IRAS* galaxies (NGC 3256, NGHC 6240, Arp 220) are in the middle.

supporting the notion that an (even moderately extincted) AGN cannot be the main source of their luminosity. The only way around this important constraint is to postulate that these sources contain AGNs that are hidden even at 15 to 30 μm, requiring $A_V \geq 100$ ($N(H_2) \geq 10^{23}$). The fact that such a compact (≤ 10 pc scale), highly optically thick source would produce bright hot dust emission in the 5 to 20 μm range argues against this explanation. All three luminous *IRAS* galaxies, however, emit most of their luminosity between 30 and 200 μm requiring minimum (black body) source sizes of several hundreds of pc. *It is thus very probable that Arp 220, NGC 6240 and NGC 3256 are powered mainly by stars (although one cannot exclude of course that an AGN contributing a fraction of the bolometric luminosity is present).*

Assuming that massive stars dominate the luminosity of Arp 220, NGC 6240 and NGC 3256, what is the evolutionary state of the starburst? For these three and other luminous IR, galaxies, a number of near-IR,/optical studies addressing these issues can be found in the literature (e.g., Lester et al. 1988; Thronson et al. 1990; Doyon et al. 1992; van der Werf et al. 1993; Moorwood & Oliva 1994; Armus et al. 1995, 1996 Larkin et al. 1995; Genzel et al. 1995; Goldader et al. 1995, 1996). The basic common conclusion of these investigations, based on the small ratio of near-IR, recombination line luminosity to total (far-IR,) luminosity is that the observed far-IR, luminosity is *not dominated by recently formed, massive young stars.* According to these observations if stars power these galaxies, the last period of very active star formation must have occurred 3108 years ago or stars more massive than 20 $M_\odot$ have not recently been forming.

The new ISO SWS data now indicate that the near-IR,/optical emission is much more affected by dust obscuration than previously thought. Observations at mid- and far-IR, wavelengths (including still significant corrections for extinction with upward corrections of the observed [Ne II], [S III] etc. lines) are required to penetrate the dust enshrouding the sources of luminosity in the luminous *IRAS* galaxies. Lutz et al. (1996) have used the star cluster evolution cluster code of Kovo & Sternberg (1996) to calculate the number of stars of different type and the global L_{Bol}/L_{Lyc}, L_K/L_{Lyc} and supernova rate to L_{Bol} ratios as a function of time in three different star formation histories: pure δ-bursts ($\Delta t=10^6$ years), extended bursts ($\Delta t=2x10^7$ years) and constant star formation. They carried out calculations for Salpeter initial mass functions ($dN(M)/dM \sim M^{-2.4}$), solar abundances and upper mass cutoffs of 25, 50 and 100 $M_\odot$. The cluster-averaged stellar spectrum was synthesized by coadding Kurucz atmospheres with the appropriate weighting of different stellar types as calculated from the Kovo & Sternberg code. The various characteristic IR, line ratios (e.g., [Ne III]/[Ne II]) were then calculated with the ION photoionization code (Netzer 1993) with log (U) = −2.5 and $n_e = 300$ cm^{-3}. The results for the specific case of $m_u = 100$ $M_\odot$ are plotted in Fig. 3, which also shows the locations of the luminous IR galaxies and starburst templates that were observed. Constant star formation models and models with low upper mass cutoffs ($m_u \sim 25$ $M_\odot$) do not fit any of the objects. From the [Ne III]/[Ne II] line ratios and for Kurucz (1992) atmospheres the effective temperatures of the radiation field in the starburst galaxies M82, NGC 4945, NGC 4038/39, NGC 5253, as well as in the luminous *IRAS* galaxies NGC 3256 and NGC 6240 are at or even above 40 000 K, indicating that young, massive O stars are present. δ-bursts fit localized regions fairly well. One

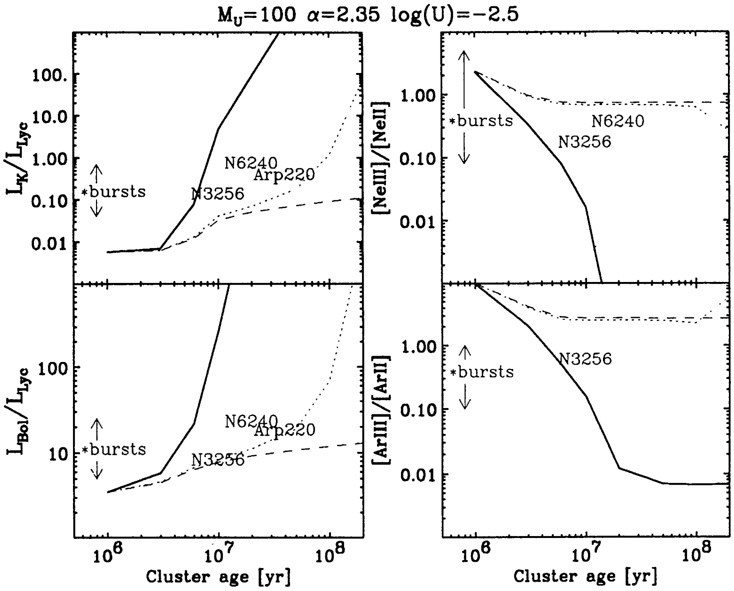

Fig. 3. L(bol)/L(Lyc), L(K-band)/L(Lyc) and characteristic IR, line ratios for evolving star cluster models (from Lutz et al. 1996). The Kovo & Sternberg cluster code, with Geneva tracks, was used to calculate the evolution of the stellar populations in different parts of the HR diagram, with different star formation histories and a Salpeter IMF (γ=-2.4, with upper mass cutoff 100 $M_\odot$ and lower mass cutoff 1 $M_\odot$). Solid curves are δ-bursts (star formation rate ~exp(-t/Δt) with $\Delta t = 10^6$ years), dotted curves are extended bursts with $\Delta t = 2 \times 10^7$ years, and dashed curves are constant star formation models. Line ratios are calculated with the ION photoionization code (Netzer 1993). The input spectrum is obtained by coadding the appropriate Kurucz models for the cluster.

particularly interesting case of such a confined, local δ-burst region is the 'overlap' region in the 'Antennae' galaxy pair (SWS: Kunze et al. 1996, LWS: Fischer et al. 1996, CAM: Vigroux et al. 1996).

The best overall fits for both starburst templates and the luminous IR galaxies observed so far are for moderately extended bursts ($\Delta t \sim 1-2\times10^7$ years) with mean ages ranging between 1 to 7 × 10^7 years and high upper mass cutoffs (50 to 100 $M_\odot$). Arp 220 and NGC 6240 still require somewhat older ages than the starburst templates but otherwise are very similar. Spatially resolved near-IR, imaging spectroscopy of M82 (Foerster et al. 1996; Satyapal et al. 1996) and NGC 1808 (Krabbe et al. 1994; Kotilainen et al. 1996; Tacconi-Garman et al. 1996) shows that bursts that appear to be extended in time when their integral emission is considered break up at high spatial resolution into a number of local, δ-bursts (~giant H II regions or massive star clusters) of different ages (see also Rieke et al. 1993).

There still remain substantial uncertainties in these conclusions. First it will obviously be necessary to observe a larger sample of (ultra-) luminous IR, galaxies before one can be sure that the conclusions reached by Lutz et al. are generally applicable and before it is clear how these findings fit into an evolutionary scheme; this is the purpose of guaranteed time observations we will be carrying out with ISO in the next year. Second while the general conclusion that the luminous IR, galaxies discussed here are powered by massive stars is fairly robust, for several reasons the detailed constraints on the starburst properties are still fairly uncertain. Stellar atmosphere models by Sellmaier et al. (1996) predict more energy output in the 20 to 50 eV range than the Kurucz (1992) models used by Lutz et al. and thus require less massive stars for the same [Ne III]/[Ne II] etc., ratios. Line fluxes, line ratios and extinction corrections all are subject to ±30% calibration uncertainties and to uncertainties in the extinction curve. Finally, there are the issues of metallicity and the effects of dust within the H II regions which need to be addressed by more detailed future studies with ISO.

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