ISO FAR-IR SPECTROSCOPY OF IR-BRIGHT GALAXIES AND ULIRGS

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Abstract.

Based on far-infrared spectroscopy of a small sample of nearby infrared-bright and ultraluminous infrared galaxies (ULIRGs) with the ISO Long

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Wavelength Spectrometer [1] we find a dramatic progression in ionic/atomic fine-structure emission line and molecular/atomic absorption line characteristics in these galaxies extending from strong [O III]52,88 μm and [N III]57 μm line emission to detection of only faint [C II]158 μm line emission from gas in photodissociation regions in the ULIRGs. The molecular absorption spectra show varying excitation as well, extending from galaxies in which the molecular population mainly occupies the ground state to galaxies in which there is significant population in higher levels. In the case of the prototypical ULIRG, the merger galaxy Arp 220, the spectrum is dominated by absorption lines of OH, H_2O, CH, and [O I]. Low [O III]88 μm line flux relative to the integrated far-infrared flux correlates with low excitation and does not appear to be due to far-infrared extinction or to density effects. A progression toward soft radiation fields or very dusty H II regions may explain these effects.

Key words: infrared-bright galaxies — ultraluminous galaxies — far-infrared spectra — starbursts — interstellar medium.

1. Introduction

In order to compare the evolutionary status, energetics, obscuration, and physical conditions of the nuclear regions of ULIRGs with those of less luminous infrared-bright galaxies with minimal sensitivity to extinction, we have used the grating mode of the ISO Long Wavelength Spectrometer (LWS) (Clegg *et al.*, 1996) to carry out (1) a full far-infrared spectral survey of a small sample of nearby IR-bright galaxies including the ULIRGs Arp 220 and Mkn 231 and (2) a fine-structure line survey of more distant galaxies, including a survey of ULIRGs in the [C II]158 μm fine-structure line. The observations allow us to analyze the dust continuum, to put constraints on the ionization parameters and the intensity of the radiation as it impinges upon the surrounding neutral clouds of gas and dust, and ultimately on the nature of the source(s) of luminosity. Detailed analyses of the spectra of the individual galaxies are presented elsewhere (Fischer *et al.*, 1996, 1997; Colbert *et al.*, 1999; Satyapal *et al.*, 1999; Lord *et al.*, 1999; Unger *et al.*, 1999; Bradford *et al.*, 1999; Harvey *et al.*, 1999; and Spinoglio *et al.*, 1999). Here we present a comparative overview of the observational results.

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2. The LWS full spectra of infrared-bright galaxies

We present full, high signal-to-noise LWS spectra of six infrared-bright galaxies in Figure 1. The LWS aperture is $\sim$ 75" (Swinyard *et al.*, 1998) and the spectral resolution is $\lambda/\Delta\lambda \sim 200$ in grating mode. The spectra are presented in sequence extending from strong [O III]52,88 μm and [N III]57 μm fine-structure line emission in the galaxies Arp 299 and M 82, to only faint [C II]158 μm line emission from gas in photo-dissociation regions in the prototypical ultraluminous galaxy Arp 220. The far-infrared spectrum of the ULIRG Arp 220 is dominated by absorption lines of OH, H_2O, CH, and [O I]. Intermediate in the sequence are Cen A, NGC 253, and NGC 4945, showing weak [O III] and [N III] lines while their PDR emission lines remain moderately strong. Interestingly, the strength and richness of the molecular absorption spectra is anti-correlated with the equivalent widths of the fine-structure emission lines. For example, M 82 shows faint OH absorption from the ground level at 119 μm (Colbert *et al.*, 1999), while NGC 253 shows absorption from the ground-state in three cross-ladder transitions and an emission line cascade at 79 μm and 163 μm (Bradford *et al.*, 1999). In NGC 4945 and Arp 220, OH absorption from both ground and excited rotational levels is present (Lord *et al.*, 1999; Fischer *et al.*, 1997). In Arp 220, although the existence of a downward cascade is suggested by the presence of emission at 163 μm, absorption from rotational levels as high as 416 K and 305 K above the ground state is seen for OH and H_2O, respectively, and the [O I]63 μm line is seen in absorption. Although the location of the excited molecules is not certain, OH and H_2O are expected to exist in abundance in dense photo-dissociation regions (PDRs) (Sternberg *et al.*, 1995), where they could be excited radiatively by the far-infrared emission from warm dust.

It is of interest to compare the far-infrared spectra of the archetypical Seyfert 2 galaxy NGC 1068 (Spinoglio *et al.*, 1999) and that of the Galactic Center (White *et al.*, 1999) with the spectra presented in Figure 1. The equivalent widths of the far-infrared fine-structure line emission in NGC 1068 resemble those in the starburst galaxy M 82. In addition to its Seyfert 2 nucleus, NGC 1068 hosts a starburst in its circumnuclear ring, that is possibly as young as the youngest clusters in M 82 (Davies *et al.*, 1998). This starburst may be responsible for much of the far-infrared emission, as suggested by Telesco *et al.* (1984). A notable difference is that in NGC 1068 the OH lines are observed in emission suggesting unique excitation conditions possibly related to its Seyfert 2 nucleus (see discussion in Spinoglio *et al.*, 1999), while in M 82 OH is observed in absorption (Colbert *et al.*, 1999). We note here that for Cen A (Unger *et al.*, 1999; Figure 1), also known to harbor an AGN, the weakness of the far-infrared [O III] lines may indicate

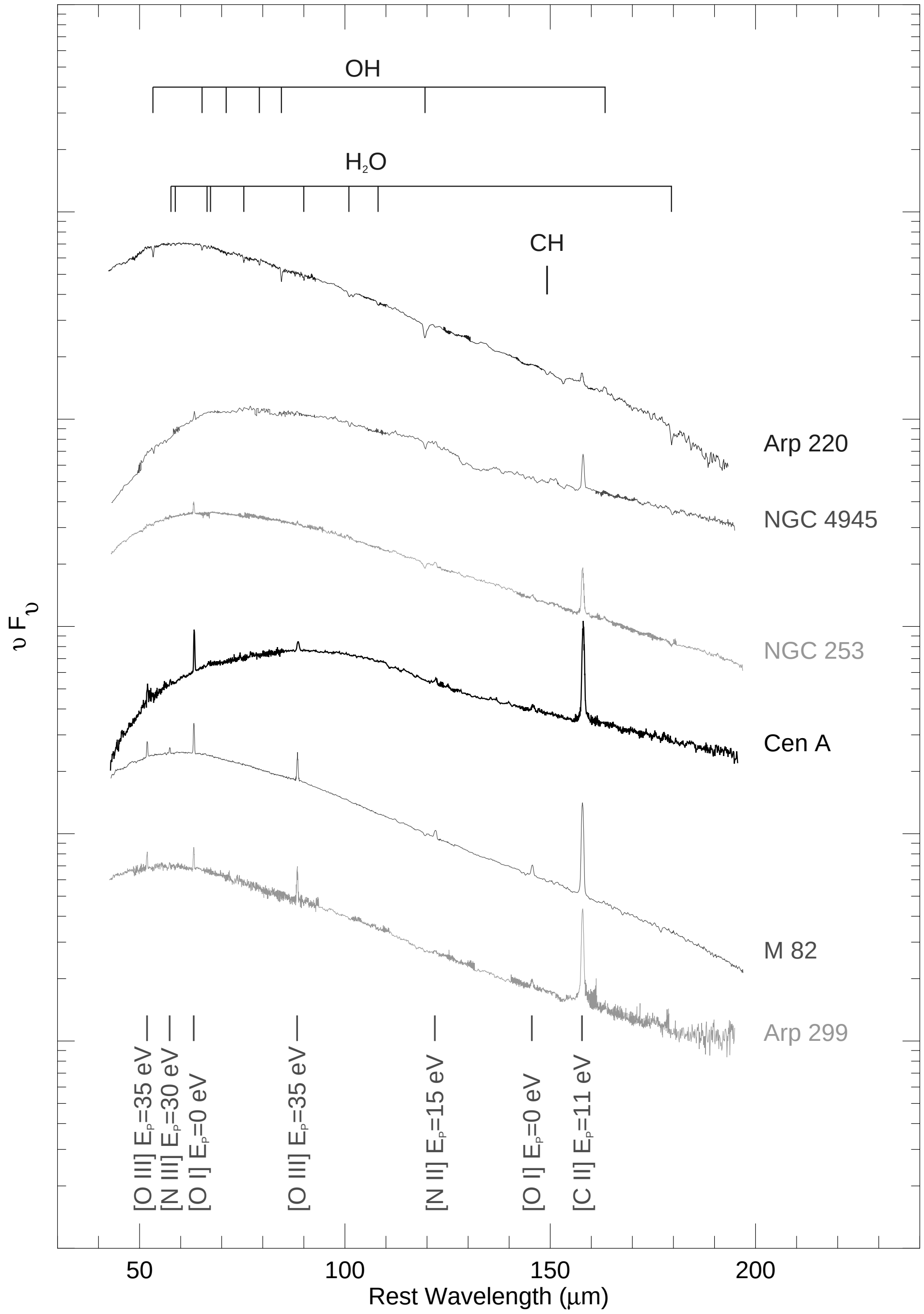

Figure 1. *The full ISO Long Wavelength Spectrometer spectra of six IR-bright galaxies. The spectra have been shifted and ordered vertically according to apparent excitation (Fischer et al. 1999) and are not in order of relative luminosity or brightness.*

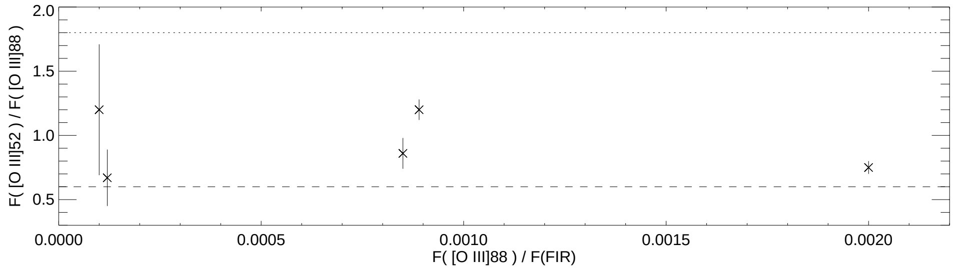

Figure 2. *The [O III]52μm/[O III]88μm line ratio versus the [O III]88μm line to integrated far-infrared continuum flux ratio for the sample galaxies. The dashed and dotted lines show the [O III] line ratio in the low density limit ($\leq$ 100 cm^{-3}) and for an electron density of 500 cm^{-3}, respectively (Fischer et al. 1999).*

that the AGN is not the dominant source powering the far-infrared luminosity. The far-infrared spectrum of the Galactic Center (White *et al.*, 1999) would fall toward the upper end of the sequence shown in Figure 1, with an added emission line component due to warm, perhaps shock-excited, neutral gas.

3. Parameterization of the far-infrared spectral sequence of IR-bright galaxies

The sequence shown in Figure 1 may be caused by variation of many parameters, but it is of interest to examine whether a single parameter or evolutionary effect can play the dominant role in the progression, and in particular to try to understand what conditions cause the ultraluminous galaxies to appear at the extreme end of the sequence.

In Figure 2 we plot the temperature-insensitive [O III]52/[O III]88 line ratio as a function of the [O III]88/F_{FIR} ratio for the galaxies in which [O III] line emission was detected in Figure 1. To within the uncertainties no clear dependence was found for our small sample and all of the measured [O III] line ratios fall within the range 0.6 - 1.2, consistent with electron densities between 100 - 500 cm^{-3}. These results suggest that neither density nor far-infrared differential extinction between 52 and 88 μm appears to be the *single dominant parameter* in the observed sequence (Fischer *et al.*, 1999). This is consistent with previous extinction estimates. Despite the inferred high column density of dust corresponding to A$_v \geq$ 1000, the estimated extinction *to the ionized gas* in Arp 220 is A$_v \sim$ 25-50 (Fischer *et al.*, 1997; Genzel *et al.*, 1998).

In Figures 3 and 4 we plot the [N III]57/[N II]122 and [O III]52/[N III]57 line ratios as a function of the [O III]88/F_{FIR} ratio for galaxies from Figure 1 (where these lines were detected). The excitation potentials of [N II],

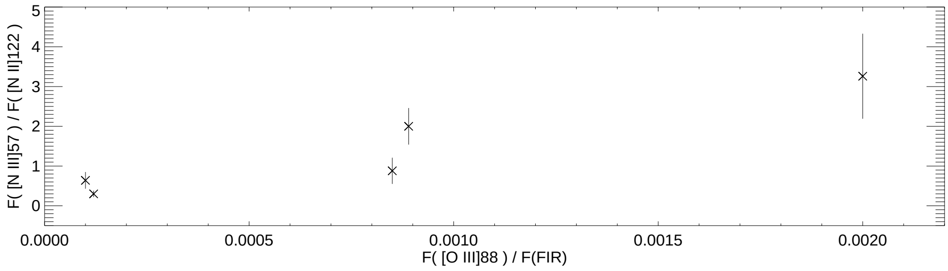

Figure 3. *As in Figure 2 for the [N III]57μm/[N II]122μm line ratio.*

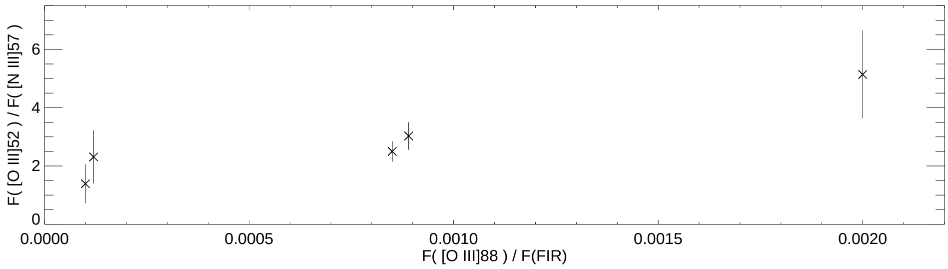

Figure 4. *As in Figure 2 for the [O III]52μm/[N III]57μm line ratio.*

[N III], and [O III] are 14.5, 29.6, and 35.1 eV, respectively. Thus for constant metallicity, both Figures 3 and 4 indicate that with progression to low relative emission line strength is a progression to lower excitation. Figure 4 strengthens our conclusion that far-infrared extinction is not responsible for the apparent excitation effects. The ionization parameter, defined as the ratio of ionizing photons to hydrogen atoms at the inner face of the cloud, plays a key role in determining ionization structure of clouds surrounding a source of ionizing radiation. It is equal to $\mathrm{Q}'(\mathrm{H})/4\pi r^2 n_H c$, where $\mathrm{Q}'(\mathrm{H})$ is the Lyman continuum rate absorbed by the gas and n_H is the hydrogen density at the inner radius, r, of the cloud. Thus if density effects alone do not explain the sequence, effects such as larger inner cloud radii due to stellar winds or lower $\mathrm{Q}'(\mathrm{H})/L_{Bol}$ due to dust within the HII regions or softer radiation fields may be responsible for the apparent excitation progression. If the latter is the case, and if starbursts are the source of the excitation, then an aging starburst or one with an IMF with a low upper mass limit could be present in the ultraluminous galaxies and other low excitation galaxies. Soft radiation fields or dusty H II regions may explain the presence of ubiquitous molecular material in close proximity to the nuclear regions of these galaxies and the prominent molecular absorption lines. It is difficult however, to reconcile the aging starburst interpretation with the high luminosity of the ultraluminous galaxies, since older starbursts have lower luminosities than their younger counterparts.

4. The far-infrared spectra of ULIRGs

The far-infrared spectrum of the second brightest ultraluminous galaxy Mkn 231 (Harvey *et al.*, 1999) is surprisingly similar to that of Arp 220 (to within the achieved signal-to-noise ratio). It is dominated by OH absorption, with similar OH absorption line ratios, and only faint PDR line emission is present. A single component absorption layer is inconsistent with the observed line ratios in these galaxies and fluorescent components do not alleviate the problem. The observed OH line ratios probably result from independent absorption and emission components (Suter *et al.*, 1998). Based on the mid-infrared spectra of a sample of nearby ULIRGs, Genzel *et al.* (1998) infer that Mkn 231 has a strong AGN component while the far-infrared luminosity of Arp 220 is powered by a starburst. Thus the similarity of the far-infrared spectra of these two ultraluminous galaxies is somewhat surprising.

The ultraluminous galaxies have lower [C II]158 μm line to far-infrared flux ratios than in normal and less luminous IR-bright galaxies by an order of magnitude (Luhman *et al.*, 1998; 1999). This has been interpreted as an indication of a lower value of the average interstellar radiation field $\langle G_o \rangle$ in Arp 220, where the upper limit for the [O I]145/[C II]158 emission line ratio is unexpectedly low (Fischer *et al.*, 1997; Luhman *et al.*, 1998). Implicit in this interpretation is the assumption that the [O I]145 μm upper limit is not affected by self-absorption, a reasonable assumption since the lower level of the [O I]145 μm line is 228 K above the ground state. On the other hand, if self-absorption is responsible for the apparent faintness of the [O I]145 μm line, then very high values of $\langle G_o \rangle$ are possible, as has been suggested by Malhotra *et al.* (1998) for a small percentage of their sample of normal galaxies. A plausible explanation for both low ionization parameters and low values of $\langle G_o \rangle$ is dusty H II regions. Low ionization parameters can be consistent with high $\langle G_o \rangle$ if molecular clouds surround very compact H II regions.

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