IR Fine-Structure Line Signatures of Central Dust-Bounded Nebulae in Luminous Infrared Galaxies

J. Fischer,[1] R. Allen,[1] C. C. Dudley,[1,2] S. Satyapal,[3] M. Luhman,[4]
M. Wolfire[5] & H. A. Smith[6]

ABSTRACT

To date, the only far-infrared spectroscopic observations of ultraluminous infrared galaxies have been obtained with the European Space Agency's Infrared Space Observatory Long Wavelength Spectrometer. The spectra of these galaxies are characterized by molecular absorption lines and weak emission lines from photodissociation regions (PDRs), but no far-infrared ($\lambda > 40$ μm) lines from ionized regions have been detected. ESA's Herschel Space Observatory, slated for launch in 2007, will likely be able to detect these lines in samples of local and moderate redshift ultraluminous galaxies and to enable measurement of the ionization parameters, the slope of the ionizing continuum, and densities present in the ionized regions of these galaxies. The higher spatial resolution of proposed observatories discussed in this workshop will enable isolation of the central regions of local galaxies and detection of these lines in high-redshift galaxies for study of the evolution of galaxies. Here we discuss evidence for the effects of absorption by dust within ionized regions and present the spectroscopic signatures predicted by photoionization modeling of dust-bounded regions.

[1]Naval Research Laboratory, Remote Sensing Division, 4555 Overlook Ave SW, Washington, DC 20375, USA, Jackie.Fischer@nrl.navy.mil

[2]NRL/NRC Research Associate

[3]George Mason University, Fairfax, VA

[4]Institute for Defense Analysis, Alexandria, VA, USA

[5]University of Maryland, College Park, MD, USA

[6]Harvard-Smithsonian, Center for Astrophysics, Cambridge, MA USA

1. Background

Prior to the launch of the European Space Agency's Infrared Space Observatory (ISO) in 1995, Voit (1992) showed how mid- and far-infrared fine-structure lines could be used to constrain the electron densities, extinction, and shape and ionization parameters of the central ionizing sources in ultraluminous infrared galaxies (ULIRGs). Moreover, the ground-based work of Roche et al. (1991) showed that the mid-IR spectra of the nuclei of galaxies could be placed into three classes: those with aromatic feature emission, featureless, and those with silicate absorption, typically associated with optically identified H II region, Seyfert 1, and Seyfert 2 nuclei respectively. Building on this early work on optically selected starburst and AGN galaxies, Genzel et al. (1998) constructed a diagnostic diagram of the ratio of high-to-low ionization fine-structure lines vs. the equivalent width of the 7.7 μm aromatic feature emission based on which they concluded that 70 - 80% of ULIRGs are powered predominantly by starbursts and 20 - 30% are powered by a central AGN. They attributed the weakness of the mid-infrared fine-structure lines relative to the infrared luminosity to the effects of extinction.

Far-infrared spectroscopy of a small sample of IR-bright and ultraluminous galaxies taken with the ISO Long Wavelength Spectrometer (LWS) has revealed a dramatic progression extending from strong fine-structure line emission from photoionized and photodissociated gas in the starburst galaxy Arp 299 (Satyapal et al. 2002) to faint [C II]158 μm line emission and absorption in lines of OH, H_2O, CH, and [O I] in the ULIRG Arp 220 (Figure 1; Fischer et al. 1999). With the progression towards weak emission line strengths, no trend in density or far-infrared differential extinction is indicated (Figure 2), i.e. the temperature-insensitive [O III]52 μm/[O III]88 μm line ratio does not show a trend with the ratio [O III]88 μm/FIR ratio as it would in either of these cases 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}. The sequence does show a trend toward lines with lower excitation potentials in the ratios [N III]57 μm/[N II]122 μm (Figure 3) and [O III]52 μm/[N III]57 μm (Figure 4). No FIR fine-structure line emission from species with excitation potentials greater than 13.6 eV were detected in Arp 220 or in Mkn 231 (Harvey et al. 1999), the two ULIRGs for which full ISO LWS spectra were taken. Voit (1992) discussed the possibility that even the mid- and far-infrared fine-structure lines would be weak in ULIRGs if they are formed in high ionization parameter regions. In such regions with high ratios of ionizing photon to electron densities, UV photons are preferentially absorbed by dust rather than gas, due to the high column densities of ionized gas in such regions. Bottorff et al. (1998) found that the L_{IR}/H_β ratios in such dust-bounded nebulae are

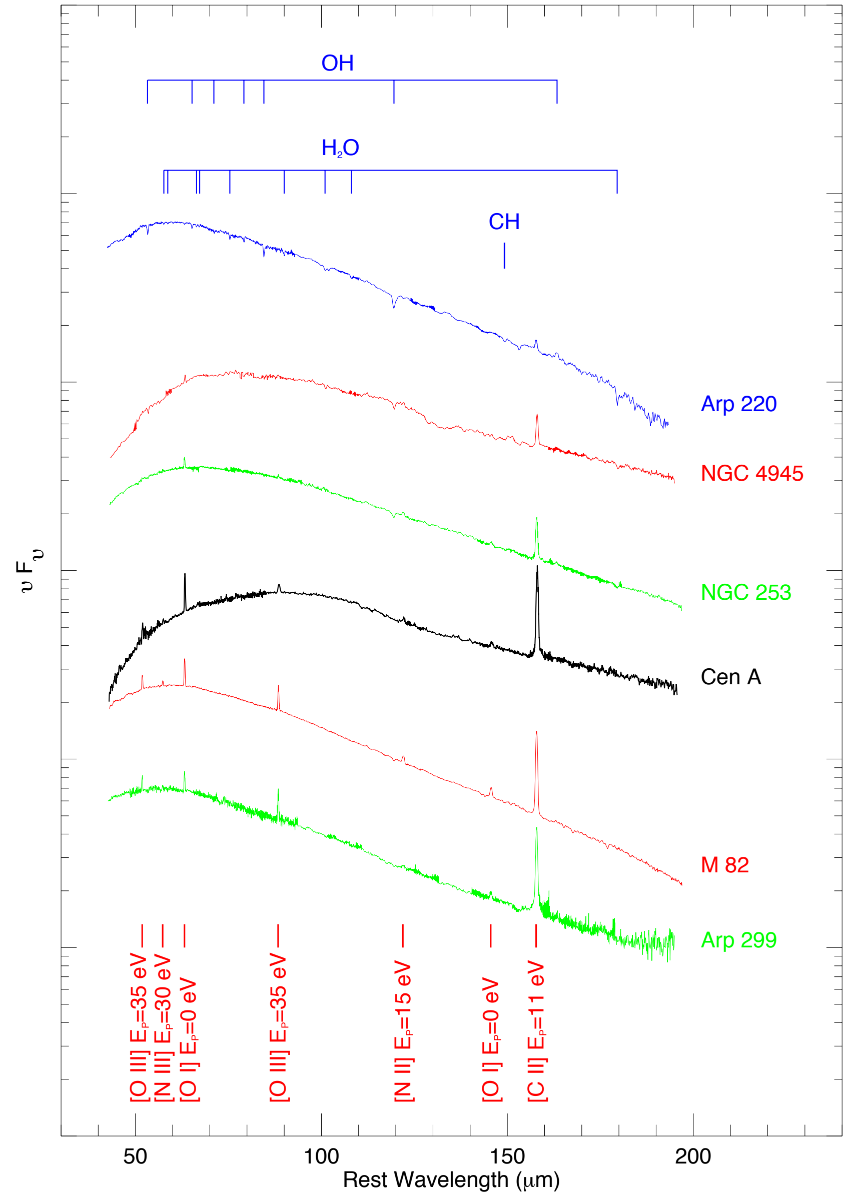

Fig. 1.— The full ISO Long Wavelength Spectrometer spectra of six IR-bright galaxies. The spectra have been shifted and ordered vertically according to the equivalent width of the [O III]88 μm line. The excitation potential, the energy required to create the species, is given in eV at the bottom of the figure. From Fischer et al. (1999).

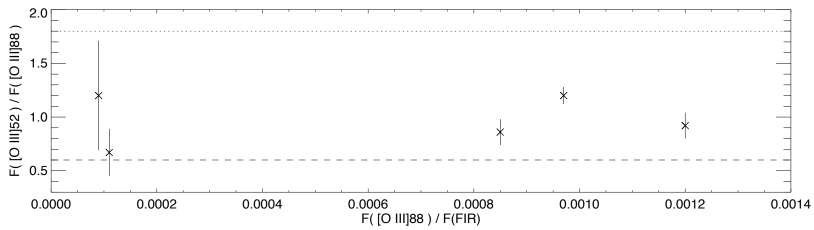

Fig. 2.— The [O III]52 μm/[O III]88 μm line ratio versus the [O III]88 μm line to integrated far-infrared continuum flux ratio for the sample galaxies. The dashed and dotted lines show the [O III] line ratio in the low density limit ($\leq 100\ cm^{-3}$) and for an electron density of 500 cm^{-3}, respectively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

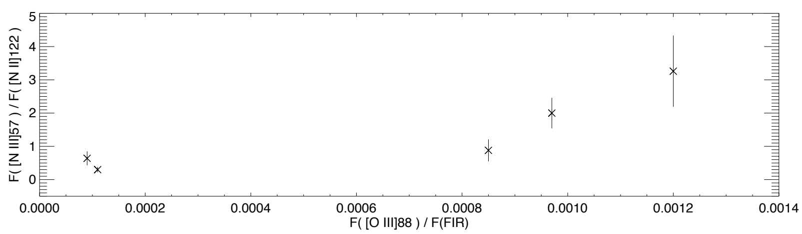

Fig. 3.— As in Figure 2 for the [N III]57 μm/[N II]122 μm line ratio.

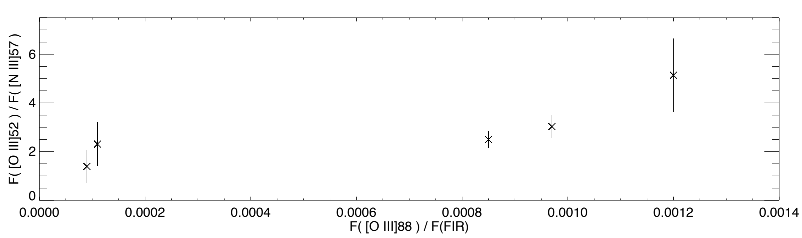

Fig. 4.— As in Figure 2 for the [O III]52 μm/[N III]57 μm line ratio.

greater than 100 for ionization parameters greater than 10^{-2}, density = 100 cm^{-3}, and stellar temperatures between 30,000 - 50,000 K.

Here we present photoionization models with starburst and power law ionization sources to predict the strengths of the fine-structure lines in dust-bounded nebulae and to compare them with the LWS spectra of the infrared-bright galaxies. Due to the weakness of the infrared fine-structure lines from photoionized gas in ULIRGs, ISO mid- and far-infrared spectroscopy produced mostly upper limits. Comparison of photoionization models of dust-bounded nebulae with spectra from future space missions such as SIRTF and Herschel will help to determine the conditions in the photoionized regions of these galaxies. The understanding yielded by these missions can then be used to probe the ionized media in high redshift galaxies by the missions being discussed in this workshop.

2. Photoionization modeling

The photoionization modeling was done using CLOUDY 94.01 (Ferland et al. 1998) for central power law (Figure 5) and instantaneous starburst (Figure 6) ionization sources. For power law models, the "table" power law option in CLOUDY was used. This option produces a continuum with $f_\nu \propto \nu^\alpha$ that is well behaved at both high and low energy limits (10^{-8} - 10^{8} Rydbergs in CLOUDY). An index α = -1.5 was used for the mid-range (10 μm - 50 keV), while the default indices of +2.5 and -2 were used for the low and high ranges, respectively. For the starburst models, we used the instantaneous, Salpeter IMF, 3 and 5 Myr aged burst models of Leitherer et al. (1999) with solar metallicity and standard mass loss. H II region abundances were used in CLOUDY.

With a central ionizing source, the ionization parameter, defined as the ratio of ionizing photons to hydrogen atoms at the inner face of the cloud, $U = Q/4\pi r^2 nc = N_{H\ II}\ \alpha_B\ /\ c$, where Q is the central Lyman continuum rate, n is the density, r is the inner radius of the cloud, and α_B is the Menzel case B recombination coefficient. It was varied from $10^{-3} - 10^{1}$ by setting $Q = 4.5 \times 10^{54}$ sec^{-1} and varying the inner radius from 30 - 1600 pc.

The power law models predict a decrease in the [N III]57 μm/[N II]122 μm and [Ne V]14 μm /[Ne III]15 μm line ratios in the high U cases. For the starburst models, only the far-infrared line ratio decreased at high U, over the range of parameters explored. In both cases the line-to-luminosity ratios drop at high U, as expected. As Figures 5 & 6 show, high densities also produce both lower values of the line ratios

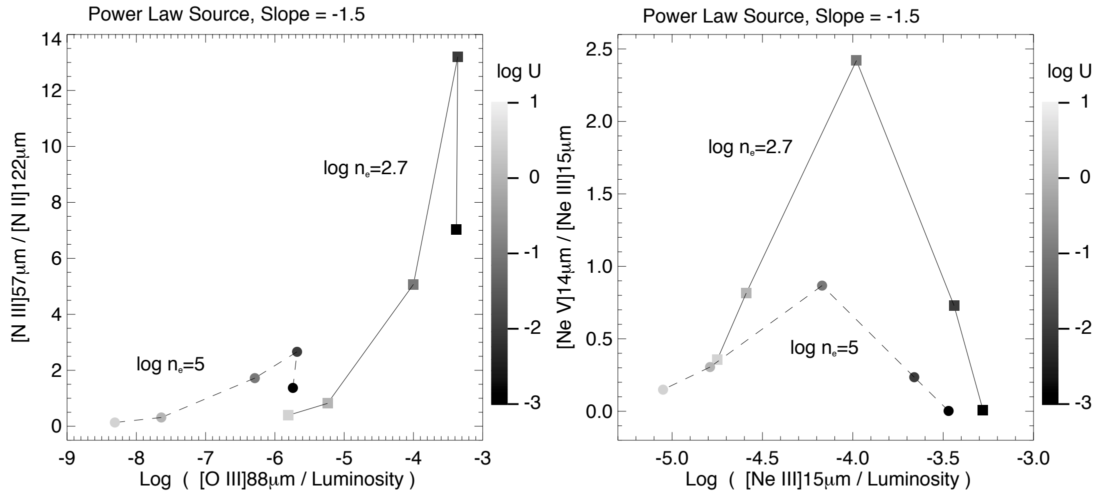

Fig. 5.— Far-infrared (left) and mid-infrared (right) line ratios vs. line-to-luminosity ratios for an AGN-like power law ionizing source for moderate (500 cm^{-3}) and high (10^5 cm^{-3}) densities are plotted for ionization parameters U, for log U = -3, -2, -1, 0, and 0.5 (as shown by the greyscale bar, right). See text for the details of the modeling.

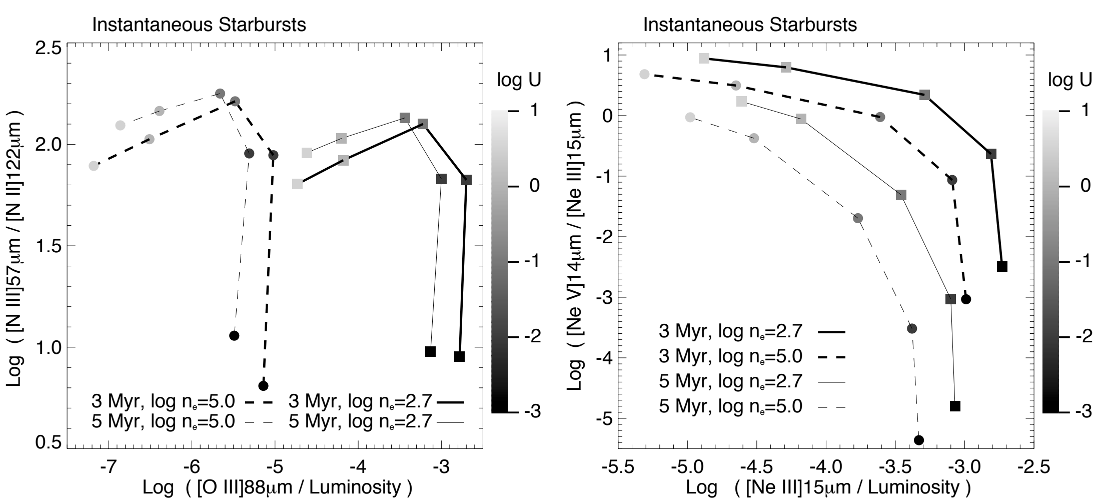

Fig. 6.— Same as Figure 5 (except for log scale in the line ratios), for ionization by instantaneous starbursts of ages 3 and 5 Myrs.

and lower line-to-luminosity ratios. Older starbursts can also produce these effects, but are unlikely to power ULIRGs (Satyapal et al. 2002).

3. The effects of high U on photodissociation region diagnostics

The CLOUDY models presented here show that under high U conditions, line emission ratios from ionization states below the dominant stage of ionization at the illuminated face of the cloud, i.e., from constituents deeper in the cloud, are often inverted compared with moderate ionization parameters due to the effects of the strong grain absorption. Some of the other infrared characteristics of ULIRGs are warm $60/100\,\mu$m colors, low aromatic feature-to-luminosity and low [C II]158 μm line-to-luminosity ratios, although their aromatic feature-to-[C II] ratios are normal (Dudley et al. 2002; Luhman et al. 2002). These characteristics may be the result of the effects of grains in ionized regions. For example in our own galaxy, Boulanger et al. (1988) find that $60/100\,\mu$m colors are higher and small grain emission lower, as traced by the IRAS $12\,\mu$m flux, within the California nebula H II region than outside of it.

SIRTF and Herschel studies will greatly improve our understanding of these diagnostics. SAFIR and future space-borne FIR/submillimeter interferometry will be able to exploit them in the high redshift universe to futher our understanding of the evolution of galaxies.

It is a pleasure to thank Gary Ferland for helpful discussions. This work was supported by the NASA Long Term Space Astrophysics program and the Office of Naval Research.

REFERENCES

Bottorff, M., Lamothe, J., Momjian, E., et al. 1998, PASP, 110, 1040

Boulanger, F., Beichman, C., Desert, F. X., et al. 1988, ApJ, 332, 328

Dudley, C. C., et al. 2002, in prep.

Ferland, G. J., Korista, K. T., Verner, D. A., et al. 1998, PASP, 110, 761

Fischer, J., Luhman, M. L., Satyapal et al. 1999, Ap&SS, 266, 91

Genzel, R. Lutz, D., Sturm, E., et al. 1998, ApJ, 498, 579

Harvey, V.I., Satyapal, S., Luhman, M.L, Fischer, J. et al. 1999, in *The Universe As Seen By ISO*, eds. P. Cox, M.F. Kessler, ESA SP-427, 889

Leitherer, C., Schaerer, D., Goldader, J. D. et al. 1999, ApJS, 123, 3

Luhman, M. L., Satyapal, S., Fischer, J., et al. 2002, ApJ, submitted.

Roche, P., Aitken, D., Smith, C. H., & Ward, M. 1991, MNRAS, 248, 606

Satyapal, S., Luhman, M. L., Fischer, J. et al. 2002, ApJ, submitted

Voit, G. M. 1992, ApJ, 399, 495