Spectroscopic Challenges of Photoionized Plasmas
ASP Conference Series, Vol. XXX, 2001
Gary Ferland and Daniel Wolf Savin, eds.

Photoionization Modeling of Infrared Fine-Structure Lines in Luminous Galaxies with Central Dust-Bounded Nebulae

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Abstract. Far-infrared spectroscopy of a small sample of IR-bright galaxies taken with the Infrared Space Observatory Long Wavelength Spectrometer has revealed a dramatic progression extending from strong fine-structure line emission from photoionized and photodissociated gas in the starburst galaxy Arp 299 to faint [C II]158 μm line emission and absorption in lines of OH, H_2O, CH, and [O I] in the ultraluminous galaxy Arp 220. The progression to weaker emission lines is accompanied by lower excitation and does not appear to be due to far-infrared extinction or density effects. Although aging of short duration starbursts with a relatively small range in age might explain much of the sequence, the spectra of Arp 220 and other ultraluminous galaxies may be more reasonably explained by high ionization parameter, dust-bounded nebulae. To test this hypothesis, we ran photoionization models of mid- and far-infrared lines for power law (index -1.5) and starburst cases with moderate (500 cm^{-3}) and high (10^5 cm^{-3}) densities. Indeed, we find that for dust-bounded nebulae and photoionization by a power law source, the relative emission line strengths and the high-to-low ionization infrared line ratios decrease with ionization parameter. For starburst ionization sources and dust-bounded nebulae, the [N III]57 μm/[N II]122 μm line ratio is found to drop with ionization parameter.

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. 2001) 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 (Fischer et al. 1999). With the progression towards weak emission line strengths, the sequence shows a trend toward lines with lower excitation potentials in the ratios [N III]57 μm/[N II]122 μm and [O III]52 μm/[N III]57 μm. No FIR fine-structure line emission from species with excitation potentials greater than 13.6 eV were detected in Arp 220. These trends do not appear to be primarily due to either differential far-infrared extinction between 52 and 88 μm or density effects, since 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} (see Fischer et al. for details). 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 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

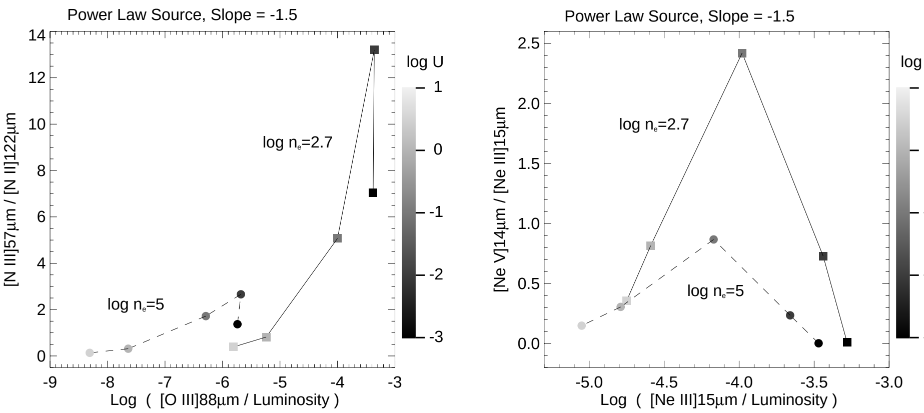

Figure 1. Far-infrared (left) and mid-infrared (right) line ratios vs. line-to-luminosity ratios for an AGN-like power law ionizing source for moderate (500 cm^{-3}) and high (10^5 cm^{-3}) densities are plotted for ionization parameters U, for log U = -3, -2, -1, 0, and 0.5 (as shown by the greyscale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

spectra from future space missions such as SIRTF and Herschel will help to determine the conditions in the photoionized regions of these galaxies.

2. Photoionization modeling

The photoionization modeling was done using CLOUDY 94.01 (Ferland et al. 1998) for central power law (Figure 1) and instantaneous starburst (Figure 2) 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 U, defined as the ratio of ionizing photons to hydrogen atoms at the inner face of the cloud, is equal to $Q/4\pi r^2 nc$, where Q is the central Lyman continuum rate, n is the density, and r is the inner radius of the cloud. 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. These effects make it difficult to distinguish between AGN and starbursts. As Figures 1 & 2 show, high densities also produce both lower values of the line ratios and lower line-to-luminosity ratios. Older starbursts can also produce these effects, but are unlikely to power ULIRGs (Satyapal et al. 2001).

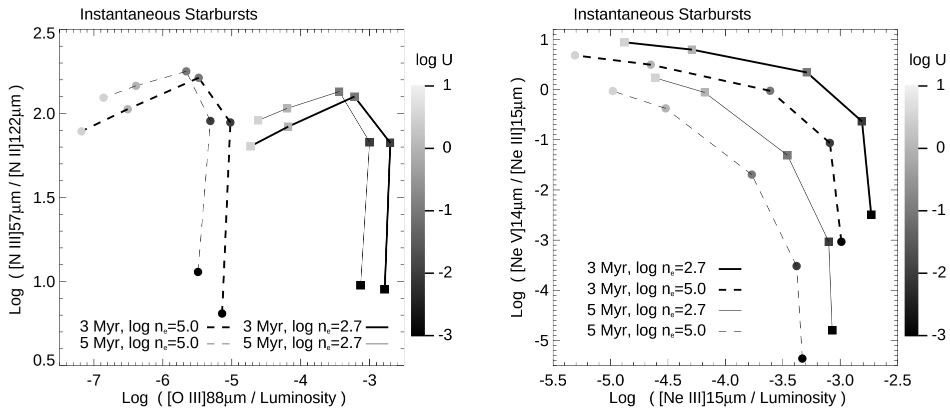

Figure 2. Same as Figure 1 (except for log scale in the line ratios), for ionization by instantaneous starbursts of ages 3 and 5 Myrs.

3. The effects of high ionization parameters on photodissociation region diagnostics

Some of the other infrared characteristics of ULIRGs are warm 60/100 μm 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. 2001; Luhman et al. 2001). These characteristics may be the result of the effects of grains in ionized regions. For example, Boulanger et al. (1988) find that 60/100 μm colors are higher and small grain emission lower, as traced by the IRAS 12 μm flux, within the California nebula H II region than outside of it.

Acknowledgments. It is a pleasure to thank Gary Ferland for helpful discussions on the use of CLOUDY and Michael Shadid for his early work on this project. This work was supported by the Office of Naval Research and the NASA Long Term Space Astrophysics program.

References

Bottorff, M., et al. 1998, PASP, 110, 1040

Boulanger, F., et al. 1988, ApJ, 332, 328

Dudley, C. C., et al. 2001, in prep.

Ferland, G. J., et al. 1998, PASP, 110, 761

Fischer, J., et al. 1999, Ap&SS, 266, 91

Genzel, R., et al. 1998, ApJ, 498, 579

Leitherer, C., et al. 1999, ApJS, 123, 3

Luhman, M. L., et al. 2001, in prep.

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

Satyapal, S., et al. 2001, ApJ, submitted

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