Dust-Bounded ULIRGs?
Model Predictions for IR Spectroscopic Surveys

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Summary and Conclusions

In preparation for Herschel, SPICA, and JWST mid- and far-infrared spectroscopic studies, we explore the suggestion that the effects of high ratios of impinging ionizing radiation density to particle density (i.e. high ionization parameters, *U*) are responsible for many of the infrared spectral properties of ultraluminous infrared galaxies (ULIRGs) such as the faintness of the infrared fine-structure line emission, including the well known "[C II] deficit", and their warm far-infrared colors. We present a theoretical study of the emergent line and continuum properties of a cloud exposed to an ionizing continuum characteristic of an Active Galactic Nucleus (AGN) or starburst, taking into account the ionized, atomic and molecular environments under conditions of pressure balance. For both starburst and AGN input spectral energy distributions, we calculate how the spectrum changes with variations in *U* and compare the trends found with data in the literature. Our calculations show that high *U* effects can explain the nearly order of magnitude drop in the [C II] 158μm/FIR ratio observed with the ISO LWS in ULIRGs and other warm galactic nuclei with high IRAS *F*(60μm)/*F*(100μm) ratios. High *U* effects also produce increases in the [O I]63μm /[C II] ratio similar to the magnitude of the trends observed, a gradual decline in the [O III]88μm/FIR and a reasonable fit to the observed Spitzer [Ne V]14μm /FIR ratio in AGN. Future missions will allow detections of the characteristically faint lines in ULIRGS and better isolation of the nuclear regions in nearby normal galaxies.

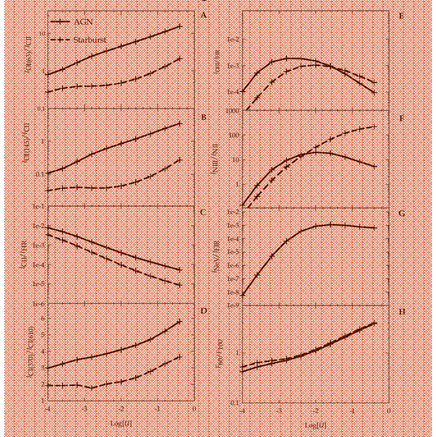
Background:

What is responsible for the observed line deficits and color differences between ULIRGs and other galaxies? Malhotra et al. (1997, 2001) attributed many of the effects seen in warm (high 60/100 ratio) galaxies including ULIRGs, to high ratios of G_0/n in the neutral galactic medium, where G_0 is the incident far-UV (FUV) radiation field, normalized to the average local interstellar radiation field, and n is the hydrogen gas density. A more general idea proposed in Luhman et al. (2003) to explain deficits from lines that trace the ionized medium as well as the neutral medium, is that ULIRGs are characterized by a higher ionization parameter (U) than in normal and starburst galaxies, where the ionization parameter U is defined as the dimensionless ratio of the incident ionizing photon density to the hydrogen density in the H^+ region:

$$U \equiv \frac{\phi_H / c}{n(H^+)} = \frac{Q(H)}{4\pi R^2 n(H^+) c}$$

where ϕ_H is the flux of hydrogen ionizing photons striking the illuminated face of the cloud per second, $n(H^+)$ is the hydrogen density at the illuminated face of the H^+ region, $Q(H)$ is the number of hydrogen ionizing photons striking the illuminated face per second, and R is the distance of the ionizing source to the illuminated face. In a grain free Stromgren slab of length L, $N(H^+) = n(H^+)\,L \approx U \times 10^{23}$, so for $U > 10^{-2}$ the UV extinction due to dust will exceed unity, i.e. the region will be "dust-bounded" (eg. Voit 1992, Bottorff et al. 1998, Abel et al. 2003). The physical explanation for increased dust absorption is that, for a fixed $n(H^+)$, as the flux of hydrogen ionizing photons increases the size of the surrounding H^+ region increases and therefore so does $N(H)$. If the gas and dust are mixed, then increasing $N(H)$ also increases the dust column density N_d. Increasing N_d increases the dust opacity in the ionized gas. Dust then absorbs an increasing number of photons in the ionized gas, reducing the size of the H^+ region relative to a region which is free of dust. Increased dust opacity decreases the number of photons available for photoabsorption by the gas, warming the gas and reducing the line to FIR continuum ratio.

Figure 1



Predicted emission line and line-to-continuum ratios as a function of *U* and SED.

Methods:

The calculations presented in Figs. 1 & 2, use the developmental version of the spectral synthesis code *Cloudy*, assuming:

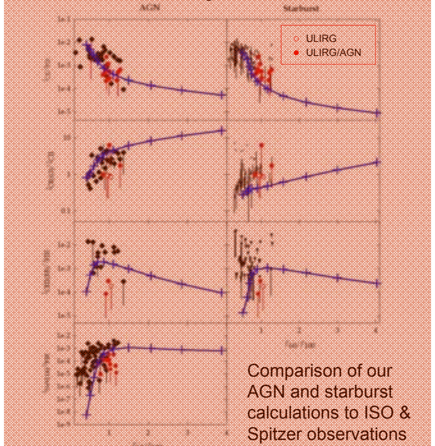
- **constant pressure, with thermal, radiation, and magnetic pressure contributing to the total pressure; beginning at $U = -0.4$, radiation pressure dominates in the ionized gas; beyond the ionized region, magnetic pressure dominates**
- **a hydrogen density of $n(H^+) = 10^3\ cm^{-3}$ at the illuminated face.**
- **a magnetic field in the ionized gas of 300 μG; we use the density-magnetic field relationship given in Crutcher (1999)**
- **$A_V = 100$ mag; there, magnetic pressure dominates thermal & radiation pressure**
- **Fig. 2 compares the models with Spitzer & ISO data (FIR data is from Brauher, Dale, & Helou 2008 and Luhman et al. 2003 for ULIRGs.)**

Future Missions:

Herschel spectroscopy of normal/starburst galaxies, AGN and ULIRGs will allow us to better understand the dust-bounded and other phenomena in galactic nuclei, with its factor of > 5 higher spatial resolution, order of magnitude higher spectral resolution, and higher sensitivity. Deep line spectroscopy of atomic fine structure and molecular lines for all 21 ULIRGs in the RBGS is planned.

Interferometers such as SPIRIT will allow isolation of the central 5 parsecs of the nuclear regions in the nearest AGN and starburst galaxies at 100 microns with its factor of 200 improvement over ISO in spatial resolution! In Arp 220, [OIII]88/FIR < 10^{-4} (3σ) and in Mrk 273 [NeV]14,24/FIR ~ 3×10^{-5}. At z=3, these ULIRGs would have line fluxes of [OIII]88 (UL/5) ~ 3×10^{-21} and [NeV]14,24 ~ 6×10^{-21} W m^{-2}, both achievable with a large cryogenic telescope such as CALISTO.

Figure 2



Comparison of our AGN and starburst calculations to ISO & Spitzer observations from the literature.

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