Far-Infrared Line Deficits in Ultraluminous Infrared Galaxies

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ABSTRACT

We study the origin of the [O I] 63, [N II] 122, [O I] 145, and [C II] 158 line deficits in $z < 0.3$ Ultraluminous Infrared Galaxies, using data from *Herschel*. The line deficits are consistent with arising from increased quantities of dust in H II regions, but part of the [C II] deficit may arise from an additional mechanism, plausibly increased grain charging. We briefly discuss some implications from these results for *SPICA*.

1. INTRODUCTION

Ultraluminous Infrared Galaxies (ULIRGs, $L_{\rm IR} > 10^{12}\,{\rm L}_\odot$, e.g. Lonsdale et al. 2006) at $z \lesssim 0.3$ are invariably observed to exhibit emission from the following four far-infrared fine-structure lines: [O I] at 63 μm, [N II] at 122 μm, [O I] at 145 μm, and [C II] at 158 μm. All four of these lines however show a deficit in their luminosities (as parameterized by the $L_{\rm Line}/L_{\rm IR}$ ratio) compared to the ratios expected from systems with lower values of $L_{\rm IR}$ (e.g. Luhman et al. 2003). In contrast, ULIRGs at $z \gtrsim 1$ do not show such pronounced deficits (e.g. Stacey et al. 2010), at least for [O I]63 and [C II]. The origin of the line deficits among low-redshift ULIRGs is controversial. Determining their cause may give insight into how different atomic and molecular features trace emission from H II regions, PDRs and the ISM, and into how different far-IR lines trace star formation as a function of redshift. We here explore the origin of these far-IR line deficits via observations of the [O I], [N II] and [C II] lines in 25 ULIRGs at $z < 0.27$, using data from the *Herschel* observatory. This study is part of the HERUS program (Efstathiou et al. 2013; Farrah et al. 2013; Spoon et al. 2013).

2. RESULTS & DISCUSSION

We find a deficit in all four lines (Figure 1), with average ratios (compared to lower luminosity systems) of 2.75, 4.46, 1.50, and 4.95 for [O I]63, [N II], [O I]145, and [C II], respectively. The deficits show no dependence on the presence of an AGN, as diagnosed via either optical spectral type or the detection of the [Ne V] line at 14.32 μm.

To investigate the far-IR line deficits further, we employ three comparison variables; the silicate dust feature at 9.7 μm ($S_{\rm Sil}$), merger stage, and PAH luminosity (see Farrah et al. 2013 for definitions). For $S_{\rm Sil}$ we see the following. There is no trend of the [O I] deficits with $S_{\rm Sil}$. For the [C II] and [N II] deficits however there is a trend; if $S_{\rm Sil} \gtrsim 1.4$ then the [C II] and [N II] deficits increase as $S_{\rm Sil}$ increases (e.g. lower middle panel of Figure 1). There is however no trend of the [C II] and [N II] deficits with $S_{\rm Sil}$ if $S_{\rm Sil} \lesssim 1.4$. Turning to merger stage; we find no evidence that the [N II] and [O I] deficits depend on merger stage, but the [C II] deficit is stronger in advanced mergers than in early-stage mergers (lower right panel of Figure 1). We checked for degeneracies between $S_{\rm Sil}$ and merger stage by examining the [C II] deficit as a function of merger stage using only those sources with $S_{\rm Sil} < 1.4$. We found that the [C II] deficit still strengthens with advancing merger stage. Finally, for PAH luminosity; ULIRGs in advanced mergers and with $S_{\rm Sil} \gtrsim 2$ have comparably low $L_{\rm PAH}/L_{\rm IR}$ and $L_{\rm [CII]}/L_{\rm IR}$ ratios, compared to ULIRGs in early-stage stage mergers and with $S_{\rm Sil} \simeq 1.4$–2 (Figure 2).

If we assume that $S_{\rm Sil}$ is a proxy for the dust column in H II regions, then the stronger [C II] *and* [N II] deficits in sources with higher $S_{\rm Sil}$ (at $S_{\rm Sil} \gtrsim 1.4$) are consistent with an origin connected to dust column and gas ionization in H II regions. In this scenario (e.g. Luhman et al. 2003; González-Alfonso et al. 2008; Abel et al. 2009; Graciá-Carpio et al. 2011), a higher fraction of the UV photons are absorbed by dust rather than gas, either because there is more dust and/or because the gas is so highly ionized that it cannot absorb more UV photons. Thus, the UV photons contribute more to $L_{\rm IR}$ but less to gas heating in the H II regions, thus decreasing line emission relative to $L_{\rm IR}$. Another possible contributing mechanism is that the dust in *compact* H II regions is likely warmer than the dust in diffuse H II regions, hence the IR emission from the dust in the compact regions will be higher for the same mass of gas. These mechanisms would also produce a deficit in [C II] and the 'deficit' in the PAH emission, even if the bulk of the [C II] and PAHs are in the PDRs, since there would be fewer UV photons for photoelectric heating of the PDRs. Furthermore, this mechanism is consistent with the [O I] deficits. From Figure 3 of Graciá-Carpio et al. (2011) the conditions consistent with the deficits of all four lines are $n \lesssim 300{\rm cm}^{-3}$ and $0.01 \lesssim \langle U \rangle \lesssim 0.1$.

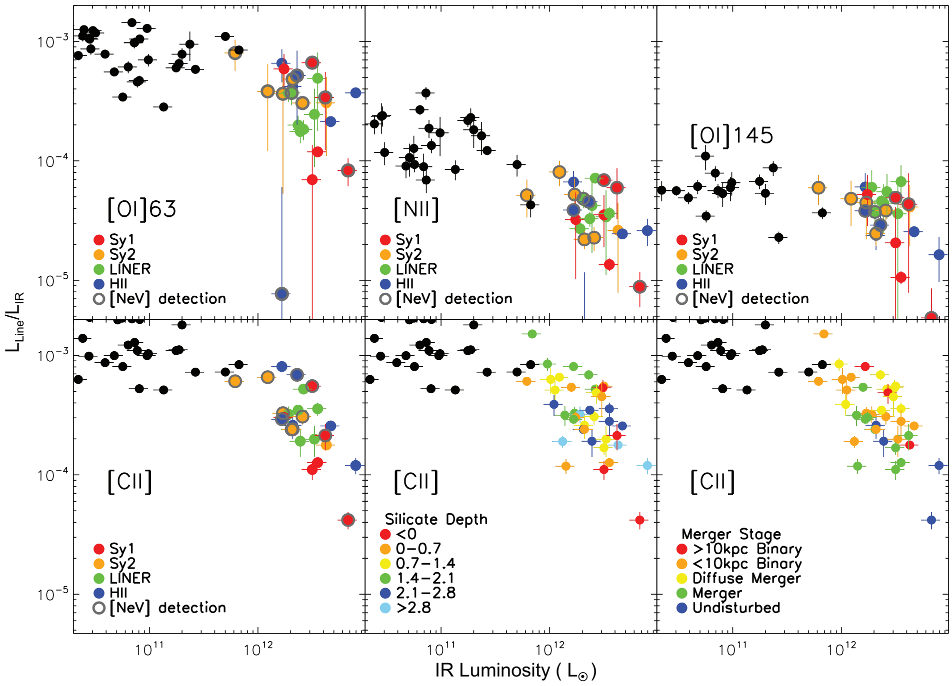

Figure 1. The [O I] 63, [N II], [O I] 145, and [C II] ratios vs. $L_{\rm IR}$. In each panel, the colored points are our sample, while the black points are from Brauher et al. (2008). The top row shows the line deficits in [O I] and [N II], coded by optical class. Objects with an [Ne V] detection are marked. The bottom row shows the deficit in [C II] coded by optical class, merger stage, and 9.7 μm silicate strength.

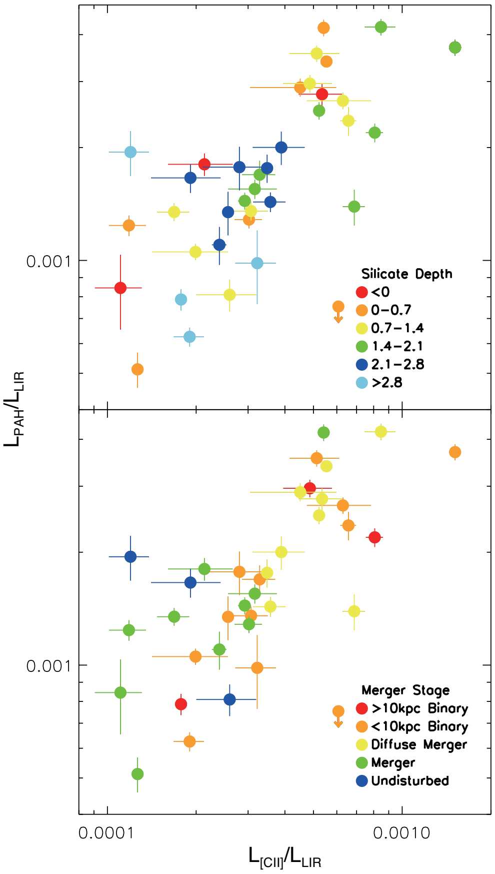

Figure 2. The [C II] deficit vs. the $L_{\rm PAH}/L_{\rm IR}$ ratio, coded by merger stage and $S_{\rm Sil}$.

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There are however two observations that are inconsistent with dustier/more ionized H II regions being the *sole* origin of the line deficits. First, none of the deficits depend on $S_{\rm Sil}$ when $S_{\rm Sil} \lesssim 1.4$; if the deficit arises entirely in H II regions then we should see a dependence. The assumption that $S_{\rm Sil}$ is a proxy for dust column in H II regions is however not proven. In particular, if $S_{\rm Sil}$ does not act as such a proxy at $S_{\rm Sil} \lesssim 1.4$ then no dependence would be seen. Second, while the [C II] deficit is stronger in advanced mergers, no other line shows a dependence on merger stage. If we assume that advanced mergers host dustier H II regions to explain the rising [C II] deficit, then the [N II] deficit should also depend on merger stage. Thus, part of at least the [C II] deficit likely does not arise due to dustier and/or more highly ionized H II regions.

We consider three possible additional contributors to the [C II] deficit. First is increased dust grain charging (e.g. Malhotra et al. 2001), leading to a lower gas heating efficiency. Second is a softer UV field in the ISM (e.g. Spaans et al. 1994), leading to reduced relative [C II] emission. Third is increased gas density and/or UV field intensity in the PDRs, making [O I] rather than [C II] the primary coolant.

The third possibility is feasible, but we do not have the data to investigate it. The second possibility is unlikely, from the arguments in Luhman et al. (2003). For the first possibility; if the origin of the additional deficit in [C II] is grain charging, then we would see a higher G_0 in advanced mergers compared to early stage mergers. From Figure 18 of Farrah et al. (2013) the advanced mergers have an order of magnitude higher G_0 for about the same n. We therefore *cautiously* infer, with the caveat that we cannot rule out [O I] providing cooling, that part of the [C II] deficit may arise due to increased grain charging. We further propose that this effect is not driven by AGN activity, since the [C II] deficit does not depend on either optical spectral type or the presence of [Ne V] 14.32.

3. PROSPECTS FOR *SPICA*

Our results suggest that determining the origin of *each* line deficit is key to using infrared spectroscopy to trace star formation across the history of the Universe. By combining *Spitzer* and *Herschel* data, we have shown that there may be multiple origins for these line deficits, but we lack key diagnostic features that are often not detected in low-z ULIRGs, even with *Spitzer* and *Herschel*. *SPICA*, by assembling high S/N spectra covering the key diagnostic features at 5–35 μm and 60–180 μm for hundreds of low-z ULIRGs, can conclusively determine the origin of the far-IR line deficits. Example diagnostics include:

- **A wider census of line deficits,** by observing, across large samples spanning $10^{10} < L_{\rm IR} < 10^{13}$, a greater number of lines than was possible with *Herschel*. Key additional diagnostics are the [N II] 205 & [O III] 88 lines.
- **The contribution from [O I] in PDRs.** *SPICA* will determine how self-absorption in the [O I] 63 line affects the observed line flux, and to see if the degree of self absorption correlates with the observed deficit. This will quantify the importance of [O I] as a coolant in PDRs.
- **The importance of heating from molecular Hydrogen,** via measurements of multiple mid-IR H_2 lines. Current constraints from *Spitzer* are relatively poor (Higdon et al. 2006).
- **The role of ionization conditions in H II regions:** Determine excitation conditions in the H II regions simultaneously from Neon, Sulfur and Silicon line ratios, to see how these conditions correlate with far-IR line deficit strength.

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