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What drives the [CII]/FIR deficit in submillimeter galaxies?

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Abstract. Submillimeter galaxies at redshift $z \geqslant 1$ show a pronounced [CII]/FIR deficit down to sub-kpc scales; however, the physical origin of this deficit remains poorly understood. We use resolved ALMA observations of the [CII], FIR and CO(3–2) emission in two $z = 3$ SMGs to distinguish between the different proposed scenarios; the thermal saturation of the [CII] emission is the most likely explanation.

Keywords. galaxies: high-redshift, galaxies: ISM, submillimeter

1. Introduction

Intrinsically bright and easy to excite, the [CII] 158-μm line has become a key probe of gas in submillimeter galaxies (SMGs) and a potentially powerful tracer of their star-formation and gas content. But the interpretation of the [CII] emission in SMGs complicated by the so-called [CII]/FIR deficit: the [CII]/FIR luminosity ratio decreases at high star-formation rate surface densities ($\Sigma_{\rm SFR}$). Indeed, recent resolved ALMA observations of $z \simeq 2-5$ SMGs have revealed a pronounced [CII]/FIR deficit ($L_{\rm [CII]}/L_{\rm FIR} = 10^{-4} - 10^{-3}$) down to sub-kpc scales (Fig. 1a).

Although several potential mechanisms for the [CII]/FIR deficit have been proposed (see below), distinguishing between them requires knowing the FUV field strength (G) and gas density ($n_{\rm H}$). While source-averaged G, $n_{\rm H}$ in SMGs have been inferred using e.g. unresolved [CII], FIR and CO observations, these can be biased as different tracers are not generally co-spatial.

2. Results and implications

We observed two z=3 SMGs – ALESS 49.1 and ALESS 57.1. – with ALMA in the [CII] and FIR continuum (Band 8, 0.15" resolution; Rybak *et al.* 2019) and CO(3–2) (Band 3, 0.6" resolution; Calistro-Rivera *et al.* 2018). Both sources show a pronounced [CII]/FIR deficit ($10^{-4} - 10^{-3}$) at 1-kpc scales (Fig. 1a), falling below the Smith *et al.* (2017) empirical trend. Concentrating on the central star-forming regions (R $\leqslant$ 2 kpc), we use the PDRToolbox photon-dominated region (PDR) models (Kaufman *et al.* 2006; Pound & Wolfire 2008) to infer G, $n_{\rm H}$ from the observed [CII]/FIR and [CII]/CO(3–2) ratios. We find $G = 10^4\ G_0$ and $n_{\rm H} = 10^4 - 10^5$ cm^{-3}, significantly higher than the source-averaged values for both $z \sim 0$ ULIRGs and high-z SMGs (Fig. 1b).

We now consider the following mechanisms for the [CII]/FIR deficit:

- **AGNs** can suppress the [CII] emission by further ionizing C$^+$ via soft X-rays, while boosting the FIR luminosity. However, the AGN X-ray luminosities in ALESS 49.1 and 57.1 correspond to a sphere of influence on the order of 100 pc, insufficient to explain the observed [CII]/FIR deficit over scales of few kpc.

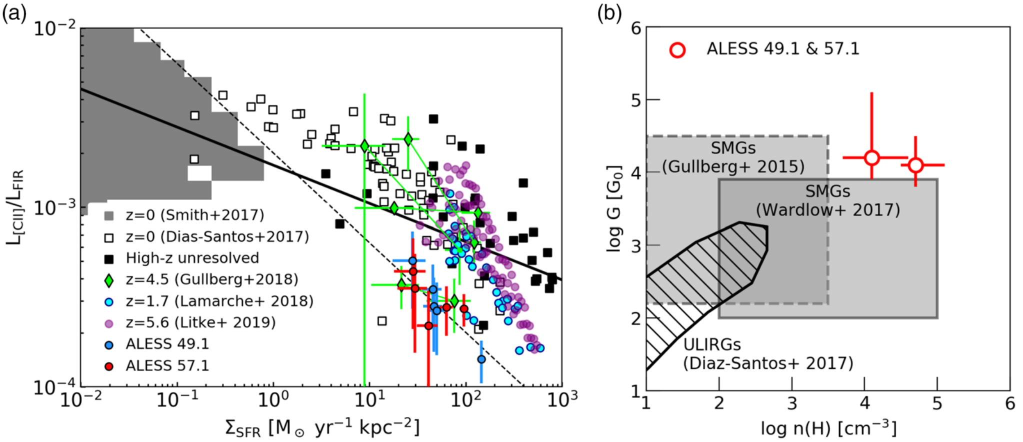

Figure 1. a): [CII]/FIR deficit in ALESS 49.1 and 57.1, compared to other $z \sim 0$ and high-redshift measurements, the empirical trend of Smith *et al.* (2017; solid line) and the thermal saturation prediction (Muñoz & Oh 2016; dashed line). **b)**: G and $n_{\rm H}$ in ALESS 49.1 and 57.1, compared to $z \sim 0$ ULIRGs and unresolved SMGs studies.

- **Positive grain charging** will reduce the photoelectric gas heating. However, although the inferred G, $n_{\rm H}$ in ALESS 49.1 and 57.1 imply substantial grain charging, the photoelectric heating is not significantly reduced.
- **Dust-bounded HII regions** where UV photons are absorbed by the dust instead of heating the gas will result in increased $L_{\rm FIR}$ and decreased $L_{\rm [CII]}$. However, the radiation pressure in ALESS 49.1 and 57.1 will expel the dust out of HII regions in $\sim 10^5$ yr, making them too short-lived to drive the [CII]/FIR deficit.
- **Thermal saturation**. At $T_{\rm gas} \gg 91$ K, the C^+ fine-structure upper-level occupancy (and $L_{\rm [CII]}$) depends only weakly on temperature (Muñoz & Oh 2016). Our PDR models imply cloud surface temperatures of $400-700$ K, indicating the [CII] emission is thermally saturated. Moreover, fitting a power-law to our data from Fig. 1a yields a best-fitting slope $\gamma = -0.5 \pm 0.1$), in agreement with the thermal saturation model ($\gamma = -0.5$).

These results imply that the pronounced [CII]/FIR deficit in SMGs is driven by the C^+ temperature saturation due to the strong FUV fields. Although limited by the sample size, this study highlights the need for resolved studies of physical conditions in SMGs, and presents a necessary stepping stone to future resolved [CII]/FIR/CO studies for representative samples of SMGs.

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