

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

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Abstract. Submillimeter galaxies at redshift $z \geq 1$ 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 is complicated by the so-called [CII]/FIR deficit: the [CII]/FIR luminosity ratio decreases at high star-formation rate surface densities (Σ_{SFR}). Indeed, recent resolved ALMA observations of $z \simeq 2 - 5$ SMGs have revealed a pronounced [CII]/FIR deficit ($L_{[\text{CII}]} / L_{\text{FIR}} = 10^{-4} - 10^{-3}$) 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_{H}). While source-averaged G , n_{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 ($R \leq 2$ kpc), we use the PDRTOLBOX photon-dominated region (PDR) models (Kaufman *et al.* 2006; Pound & Wolfire 2008) to infer G , n_{H} from the observed [CII]/FIR and [CII]/CO(3–2) ratios. We find $G = 10^4 G_0$ and $n_{\text{H}} = 10^4 - 10^5 \text{ cm}^{-3}$, 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.

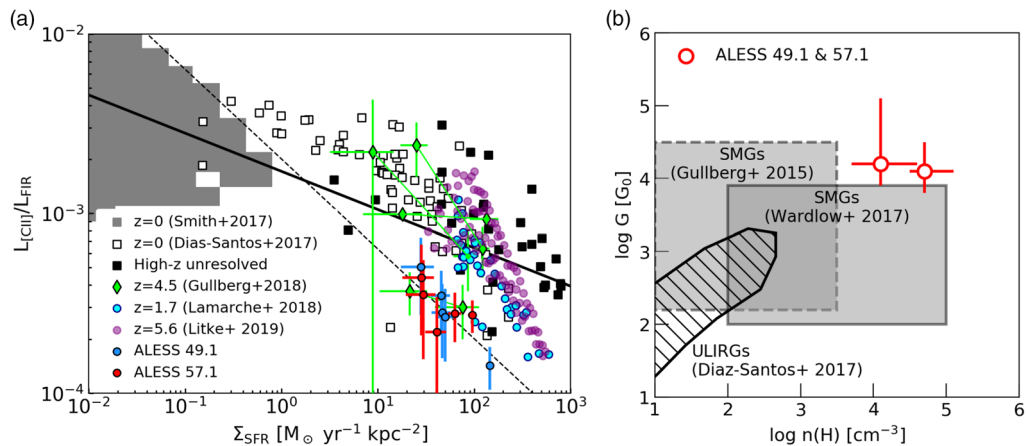


Figure 1. a): [CII]/FIR deficit in ALESS 49.1 and 57.1, compared to other $z \sim 0$ and high-redshift measurements, the empirical trend of Smith *et al.* (2017; solid line) and the thermal saturation prediction (Muñoz & Oh 2016; dashed line). b): G and n_{H} in ALESS 49.1 and 57.1, compared to $z \sim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

• **Positive grain charging** will reduce the photoelectric gas heating. However, although the inferred G , n_{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_{FIR} and decreased $L_{\text{[CII]}}$. 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 $T_{\text{gas}} \gg 91$ K, the C^+ fine-structure upper-level occupancy (and $L_{\text{[CII]}}$) 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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