



Universiteit
Leiden
The Netherlands

The colours of the extreme universe

Calistro Rivera, G.

Citation

Calistro Rivera, G. (2019, January 10). *The colours of the extreme universe*. Retrieved from <https://hdl.handle.net/1887/68466>

Version: Not Applicable (or Unknown)

License: [Licence agreement concerning inclusion of doctoral thesis in the Institutional Repository of the University of Leiden](#)

Downloaded from: <https://hdl.handle.net/1887/68466>

Note: To cite this publication please use the final published version (if applicable).

Cover Page



Universiteit Leiden



The handle <http://hdl.handle.net/1887/68466> holds various files of this Leiden University dissertation.

Author: Calistro, Rivera G.

Title: The colours of the extreme universe

Issue Date: 2019-01-10

The Resolution Frontier II: Strong FUV fields drive the [C II]/FIR deficit in $z \sim 3$ dusty, star-forming galaxies

We present 0.15-arcsec (1 kpc) resolution ALMA observations of the [C II] 157.74 μm line and rest-frame 160- μm continuum emission in two of the $z \sim 3$ dusty, star-forming galaxies presented in the previous chapter - ALESS 49.1 and ALESS 57.1. The [C II] surface brightness distribution is dominated by a compact core ≤ 1 kpc in radius, a factor of 2–3 smaller than the CO (3–2) emission. In ALESS 49.1, we find an extended (8-kpc radius), low surface-brightness [C II] component. Based on an analysis of mock ALMA observations, the [C II]/160- μm continuum surface brightness distributions are inconsistent with a single-Gaussian surface brightness distribution with the same size as CO (3–2) emission. The [C II] rotation curves flatten only at few-kpc radius, suggesting the kinematics of the central regions are dominated by a baryonic disc. Both galaxies exhibit a strong [C II]/FIR deficit on 1-kpc scales, with FIR-surface-brightness to [C II]/FIR slope steeper than in local star-forming galaxies. A comparison of the [C II]/CO(3–2) observations with PDR models suggests a strong FUV radiation field ($G_0 \sim 10^4$) and high gas density ($n(\text{H}) \sim 10^4 \text{ cm}^{-3}$) in the central regions of ALESS 49.1 and 57.1. The most direct interpretation of the pronounced [C II]/FIR deficit is a thermal saturation of the C^+ fine-structure levels at temperatures ≥ 500 K, driven by the strong FUV field.

M. Rybak, G. Calistro Rivera, J. A. Hodge, Ian Smail, F. Walter, P. van der Werf, et al.
ApJ, (submitted).¹

¹This chapter is part of this PhD Thesis due to my significant contribution to this project at all levels. The main results of this chapter are based on the comparison of the [C II] data to the CO observations and analysis that was carried out and presented in Chapter 4. Additionally, I have been active in both the realization and discussion of this comparative analysis. I have carried out the kinematic modelling of the [C II] data presented in section 2.3 and have written the description of the process in this chapter. Finally, I have proof-read and edited different versions of this chapter, and have led the ALMA Cycle 4 proposal to complete the [C II] observations for the two remaining sources from Calistro-Rivera et al. (2018).

5.1 Introduction

Dusty, star-forming galaxies (DSFGs) are a major contributor to the global star-formation rate between redshifts $z = 2 - 4$, at an epoch when the star-forming activity of the Universe was at its peak (e.g. Casey et al. 2014). Although low in numbers, thanks to their high star-formation rates ($\text{SFR} > 100 M_{\odot} \text{ yr}^{-1}$), up to 20 per cent of all the star formation at $z \sim 3$ takes place in DSFGs (Swinbank et al. 2014).

The eponymous massive dust reservoirs in DSFGs absorb the UV/optical radiation from the newborn stars, mostly re-radiating it thermally as a rest-frame FIR/sub-mm continuum. Therefore, studying the structure and physical properties in these extreme sources requires relying on sub-mm/mm bright tracers - the dust continuum (which directly traces the obscured star formation) and low- J CO rotational transitions² (which trace the cold, molecular gas that fuels the star formation, Carilli & Walter 2013).

Besides the FIR continuum and CO emission, the third bright rest-frame FIR tracer of the star-forming interstellar medium (ISM) is the [C 2] 157.74 μm line, a fine-structure transition of C^+ ions. Due to its low ionization energy (11.3 eV) and a relatively low critical density, [C 2] traces a wide range of ISM phases - from the ionized H 2 regions to warm molecular clouds to diffuse gas. Depending on the environmental conditions, the upper fine-structure level is populated predominantly by collisions with H, H_2 or e^- (Goldsmith et al. 2012).

Starting in the early 1990's, systematic studies of [C 2] emission in local galaxies were enabled by the *Infrared Space Observatory* and the Kuiper Airborne Observatory. These observations revealed a tight correlation between the [C 2] line and FIR continuum emission from the heated dust at low SFR surface densities (e.g. Stacey et al. 1991). However, this correlation was found to break at larger FIR surface brightness Σ_{FIR} - the so-called “[CII]/FIR deficit” (e.g. Malhotra et al. 1997; Luhman et al. 1998; Malhotra et al. 2001; Luhman et al. 2003) - with the [C 2]/FIR ratio decreasing with increasing Σ_{FIR} .

In the last decade, the study of [C 2] emission in the nearby Universe was further revolutionized by *Herschel*. [C 2] emission in a large number of nearby galaxies was targeted by *Herschel*: the largest such sample of [C 2] was presented by Díaz-Santos et al. (2013), who obtained PACS spectroscopic observations of the 241 galaxies from the Great Observatories All-sky LIRG Survey (GOALS) (Armus et al. 2009). Further systematic studies of the [C 2] emission in nearby galaxies have been presented by Graciá-Carpio et al. (2011); Díaz-Santos et al. (2017); Smith et al. (2017); Herrera-Camus et al. (2018), confirming a strong correlation of the [C 2]/FIR deficit with Σ_{SFR} down to 200-pc scales in a wide range of environments.

At the highest redshifts ($z > 4$), the importance of the [C 2] line increases dramatically, as the raised CMB temperature renders the low- J CO emission undetectable, while the [C 2] line remains relatively unaffected (da Cunha et al. 2013; Vallini et al. 2015; Lagache et al. 2018). Indeed, with the advent of Atacama Large Millimeter/submillimeter Array (ALMA), [C 2] observations are now being routinely used to determine redshifts and dynamical masses of high-redshift galaxies, including some of the most distant systems (Walter et al. 2009; Brisbin et al. 2015; Gullberg et al. 2015; Oteo et al. 2016; Carniani et al. 2017; Decarli et al. 2018; Smit et al. 2018). Most recently, Gullberg et al. (2018) presented deep, 30-mas resolution (200 pc physical size) ALMA observations of the [C 2] line in four $z=4.4-4.8$ galaxies. Although their observation suffered from a very sparse uv -plane coverage, they found the resolved [C 2]-FIR deficit at $z \sim 4.5$ to follow the trend seen in local galaxies.

Despite the recent progress, it is still unclear how well the results and relations derived from local observations hold for the high-redshift population, especially the intensely star-forming high-redshift DSFGs, with Σ_{SFR} some two to three orders of magnitude higher than

²In this work, we use the term “low- J ” transitions for the rotational transitions with $J_{\text{upp}} \leq 3$.

the local star-forming galaxies ($10^{-3} - 10^0 M_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$, e.g. Smith et al. 2017). To directly compare the [C 2] emission in high-redshift DSFGs to the local galaxies and study its connection to the star-formation, high-resolution (kpc-scale) observations of the [C 2] emission, alongside the rest-frame FIR continuum (tracing the obscured star formation) and the low- J CO emission tracing the molecular gas are necessary.

At high redshift, such resolved, multi-tracer studies are typically limited by the angular extent of the source (few arcsec at most), and the need for robust redshifts to ensure that both [C 2] and low- J CO emission are observable from the ground. For example, Stacey et al. (2010) compared unresolved [C 2]/FIR/ CO ($J_{\text{upp}} \leq 4$) observations of a heterogeneous sample of $z = 1 - 2$ galaxies. Gullberg et al. (2015) compared [C 2], FIR and CO (2–1)/(1–0) observations in 20 strongly lensed DSFGs ($z_{\text{source}}=2.1-5.7$); they found the [C 2] and CO line profiles to be very similar, suggesting that they originate from the same source-plane regions. However, the limited resolution of these observations prevented a robust source-plane reconstruction of the CO/[C 2] emission; the *differential magnification* bias therefore could not be eliminated (e.g. Serjeant 2012). In addition, several individual sources at $z > 4.5$ have been studied in both [C 2] and low- J CO emission (e.g. Walter et al. 2009; Huynh et al. 2014; Cicone et al. 2015), though these tend to be extreme sources in terms of brightness and AGN activity.

Finally, the [C 2] line has been proposed as an alternative molecular gas tracer to CO emission. (e.g. Zanella et al. 2018). However, in DSFGs, the spatial extent of CO emission has been shown to vary strongly with J_{upp} (e.g. Ivison et al. 2011; Riechers et al. 2011). If [C 2] emission traces only a subset of the molecular gas reservoir, [C 2]-based mass estimates might be severely biased.

In this paper, we explore a new regime in resolved, multi-tracer studies by investigating resolved [C 2], FIR continuum and CO (3–2) emission on kpc-scales in two (non-lensed) $z \sim 3$ sources. This allows us to address the following questions:

- How does the resolved [C 2]/FIR ratio at $z \sim 3$ compare to that seen in local and high-redshift star-forming galaxies?
- What drives the [C 2]/FIR deficit in DSFGs?
- How well does the [C 2] emission trace the molecular gas reservoir in DSFGs?

Compared to the high-redshift, high-resolution [C 2]-only studies (e.g. Gullberg et al. 2018; Zanella et al. 2018), resolved emission line maps of two different species (C^+ and ^{12}CO) allow us to study the relation between [C 2] emission and the colder molecular gas.

This paper is structured as follows: in Section 5.2, we give the details of ALMA observations. Section 5.3 details the processing of the data in both the image- and uv -plane, the assessment of the systematic errors and kinematic modelling. Section 5.4 presents the spatial and kinematic comparison of the interpretation of the [C 2]/CO(3–2)/FIR observations, results of PDR modelling and a discussion of the physical processes driving the [C 2]/FIR deficit. Finally, Section 5.5 summarizes the conclusions of this paper.

Throughout this paper, we use a flat Λ CDM cosmology from Planck Collaboration et al. (2016). We adopt the CO (3–2) spectroscopic redshifts from Calistro Rivera et al. (2018): $z=2.943 \pm 0.001$ and $z=2.943 \pm 0.002$ for ALESS 49.1 and 57.1. Consequently, 1 arcsec corresponds to 7.9 kpc for both ALESS 49.1 and ALESS 57.1; the luminosity distance to both sources is 25445 Mpc (Wright 2006).

5.2 Observations and data reduction

5.2.1 Sample selection

The two galaxies analysed in this paper were identified by Hodge et al. (2013) as a part of the ALESS survey. The ALESS survey was an ALMA Cycle 0 870 μm imaging campaign targeting all 126 sources discovered in the LABOCA Extended *Chandra* Deep Field South Submillimeter Survey (LESS, Weiß et al. 2009). With ALMA Cycle 0 observations providing a significant improvement over the LABOCA bolometer in both resolution (beam area reduced by a factor of ~ 200) and sensitivity (increased by a factor of ~ 3), the ALESS survey identified 99 distinct sub-mm bright sources in its primary sample (Hodge et al. 2013). Out of these, at the time of the proposal (2015 April) only four – ALESS 49.1, 57.1, 67.1 and 122.1 – had robust redshifts that allowed for ALMA observations of both the low- J CO and [C 2] lines. The spectroscopic redshifts were acquired using VLT-FORS2/VIMOS and Keck-DEIMOS, and are based on multiple line detections (Danielson et al. 2017).

In this paper, we present the ALMA Band 8 observations targeting the [C 2] line and rest-frame 160- μm continuum. The corresponding Band 3 observations, targeting the CO (3-2) ($\nu_{\text{rest}}=345.795$ GHz) emission, were recently presented by Calistro Rivera et al. (2018).

5.2.2 ALMA Band 8 observations

The observations were carried out as part of the ALMA Cycle 3 Project #2015.1.00019.S (PI: J. Hodge) on 2016 August 12. Only ALESS 49.1 and 57.1 ([C 2] line in ALMA Band 8) were observed; ALESS 67.1 and 122.1 have [C 2] line in ALMA Band 9, and were not observed. The total time including calibration and overheads was 72 mins, with an on-source time of 11 mins per target. The array configuration consisted of 38 12-m antennas, with baselines extending up to 1400 m. The largest angular scale of the observations is ~ 1.9 arcsec for both sources³. The primary beam FWHM is 14.1 arcsec. Synthesized beam sizes and σ_{rms} for the 160- μm continuum and the [C 2] emission are listed in Table 5.1. The target elevation range was 66–73 deg for ALESS 49.1 and 67–76 deg for ALESS 57.1.

The frequency setup was configured in four spectral windows (SPWs) in Band 8. The individual SPWs were centered at 481.953, 483.183, 493.506, 495.386 GHz. Each SPW was split into 480 frequency channels 3.90625 MHz wide, for a total bandwidth of 1.875 GHz per SPW. The radio-velocity resolution was 2.42 km s⁻¹. Both the Stokes XX and YY parameters were observed.

The data were calibrated using the standard ALMA pipeline, with additional flagging necessary to remove atmospheric features (see below). All the visibility data processing apart from imaging was performed using CASA versions 4.7 and 5.0 (McMullin et al. 2007).

The spectral structure of the [C 2] line overlaps with atmospheric absorption features at 481.2 and 481.6 GHz. Consequently, the noise level in the affected channels is raised by factor of ~ 2 . This issue is particularly severe for ALESS 49.1. Another atmospheric feature is located in a line-free SPW at 496.35 GHz; here, the affected channels were flagged to improve the continuum SNR. As will be outlined in Section 5.3.1, we use a channel-dependent threshold for the deconvolution process to avoid introducing noise features from the affected channels.

To increase the signal-to-noise ratio, each line was split into frequency bins ~ 120 km s⁻¹ wide. Additionally, we time-averaged the data using a 30-second bin; this corresponds to an average intensity loss of < 0.5 per cent at 5 arcsec from the phase-tracking centre, which we

³The largest angular scale is estimated as $0.983/\lambda_{5\%}$, where $\lambda_{5\%}$ is the 5-th percentile uv -distance (ALMA Cycle 5 Technical Handbook).

Table 5.1: Source positions (corresponding to the 160- μm continuum surface brightness maximum), redshifts, ALMA Band 8 naturally-weighted beam sizes and noise levels, observed 160- μm continuum/[C 2] flux-densities and [C 2] and FWHM.. The redshifts are based on CO (3–2) observations Calistro Rivera et al. (2018). The spatially-integrated flux-densities $S_{160\mu\text{m}}/S_{\text{[CII]}}$ are measured within a circular aperture with 1-arcsec diameter, centered on the continuum surface brightness maximum.

Source		ALESS 49.1	ALESS 57.1
RA (J2000)		3:31:24.71	3:31:51.94
DEC (J2000)		–27:50:46.9	–27:53:27.0
z		2.943 ± 0.001	2.943 ± 0.002
Beam FWHM	[arcsec]	0.16×0.12	0.16×0.12
Beam PA	[deg]	53	56
$S_{160\mu\text{m}}$	[mJy]	10.7 ± 1.0	8.2 ± 0.5
$I_{160\mu\text{m}}^{\text{max}}$	[mJy beam $^{-1}$]	3.42 ± 0.16	1.53 ± 0.17
$S_{\text{[CII]}}$	[mJy]	15.4 ± 2.8	8.8 ± 2.5
$I_{\text{[CII]}}^{\text{max } a}$	[mJy beam $^{-1}$]	2.0 ± 0.4	3.0 ± 0.4
FWHM $_{\text{[CII]}}$	[km s $^{-1}$]	600 ± 130	390 ± 70
FWHM $_{\text{CO}}^c$	[km s $^{-1}$]	610 ± 30	360 ± 90

^a per 120 km s $^{-1}$ velocity bin.

^b integrated over 800 and 710 km s $^{-1}$ for ALESS 49.1 and 57.1, respectively.

^c adopted from Calistro Rivera et al. (2018).

consider negligible⁴. The time-bin size was chosen so as to prevent significant time-averaging smearing. The two linear polarizations were combined into the Stokes intensity I .

5.2.3 ALMA Band 3 observations

ALMA Cycle 2/4 Band 3 observations of the CO (3–2) and rest-frame 1.0-mm continuum in ALESS 49.1 and 57.1 was presented by Calistro Rivera et al. (2018). These consisted Cycle 2 observations of ALESS 49.1 and 57.1 (Project #2013.1.00470.S; PI:Hodge) at 0.34–0.67 arcsec resolution; and additional Cycle 4 observations of ALESS 49.1 (Project #2016.1.00754.S; PI: Wardlow) at 1.1-arcsec resolution. The naturally-weighted Band 3 synthesized beam size is 0.69×0.63 arcsec for ALESS 49.1 (after concatenating Cycles 2 and 4 data) and 0.67×0.60 arcsec for ALESS 57.1, with a continuum σ_{rms} of 17.6 and 19.5 $\mu\text{Jy beam}^{-1}$, respectively. For a detailed description of the data and the resulting analysis, we refer the reader to Calistro Rivera et al. (2018).

5.3 Results

5.3.1 Image analysis

Imaging

We perform synthesis imaging of the visibility data using the WS-CLEAN algorithm introduced by Offringa et al. (2014), specifically its multi-scale version (Offringa & Smirnov

⁴Taylor et al. (1999), equation (18–42).

2017). The multi-scale WS-CLEAN is an advanced deconvolution algorithm with a multi-scale, multi-frequency capability (Offringa & Smirnov 2017). Another advantage of the WS-CLEAN as opposed to the CASA implementation is the channel-dependent deconvolution threshold. As the noise level changes appreciably with frequency due to atmospheric lines, this prevents us from introducing noise-peaks from the affected channels into the reconstructed images.

For the line imaging, we first subtract the continuum by linearly interpolating the line-free channels in SPWs 1, 2, and 3 and subtract the continuum slope from the line-containing channels. The continuum channels overlapping with the atmospheric lines were flagged before the continuum subtraction. For the continuum imaging, we discard the entire SPW 0 and the line-containing channels in SPW1, as well as the channels affected by the atmospheric feature around 496.35 GHz.

The data were deconvolved on a sky-plane grid of 1024×1024 5-mas pixels (total FoV size = 5.115×5.115 arcsec), using natural weighting. We use the automatic SNR-based masking, with `auto-mask` SNR threshold of 2. Table 5.1 lists the source positions, redshifts and the rms noise for the synthesized images.

ALMA 160- μ m continuum

The rest-frame 160- μ m continuum is detected in both sources at $>10 \sigma$ -confidence (Figure 5.1). In both sources, the continuum emission shows only a single brightness peak at 0.15-arcsec resolution. In ALESS 49.1, the continuum emission is almost circularly symmetric, with a minor extension in the east-west direction. In ALESS 57.1, the continuum is noticeably extended in the east-west direction (axis ratio at FWHM 2:1). The spatially-integrated 160- μ m continuum flux-density for ALESS 49.1 and 57.1 is given in Table 5.1. The 160- μ m flux-density is calculated from an aperture with a 1.0 arcsec radius, centered on the 160- μ m continuum surface brightness maximum. The aperture size was chosen based on the CO (3–2) sizes measured in Calistro Rivera et al. (2018); additionally, based on the uv -plane size measurements (Section 5.3.2), we do not expect significant surface brightness contribution ≥ 1 arcsec from the centre of the source.

[CII] emission

The velocity-integrated maps of the [C 2] emission are presented in Figure 5.1. The [C 2] emission is detected at 5 and 8- σ significance in ALESS 49.1 and 57.1, respectively. The [C 2] emission is relatively compact (<0.5 arcsec diameter), similar in extent to the 160- μ m continuum. The [C 2] emission in ALESS 57.1 is highly elliptical (axis ratio $\geq 2:1$) and elongated in the east-west direction; the [C 2] does not show any significant offset from the 160- μ m peak. Note that the low-significance clumpy substructure such as that seen in ALESS 49.1 [C 2] maps is often an artifact of low SNR (e.g. Hodge et al. 2016; Gullberg et al. 2018), rather than a real physical feature.

5.3.2 uv -plane analysis

We estimate the size of the continuum and [C 2] emission regions by directly fitting the observed visibility function. Given the relatively low SNR of the data, we assume the surface brightness distribution to follow a circularly symmetric Gaussian profile.

The size is measured using the frequency-integrated continuum and line datasets. To correct the offset between the phase-tracking centre and the centroid of the surface brightness distribution given in Table 5.1, each dataset is phase-shifted to center the field-of-view on the

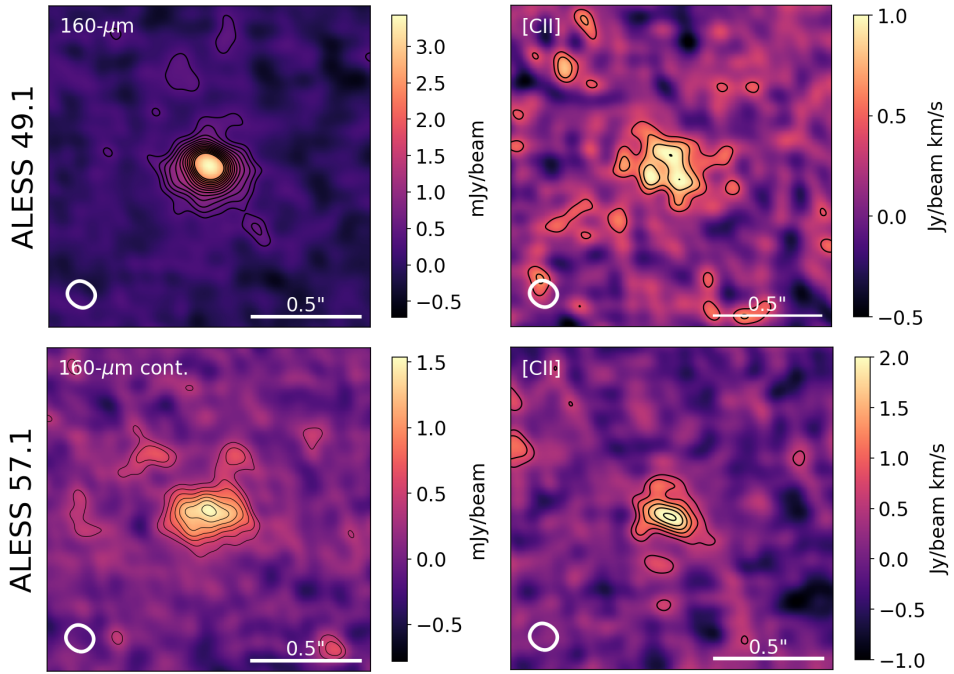


Figure 5.1: ALESS 49.1 and 57.1 imaging: continuum (right) and integrated [C 2] emission (left) maps. The contours start at $2\text{-}\sigma$ level and increase by $1\text{-}\sigma$. The FWHM beam size is indicated by the ellipse in the lower left corner. The [C 2] and $160\text{-}\mu\text{m}$ emission is well-resolved in both sources, and almost co-spatial.

centroid of the source. The data are then radially binned into bins of equal width. To test the robustness of the uv -plane fitting against the uv -bin size, we vary the uv -bin size from 5 to 50 $k\lambda$.

We fit each uv -plane dataset with (1) a single Gaussian profile, (2) two Gaussian components to investigate the possibility of having compact, bright [C 2] emission embedded in an extended, low surface-brightness component; (3) a combination of a single Gaussian profile and a constant term, corresponding to a point-source in the image plane. To determine whether the two-component model significantly improves the goodness-of-fit compared to the one-component model, we compare the two models using the F-test (Bevington 1969). The single-component model is preferred for the continuum emission in ALESS 49.1 and [C 2] emission in ALESS 57.1, independently of the uv -bin size. We will address the robustness of the inferred $R_{1/2}$ in Section 5.3.2. The two-component model is strongly ($p > 0.95$) preferred for the [C 2] emission in ALESS 49.1 and the continuum emission in ALESS 57.1. We do not find the Gaussian-and-constant-term (point-source) model to be preferred over the single-Gaussian model for any dataset considered. The best-fitting values for the two-component model are listed in Table 5.2. Figure 5.2 shows the visibility function for the [C 2] and 160- μm continuum, as well as the CO (3–2) observations from Calistro Rivera et al. (2018), and the corresponding best-fitting profiles.

In physical units, for the single-Gaussian models, the [C 2] and 160- μm emission are rather compact (0.8–1.4 kpc) in both sources. The [C 2] and 160- μm continuum sizes from the single-Gaussian fitting agree within 1–2- σ uncertainty. For the two-Gaussian models, the compact and extended [C 2] components in ALESS 49.1 have half-light radii of 1.01 ± 0.12 kpc and 8.7 ± 1.6 kpc, respectively. The compact and extended 160- μm components in ALESS 57.1 have half-light radii of 0.86 ± 0.07 and 5.3 ± 1 kpc, respectively.

For the two-component [C 2] model in ALESS 49.1, the extended [C 2] components accounts for up to 80 cent of the total [C 2] luminosity. Note that the systematic uncertainty on this estimate might be significant, as it is unclear how much does the extended component depart from the assumption of a circular Gaussian profile. For ALESS 57.1, the single-Gaussian model is preferred. However, if ALESS 57.1 has a very faint extended [C 2] component with the same size as in ALESS 49.1, the upper 3- σ limit on the total flux-density contributed by this hypothetical component is 80 per cent.

How will the extended components in ALESS 49.1 [C 2] emission and ALESS 57.1 160- μm continuum contribute to the observed [C 2]/160- μm surface brightness distribution? The half-light radius of the ALESS 57.1 160- μm extended component is well below the maximum recoverable scale and therefore should be fully accounted for in the synthesized images. This is supported by the results from the spectral energy distribution modeling (Section 5.3.4), which indicate that the 160- μm continuum is not significantly resolved out. For the [C 2] emission, the half-light radius of the extended component in ALESS 49.1 is comparable to the maximum recoverable scale (1.9 arcsec) and some emission is likely resolved out in the synthesized images. However, while the extended [C 2] component in ALESS 49.1 dominates the total [C 2] luminosity, it contributes only between 5–20 per cent of the surface brightness across the inner $R < 2$ kpc region. It is for this reason that our analysis in Sections 4.2, 4.3 and 4.4 focuses on the central regions ($R \leq 2$ kpc) of ALESS 49.1 and 57.1, including the uncertainty from the extended components in further analysis.

How robust are the source sizes determined from the uv -plane fitting?

Before analyzing our resolved [C 2] and 160- μm continuum observations, we assess the reliability of the inferred source sizes. In particular, we investigate a possibility that the [C 2]/160- μm emissions follow CO (3–2) surface distribution, and that the source sizes inferred in Sec-

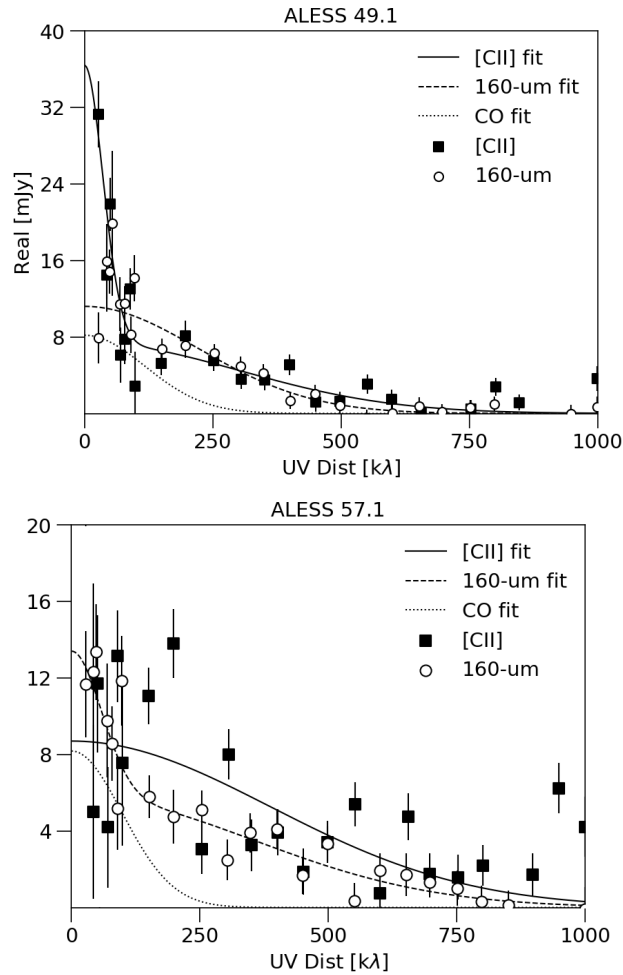


Figure 5.2: Azimuthally averaged visibility function for ALESS 49.1 (left) and ALESS 57.1 (right), for the [C 2], 160- μm continuum with best-fitting model (full and dashed lines), and best-fitting single-Gaussian profiles to the CO (3–2) data (dotted line, increased by a factor of 10, Calistro Rivera et al. 2018). For added clarity, the data is binned with a 10 – 50 k λ bin size and truncated at 1000 k λ . In ALESS 49.1, the excess [C 2] flux at short baselines - corresponding to the extended component - is clearly visible.

tion 5.3.2 are an artifact of the limited short-spacing coverage of our Band 8 observations. We estimate this uncertainty using simulated ALMA observations.

The mock observations are created as follows. First, we calculate the mean and rms scatter for the [C 2] / 160- μm continuum visibilities within a given uv -bin. We then subtract the mean signal from the data, which gives us a uv -plane coverage corresponding exactly to a given observation, along with a realistic noise measurement for each baseline. We choose this approach to account for the different noise levels for each dataset, and the effect of the atmospheric lines on our [C 2] data. We then inject an artificial source into the data, generating 1000 datasets with different noise realizations for each source. We consider sources with a half-light radius of 0.1–1.0 arcsec and peak surface brightness of 0.05 – 4.0 mJy beam⁻¹. Finally, we bin the mock visibilities in the uv -plane using exactly the same procedure as applied to real data in Section 5.3.2.

Figure 5.3 shows the inferred radius as a function of the surface brightness maximum alongside the 1- σ uncertainty from the uv -plane fitting. The measured [C 2] and 160- μm continuum sizes in ALESS 49.1 and 57.1 are all smaller than sizes inferred for input sources with $R_{1/2} \geq 0.2$ arcsec in the relevant peak surface brightness range. In other words, given the observed peak surface brightness, $R_{1/2}^{[\text{CII}]} > 0.2$ arcsec would be recovered within 10 per cent uncertainty for both ALESS 49.1 and 57.1. For comparison, the CO (3–2) half-light radii in ALESS 49.1 and 57.1 are $R_{1/2}^{\text{CO}} = 0.33 \pm 0.06$ and 0.39 ± 0.06 arcsec, respectively.

Therefore, we consider it unlikely that the [C 2]/160- μm continuum follow a single-Gaussian surface brightness distribution with the same size as CO (3–2) emission (0.33 ± 0.05 and 0.39 ± 0.06 arcsec for ALESS 49.1 and 57.1, respectively). Nevertheless, we can not exclude a combination of a bright compact and faint extended components. In the following analysis, we will focus on the center of the sources where the extended [C 2] component is not expected to contribute significantly.

5.3.3 [CII] spectra and kinematics

Figure 5.4 presents the [C 2] moment-one (intensity-weighted velocity) maps and the comparison of [C 2]/CO (3–2) line profiles in ALESS 49.1 and 57.1. The spectra were extracted from the naturally-weighted channel maps, using an aperture 1 arcsec (~ 8 kpc) in radius.

The [C 2] line profile in ALESS 49.1 largely traces the CO (3–2) profile, exhibiting an increased brightness in the blue channels. The [C 2] and CO (3–2) line profiles are consistent within errors for both sources. The moment-one maps reveal a clear velocity gradient across both ALESS 49.1 and 57.1.

We model the velocity-fields using the GALPAK3D software (Bouché et al. 2015). GALPAK3D uses a Monte-Carlo approach to extract the kinematic and morphological parameters from three-dimensional image cubes, accounting for both the spatial and spectral response of the instrument, assuming a parametric model for a rotating disc. For our simulations, we assume an exponential disc profile - an appropriate choice for ALESS DSFGs, which show a mean Sérsic index of $n = 0.9 \pm 0.2$ (Hodge et al. 2016, $n = 1$ corresponds to an exponential profile.). To improve the SNR and the speed of the calculations, we re-sampled our data onto cubes with a pixel size of 25 mas, using natural weighting.

Figure 5.5 shows the input and reconstructed moment-0 and moment-1 maps for ALESS 49.1 and 57.1. At the SNR of our Band 8 observations, velocity fields in both sources are consistent with an ordered, disc-like rotation. The deconvolved [C 2] rotational curves are shown in Figure 5.6, which also lists the FWHM velocity measurements obtained from the fitting of the spatially-integrated CO (3–2) spectra (Calistro Rivera et al. 2018). The source inclinations are inferred by fitting the moment-0 map and agree with those derived from CO (3–2) imaging by Calistro Rivera et al. (2018) within 1–2 σ uncertainty.

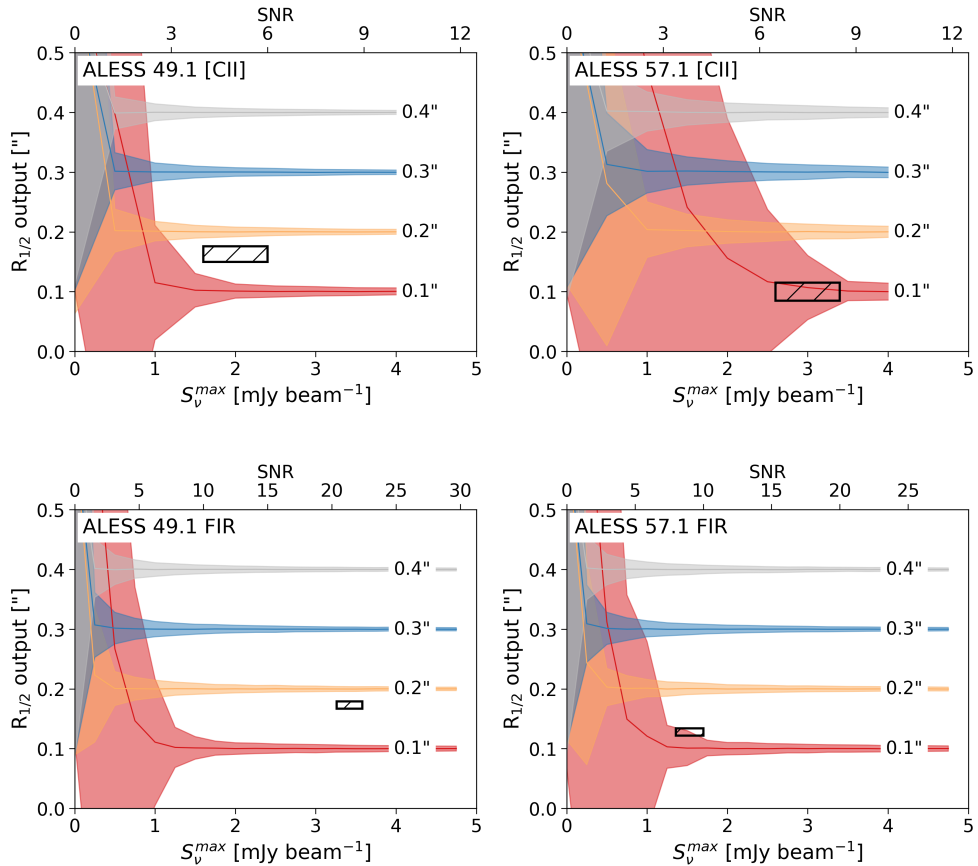


Figure 5.3: Comparison of the inferred and true $R_{1/2}$ for the [C 2] line (upper) and 160- μm data continuum (lower). The bold lines denote the mean inferred $R_{1/2}$ for input $R_{1/2}=0.1\text{--}0.4$ arcsec, with coloured regions denoting the $1\text{-}\sigma$ uncertainty from the uv -plane fitting only. For $R_{1/2} > 0.4$ arcsec, the source sizes are inferred robustly and are now shown for clarity. The boxed regions indicate the measured source sizes and peak surface brightness for ALESS 49.1 and 57.1 with 1σ uncertainties. Given the SNR of our observations, we rule out the possibility that [C 2] and 160- μm continuum follow the same single Gaussian profile as the CO (3–2) emission.

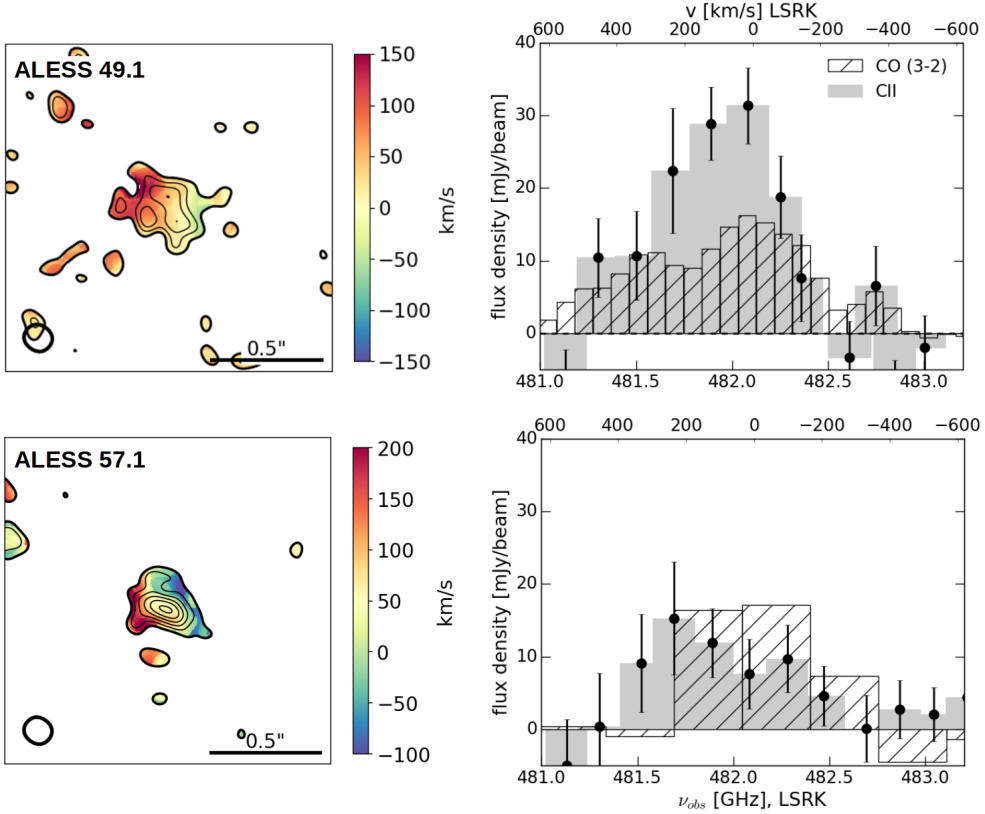


Figure 5.4: Moment-one (velocity) maps and [C 2] line profiles for ALESS 49.1 and ALESS 57.1. The contours correspond to [C 2] moment-zero maps as shown in Figure 5.1. The [C 2] velocity fields in both galaxies show a clear gradient across the source, without any major perturbations. The CO (3–2) spectra are taken from Calistro Rivera et al. (2018); the CO (3–2) flux-density is scaled up by a factor of 10 for clarity. The velocity is given in the LSRK frame with respect to the redshift of $z = 2.943$, using the radio definition of velocity. The line intensity was measured from images obtained using natural weighting, for an aperture with 1 arcsec diameter, centered on the surface-brightness maximum of the integrated [C 2] line. The error-bars indicate $1\text{-}\sigma$ uncertainty. The frequency coverage of our Band 8 observations does not extend below 481.0 GHz. The [C 2] and CO (3–2) line widths match each other (Table 5.1).

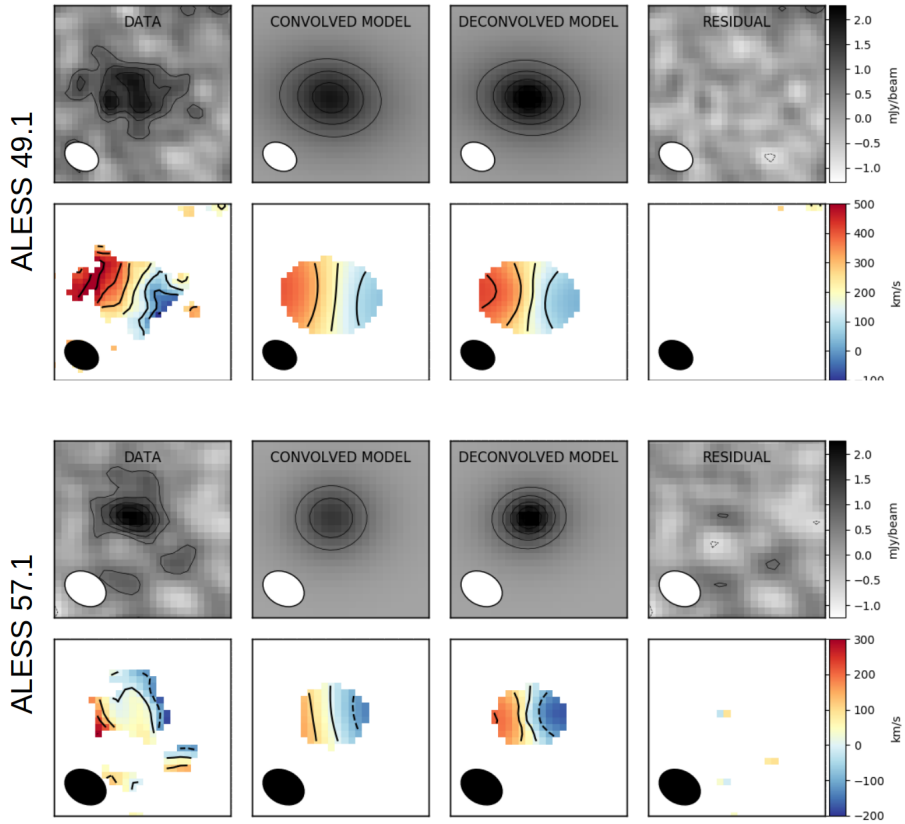


Figure 5.5: GALPAK3D models of the [C2] velocity field in ALESS 49.1 (upper) and ALESS 57.1 (lower), using an exponential disc model. The upper row shows, respectively, the velocity moment-0 (surface brightness) data, best moment-0 model convolved with the beam, best moment-0 model (deconvolved) and the moment-0 residuals. The moment-zero contours start at $\pm 2\sigma_{\text{rms}}$ level and increase in steps of $1\sigma_{\text{rms}}$. The moment-one contours are drawn in steps of $\pm 100 \text{ km s}^{-1}$. The lower row shows the reconstructed moment-one (velocity) maps for regions with surface brightness $> 2\sigma_{\text{rms}}$. The data is fully consistent with the exponential disc model, with no residuals at $> 2\sigma_{\text{rms}}$ significance. The field-of-view size is 1.6×1.6 arcsec and 1.4×1.4 arcsec, respectively.

Table 5.2: Inferred source properties for ALESS 49.1 and ALESS 57.1. For the global source properties derived from the SED-fitting, we provide the median value of the posterior probability density function. The [C 2] and CO (3–2) line luminosities are spectrally integrated over the full extent of the [C 2], rather than over FWHM only (as in Calistro Rivera et al. 2018) as the [C 2] line exhibits a non-Gaussian profile.

Source		ALESS 49.1	ALESS 57.1
SED fitting			
$L_{3-2000\mu\text{m}}$	[$10^{12} L_{\odot}$]	$7.1^{+0.8}_{-0.9}$	$7.4^{+0.9}_{-0.9}$
SFR	[$M_{\odot} \text{ yr}^{-1}$]	490^{+30}_{-60}	480^{+70}_{-60}
T_{dust}	[K]	46^{+6}_{-2}	51^{+7}_{-4}
M_{\star}	[$10^{10} M_{\odot}$]	$4.4^{+1.8}_{-0.3}$	$4.3^{+1.7}_{-0.8}$
M_{gas}^b	[$10^{10} M_{\odot}$]	5 ± 2	5 ± 2
M_{dust}	[$10^8 M_{\odot}$]	$4.4^{+0.5}_{-0.7}$	$4.1^{+0.5}_{-0.6}$
Line Luminosities			
$L_{[\text{CII}]}$	[$10^9 L_{\odot}$]	3.0 ± 0.8	1.1 ± 0.4
$L'_{[\text{CII}]}$	[$10^{10} \text{ K km s}^{-1} \text{ pc}^2$]	14 ± 4	5.1 ± 1.7
$L_{\text{CO}(3-2)}^a$	[$10^9 L_{\odot}$]	0.070 ± 0.005	0.062 ± 0.016
$L'_{\text{CO}(3-2)}^a$	[$10^{11} \text{ K km s}^{-1} \text{ pc}^2$]	0.51 ± 0.04	0.05 ± 0.01
$L_{\text{CO}(1-0)}^a$	[$10^6 L_{\odot}$]	2.1 ± 0.2	2.6 ± 0.7
Source sizes - single Gaussian			
$R_{1/2}^{[\text{CII}]}$	[arcsec]	0.163 ± 0.013	0.101 ± 0.010
$S^{[\text{CII}]}$	[mJy]	10.9 ± 0.9	8.6 ± 0.9
$R_{1/2}^{160\mu\text{m}}$	[arcsec]	0.173 ± 0.009	0.128 ± 0.006
$S^{160\mu\text{m}}$	[mJy]	11.2 ± 0.4	7.6 ± 0.4
$R_{1/2}^{\text{CO}}^a$	[arcsec]	0.33 ± 0.5	0.39 ± 0.06
Source sizes - two Gaussians			
$R_{1/2}^{[\text{CII}]} \text{ (compact)}$	[arcsec]	0.128 ± 0.015	–
$R_{1/2}^{[\text{CII}]} \text{ (extended)}$	[arcsec]	1.1 ± 0.3	–
$S^{[\text{CII}]} \text{ (compact)}$	[mJy]	7.4 ± 1.1	–
$S^{[\text{CII}]} \text{ (extended)}$	[mJy]	29 ± 8	–
$R_{1/2}^{160\mu\text{m}} \text{ (compact)}$	[arcsec]	–	0.109 ± 0.007
$R_{1/2}^{160\mu\text{m}} \text{ (extended)}$	[arcsec]	–	0.67 ± 0.11
$S^{160\mu\text{m}} \text{ (compact)}$	[mJy]	–	5.8 ± 0.5
$S^{160\mu\text{m}} \text{ (extended)}$	[mJy]	–	7.6 ± 1.4
[C 2] and CO (3–2) kinematics			
$i_{[\text{CII}]}$	[deg]	39 ± 5	58 ± 5
$M_{\text{dyn}}^{[\text{CII}]} (R \leq 2 \text{ kpc})$	[$10^{10} M_{\odot}$]	6.2 ± 5.5	2.7 ± 1.6
$M_{\text{dyn}}^{\text{CO}} (R < R_{1/2}^{\text{CO}})$	[$10^{10} M_{\odot}$]	11 ± 2	11 ± 5

^a Calistro Rivera et al. (2018): L_{line} integrated over the entire line width as opposed to integrating only over FWHM as in Calistro Rivera et al. (2018)

^b Calistro Rivera et al. (2018). M_{gas} estimated assuming $\alpha_{\text{CO}} = 1.0$.

5.3.4 Spectral energy distribution modelling

We infer the global stellar and interstellar medium properties of ALESS 49.1 and 57.1 from the spatially-integrated spectral energy distributions (SEDs) using the MAGPHYS package (da Cunha et al. 2008). These differ from the previously published models (da Cunha et al. 2015) by using the CO (3–2)-derived spectroscopic redshifts compared to the photometric ones from da Cunha et al. (2015), and inclusion of ALMA Bands 3/4/8 continuum flux-densities. Namely, we include Band 4 continuum measurements ($S_{2.1\text{mm}} = 380 \pm 100 \mu\text{Jy}$ and $65 \pm 50 \mu\text{Jy}$ for ALESS 49.1 and 57.1; da Cunha et al., in prep.), as well as the ALMA Band 3 continuum measurement for ALESS 49.1, $S_{3.3\text{mm}} = 37 \pm 5 \mu\text{Jy}$ (Wardlow et al. 2018), as well as the Band 8 continuum measurements from Table 5.1. The updated source properties are listed in Table 5.2. The estimated dust temperatures $T_{\text{dust}} = 47^{+5}_{-9}/52^{+10}_{-6}$ K in ALESS 49.1 and 57.1 are warmer than the median $T_{\text{dust}} = 42 \pm 2$ K of the ALESS DSFGs inferred from MAGPHYS modelling (da Cunha et al. 2015). However, median $T_{\text{dust}} = 55 \pm 4$ K was found in a sample of $z \sim 4.5$ emitters by Cooke et al. (2018), who interpreted the high T_{dust} as evidence for high Σ_{SFR} at high redshift. Compared to the MAGPHYS models of entire ALESS sample (da Cunha et al. 2015), ALESS 49.1 and 57.1 have SFR higher by a factor of ~ 2 (da Cunha et al. 2015: median SFR = $280 \pm 70 M_{\odot} \text{ yr}^{-1}$) and stellar mass factor of 2 lower (da Cunha et al. 2015: $M_{*} = (8.9 \pm 0.1) \times 10^{10} M_{\odot} \text{ yr}^{-1}$); the dust mass is consistent with the median da Cunha et al. (2015) value ($(5.6 \pm 1.0) \times 10^{10} M_{\odot}$). The gas depletion timescale ($M_{\text{gas}}/\text{SFR}$) is 100 ± 40 Myr in both ALESS 49.1 and 57.1, in line with redshift 2–4 DSFGs (Huynh et al. 2017; Bothwell et al. 2013), and few times lower than in $z = 1 - 3$ massive main-sequence galaxies from the PHIBBS survey (0.7 ± 0.1 Myr, Tacconi et al. 2018).

Using the SED models, we can estimate the fraction of the 160- μm continuum that is resolved out by comparing the observed rest-frame 160- μm continuum fluxes with SED modeling predictions, assuming that T_{dust} and optical depth are constant across the source. Namely, we use MAGPHYS (da Cunha et al. 2008) to perform SED modeling using all the photometry points apart from the rest-frame 160- μm continuum. The predicted 160- μm flux-densities are 11.8 and 7.6 mJy for ALESS 49.1 and 57.1, respectively; the observed flux densities match the predicted ones to < 10 per cent. Therefore, we conclude that our observations recover the bulk of the 160- μm emission.

5.4 Discussion

5.4.1 Comparison with CO (3–2) emission

Based on the uv -plane analysis in Section 5.3.2 and test on mock ALMA data in Section 5.3.2, we found the [C 2]/160- μm continuum surface brightness distribution to be dominated by a compact component, embedded within a low-surface-brightness, extended emission. We now compare these morphologies to the CO (3–2) surface brightness profiles, and other low- and high-redshift observations and simulations.

160- μm continuum size

Comparing the 160- μm continuum emission sizes with the CO (3–2) sizes (Table 5.2), the 160- μm continuum is 1.9 ± 0.3 (ALESS 49.1) and 3.1 ± 0.7 (ALESS 57.1) more compact than the CO (3–2) emission.

Compact dust continuum emission embedded in a larger molecular gas reservoir has been observed in a number of high-resolution studies of $z = 2 - 4$ DSFGs. For example, PdBI/VLA imaging of GN20 ($z = 4.05$) revealed a compact dusty, star-forming region within a large disc

as traced by the CO (2–1) emission (Hodge et al. 2012, 2015). At very high spatial resolutions (~ 100 pc), similar morphology has been seen in the strongly-lensed $z = 3$ DSFG SDP.81 (ALMA Partnership et al. 2015), which shows a compact (~ 3 kpc across), dusty star-forming disc (Rybak et al. 2015a), embedded in a large (≥ 10 kpc) molecular gas reservoir, as traced by the CO (1–0) emission (Valtchanov et al. 2011; Rybak et al. 2015b). Similarly, Spilker et al. (2015) observed compact ALMA Band 7 continuum and extended CO(3–2)/(1–0) emission in two strongly lensed galaxies from the South Pole Telescope sample; note that in DSFGs, the CO (3–2) is typically significantly less extended than the CO (1–0) line (e.g. Ivison et al. 2011; Riechers et al. 2011). Using ALMA 860- μm continuum, VLA CO (3–2) and SINFONI $\text{H}\alpha$ observations of ALESS 67.1 ($z=2.1$), Chen et al. (2017) found the ALMA continuum to be a factor of ~ 5 more compact than CO (3–2) and $\text{H}\alpha$ emission (which are similar in size). Finally, Calistro Rivera et al. (2018) compared stacked CO (3–2) and Hodge et al. (2016) 860- μm ALMA observations of a sample of 4/18 DSFGs from the ALESS sample, showing the FIR continuum to be more compact by a factor of >2 . Based on a radiative transfer modelling, Calistro Rivera et al. (2018) found that the compact FIR and extended CO (3–2) sizes are consistent with a decrease in dust temperature and optical depth towards the outskirts of the source. The compact continuum sizes in ALESS 49.1 and 57.1 thus add to the growing evidence for variations ISM conditions in DSFGs on scales of few kpc.

[CII] emission size

Based on the source sizes inferred from uv -plane fitting, the [C 2] emission is 2.0 ± 0.4 (ALESS 49.1) and 3.9 ± 0.7 (ALESS 57.1) times more compact than CO (3–2). The compact size of the high surface-brightness [C 2] component contrasts with a relatively similar extent of the [C 2] and low- J CO emission in local galaxies, as recently presented by de Blok et al. (2016), who found the [C 2] to be “*slightly less compact than the CO*” (scale radius $\sim 70 \pm 20$ per cent larger). Note that the de Blok et al. (2016) galaxies have Σ_{SFR} much lower than ALESS 49.1 and 57.1 ($10^{-3} - 10^{-2} \text{ M}_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$ vs. $10^1 - 10^2 \text{ M}_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$).

The [C 2] morphologies consisting of a high surface-brightness compact, and a low surface-brightness extended component have been observed in several local star-forming galaxies. For example, early Kuiper Airborne Observatory imaging of [C 2] emission in NGC 6946 (Madden et al. 1993) resolved three distinct components: (1) a bright, compact nucleus ($R < 300$ kpc); (2) a faint, diffuse component at least 12 kpc in radius, contributing ~ 40 per cent of the total [C 2] flux (Contursi et al. 2002) and (3) local enhancements corresponding to the spiral arms.

Furthermore, one of the best-studied $z \geq 5$ sources with resolved [C 2]/low- J CO observations - $z \sim 6.42$ quasar SDSS J1148+5251 (Walter et al. 2004, 2009) - has a compact ($R \sim 0.75$ kpc) [C 2] emission embedded within a much more extended ($R \sim 2.5$ kpc) CO (3–2) reservoir (Walter et al. 2009; Stefan et al. 2015). Ciccone et al. (2015) found an extremely extended (out to ~ 30 kpc) [C 2] emission associated with powerful outflows likely driven by the central engine in J1148+5251.

Apart from observational evidence, a compact, high surface-brightness [C 2] component in star-forming galaxies has been predicted by simulations. In particular, Olsen et al. (2015) predicted using zoomed-in cosmological SPH simulations of several mildly star-forming $z \sim 2$ galaxies ($\text{SFR}=5\text{--}60 \text{ M}_{\odot} \text{ yr}^{-1}$) that the [C 2] emission is concentrated into a compact central region ($R \sim 1$ kpc), with a much fainter (by up to 1 dex) extended component – similar to our double-component model of [C 2] emission in ALESS 49.1. In the Olsen et al. (2015) simulations, the compact size of the [C 2] emission is due to gas inflows into the central star-forming regions, and the [C 2] emission is dominated by the dense, molecular phase of the ISM. This contrasts with low-SFR galaxies, where the bulk of the star-formation takes place

in the spiral arms at large galactocentric radii (e.g. Pineda et al. 2013).

Inferring FIR source sizes using the Stacey et al., 2010 relation

Given the limited angular resolution of many high-redshift [C 2] detections, the source size can not be inferred directly from unresolved/marginally resolved data. However, parallel [C 2]/CO/FIR continuum observations have been used to constrain the source size, assuming the bulk of the line and continuum emission originates in PDR regions.

This technique, introduced by Stacey et al. (2010), compares the observed [C 2]/CO/FIR fluxes with predictions from the PDR models of (Kaufman et al. 1999, see Section 5.4.4) to infer the FUV field strength G_0 and the density n . The observed L_{FIR} and inferred G_0 are then used to infer the FIR size R_{FIR} using the Wolfire et al. (1990) relations. In particular, Wolfire et al. (1990) distinguish two main regimes:

1. $\langle \lambda_{\text{FUV}} \rangle < R_{\text{FIR}}$

$$\langle G_0 \rangle = 3 \times 10^4 \left(\frac{L_{\text{FIR}}}{10^{10} L_{\odot}} \right) \left(\frac{\langle \lambda_{\text{FUV}} \rangle}{100 \text{ pc}} \right) \left(\frac{100 \text{ pc}}{R_{\text{FIR}}} \right)^3 (1 - \exp(-R_{\text{FIR}}/\langle \lambda_{\text{FUV}} \rangle)), \quad (5.1)$$

2. $\langle \lambda_{\text{FUV}} \rangle \geq R_{\text{FIR}}$

$$\langle G_0 \rangle = 3 \times 10^4 \left(\frac{L_{\text{FIR}}}{10^{10} L_{\odot}} \right) \left(\frac{100 \text{ pc}}{R_{\text{FIR}}} \right)^2, \quad (5.2)$$

where G_0 is given in the units of the Habing field ($1.6 \times 10^{-3} \text{ erg cm}^{-2} \text{ s}^{-1}$) and R_{FIR} and the FUV photon mean free path $\langle \lambda_{\text{FUV}} \rangle$ are in pc. Stacey et al. (2010) assume that $\langle \lambda_{\text{FUV}} \rangle$ in $z = 1 - 2$ star-forming galaxies is the same as in a nearby starburst M82. For M82, Stacey et al. (2010) assume $L_{\text{FIR}} = 2.8 \times 10^{10} L_{\odot}$, $G_0 = 10^3$, $R_{\text{FIR}} = 150 \text{ pc}$.

With high-resolution [C 2], CO (3–2) and FIR observations and robust source sizes in hand, we now investigate the applicability of the Stacey et al. (2010) relations to high-redshift DSFGs. Assuming that $\langle \lambda_{\text{FUV}} \rangle$ is smaller than R_{FIR} (an appropriate choice given the heavily obscured, dusty environment), we infer $R_{\text{FIR}} = 410 \pm 50$ and $420 \pm 70 \text{ pc}$ for ALESS 49.1 and 57.1, respectively; a factor of 2.5–3.5 smaller than the actual FIR half-light radii measured from the uv -plane fitting (Section 5.3.2). We note that the M82 L_{FIR} , G_0 and R_{FIR} estimates from the literature show a considerable scatter; alternatively, the $\langle \lambda_{\text{FUV}} \rangle$ in DSFGs differs from that in M82. Crucially, if the FIR sizes of high-redshift DSFGs are systematically underestimated by similar factors, the star-formation rate surface density $\Sigma_{\text{SFR}} \propto L_{\text{FIR}}/R_{\text{FIR}}^2$ will be *overestimated* by 0.5–1.0 dex - a shift that might affect a number of unresolved datapoints in e.g. the [C 2]/FIR – Σ_{SFR} plane (Figure 5.7).

5.4.2 Molecular gas kinematics

The [C 2] and CO (3–2) lines provide two independent measurements of the molecular gas velocity structure. Due to their different spatial extents (Section 5.3.2), the [C 2] and CO (3–2) emission trace the velocity field at different radii. Figure 5.6 shows the line-of-sight velocity as traced by the [C 2] and CO (3–2) emission, and the GALPAK3D model of the [C 2] disc. In particular, the [C 2] emission probes the velocity field within the inner 2-kpc region. Typically, rotational curves of disc-like galaxies are decomposed into contributions from the

dark matter halo, and baryons in the form of a galactic bulge and disc. Given the baryonic mass $M_{\text{bar}} = M_* + M_{\text{gas}}$ is comparable to the dynamical mass enclosed within twice the CO (3–2) half-light radius (5.2 and 6.0 kpc in ALESS 49.1 and 57.1, respectively; Table 5.2), we conclude that the inner rotation curve is baryon-dominated.

In both ALESS 49.1 and 57.1, the line-of-sight velocity v_{los} flattens at 2–4 kpc radius. As a dominant bulge would cause the v_{los} to increase rapidly on sub-kpc scales, we speculate that the inner ($R \leq 2$ kpc) rotational curves in ALESS 49.1 and 57.1 are disc-dominated. However, higher-SNR data are necessary to confirm this hypothesis.

The rotation curves have been studied at a comparable resolution in only a handful of DSFGs. In this respect, ALESS 49.1 and 57.1 velocity fields are most directly comparable to those in $z = 2.4$ twin hyperluminous DSFGs H-ATLAS J084933 (Ivison et al. 2013) and strongly lensed DSFGs SMM J2135-0102 ($z = 2.032$, Swinbank et al. 2011) and SDP.81 ($z = 3.042$, Dye et al. 2015; Rybak et al. 2015b), which flatten out at ~ 200 km s $^{-1}$ within the inner 2-kpc radius. The dynamical mass enclosed within the central 2-kpc radius region of ALESS 49.1 and 57.1 is $M_{\text{dyn}}(R \leq 2 \text{ kpc}) = (6.2 \pm 5.5) \times 10^{10}$ and $(2.7 \pm 1.6) \times 10^{10} M_{\odot}$, respectively; although CO (3–2) observations provide mass estimates at 5–6 kpc radius, the large uncertainties prevent us from investigating the mass profiles of the two sources. The limited extent of the bright [C 2] component and the possibility that an extended [C 2] emission in ALESS 49.1 is resolved out highlight the limits of using very high-angular-resolution observations to trace the kinematics of the cold gas reservoir.

Finally, given the ordered rotation in ALESS 49.1 and 57.1, we can use the [C 2]/CO(3–2) ratio to search for variations in gas physical conditions in different regions of the source. We bin the one-dimensional spectra from Figure 5.4 into bins 250 km s $^{-1}$ wide. Although by eye the [C 2] and CO (3–2) ratio in ALESS 49.1 seems to vary between across the spectrum, we do not find any change in [C 2]/CO(3–2) ratio in either source at $\geq 2\text{-}\sigma$ level given the current depth of the Bands 3 and 8 observations.

5.4.3 The resolved [CII]-FIR ratio

The high resolution of ALMA Band 8 data allows us to investigate the $L_{[\text{CII}]} / L_{\text{FIR}}$ ratio at $z \sim 3$ on 1-kpc scales. Here, we focus on the *central region* ($R \leq 2$ kpc), in which the contribution of any extended [C 2] component is below 20 per cent. This discussion does not include the *global* tracer ratios, as the Band 8 observations might resolve out significant fraction of the total [C 2] flux from an extended component.

The star-formation rate surface density Σ_{SFR} is estimated by adopting the global SFR from our SED fits 5.3.4, assuming (1) a linear mapping between the rest-frame 160- μm emission and SFR; (2) no AGN contribution to the rest-frame FIR luminosity; (3) universal IMF (c.f. Zhang et al. 2018a). The linear mapping between the FIR continuum and SFR density assumes a constant dust temperature and opacity across the source. Further high-resolution, multi-band observations of the dust continuum and spatially-resolved SED modelling would be required for a more precise Σ_{SFR} estimate for different parts of the source. The [C 2]/FIR ratio was extracted by binning the [C 2] and 160- μm continuum maps (Fig. 5.1) into pixels 1 beamwidth large; only pixels for which both the [C 2] and 160- μm continuum have $\text{SNR} \geq 2$ are considered.

Figure 5.7 shows the resolved $L_{[\text{CII}]} / L_{\text{FIR}}$ for ALESS 49.1 and 57.1 as a function of the SFR surface density Σ_{SFR} , compared to resolved and unresolved measurements from both local and high-redshift sources (Smith et al. 2017; Díaz-Santos et al. 2017; Gullberg et al. 2018 and references therein). In both ALESS 49.1 and 57.1, the resolved ratio decreases sharply with Σ_{SFR} , confirming the [C 2]/FIR deficit on 1-kpc scales.

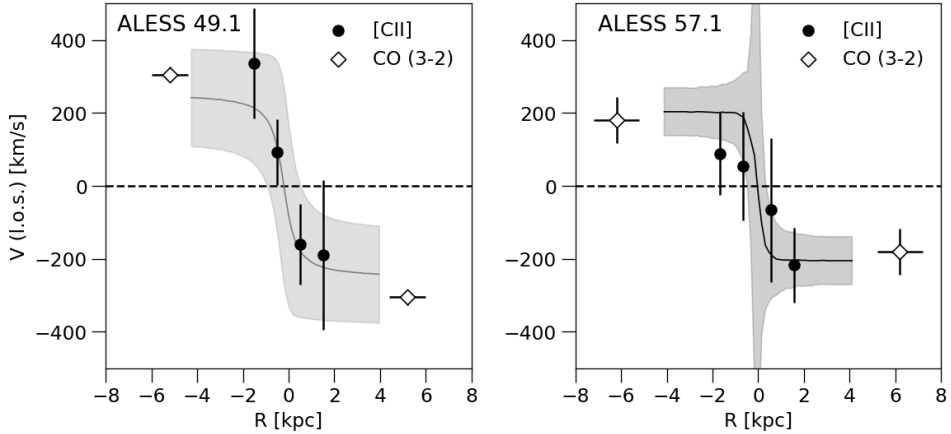


Figure 5.6: Line-of-sight velocity curves for ALESS 49.1 and 57.1, showing the [C 2] velocity and velocity dispersions measured from the image cubes (full dots), with inferred rotation curve from GALPAK3D (full line, velocity dispersion estimate indicated by the shaded region), alongside the CO (3–2) measurements (empty diamonds, Calistro Rivera et al. 2018). The [C 2] measurements were extracted along the major kinematic axis determined by the GALPAK3D modelling from an aperture 1 beamwidth wide. The line-of-sight velocity flattens out at ~ 2 -kpc radius, suggesting disc-dominated kinematics. The large GALPAK3D-predicted velocity dispersion at the centre of ALESS 57.1 is a numerical artefact.

Comparing our measurements with an empirical relation between [C 2]/FIR ratio and Σ_{SFR} proposed by Smith et al. (2017),

$$\Sigma_{\text{SFR}} = (12.7 \pm 3.2) \left(\frac{L_{[\text{CII}]} / L_{\text{FIR}}}{0.001} \right)^{-4.7 \pm 0.8} M_{\odot} \text{yr}^{-1} \text{kpc}^{-2}. \quad (5.3)$$

we find that the bulk of the ALESS 49.1 and 57.1 [C 2]/FIR measurements are below the $1\text{-}\sigma$ scatter of the Smith et al. (2017) relation, with Σ_{SFR} almost 1–2 dex lower than those predicted by the Smith et al. (2017) relation. This suggests that the Smith et al. (2017) $\Sigma_{\text{SFR}} - L_{[\text{CII}]} / L_{\text{FIR}}$ might not be directly applicable in the high- Σ_{SFR} regime in ALESS 49.1 and 57.1.

We note that the ALESS 49.1 and 57.1 [C 2]/FIR measurements fall below the redshift ~ 4.5 resolved measurements of Gullberg et al. (2018). This can be attributed to several factors: (1) different object selection; (2) aperture-averaging effects in Gullberg et al. (2018), as the [C 2]/FIR ratio is calculated for apertures several kpc wide; (3) systematic uncertainties such as assuming uniform T_{dust} for each source. Regarding object selection, ALESS 49.1 and 57.1 have L_{FIR} more than $2\times$ higher than Gullberg et al. (2018) sources, while being more compact in the rest-frame FIR continuum; consequently, our measurements might probe a higher Σ_{FIR} regime, which would correspond to lower [C 2]/FIR ratio and potentially higher T_{gas} (see Section 5.4.4).

The radial variation of $L_{[\text{CII}]} / L_{\text{FIR}}$ in ALESS 49.1 and 57.1 is shown in Figure 5.8. A decrease in the [C 2]/FIR ratio towards the centre of the source is seen in both local star-forming galaxies (e.g. Madden et al. 1993; Smith et al. 2017) and high-redshift sources (Gullberg et al. 2018) and indicates that the [C 2]/FIR deficit is driven by local processes, as opposed to global properties of the sources. In particular, Smith et al. (2017) found the [C 2]/FIR ratio to be suppressed by on average 30 ± 15 per cent in the central $R \leq 400$ pc regions of galaxies without an AGN. On the other hand, [C 2]/FIR ratio drops by a factor of a few over the inner 2 kpc in nu-

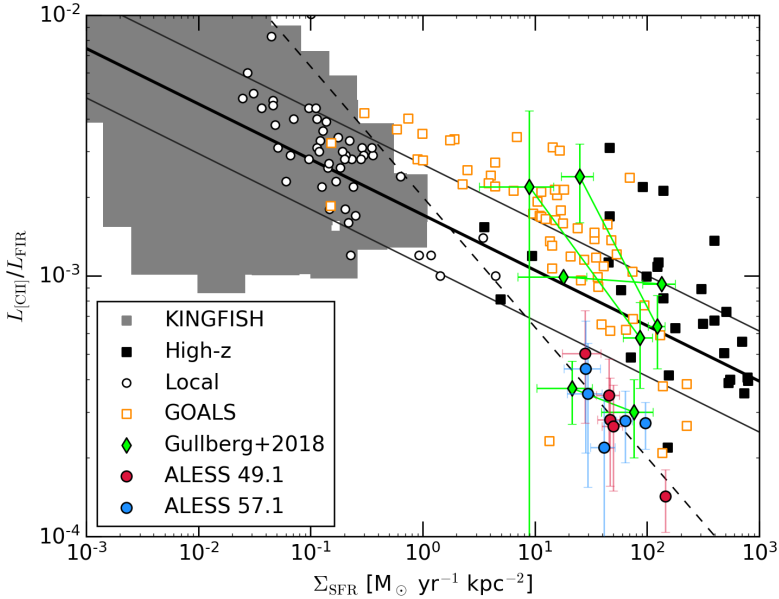


Figure 5.7: Resolved [C 2]/FIR deficit in ALESS 49.1 and 57.1, compared to the KINGFISH Smith et al. (2017) and GOALS Díaz-Santos et al. (2017) samples and other local (empty circles) and high-redshift measurements (black squares), adapted from Smith et al. (2017) and Gullberg et al. (2018). For each of the Gullberg et al. (2018) sources, we show the ratio for the inner and outer region, connected by a line. The thick black lines indicates the Smith et al. (2017) empirical fit to the [C 2]/FIR data (equation (5.3) and the corresponding $1\text{-}\sigma$ scatter; the dashed line indicates the prediction from the Muñoz & Oh (2016) temperature-saturation model (equation (5.5)), for $f_{[\text{CII}]}=0.13$. The resolved ALESS 49.1 and 57.1 data-points fall below the Smith et al. (2017) trend, and follow a much steeper slope, indicating a [C 2]-saturation regime. The errorbars on ALESS 49.1 and 57.1 measurements include a contribution from an extended [C 2]/160- μm continuum components.

clear starbursts in M82 and M83 (Herrera-Camus et al. 2018). Fitting the resolved [C 2]/FIR data with a power-law $L_{[\text{CII}]} / L_{[\text{CII}]} \propto R^\alpha$, we find a strong evidence for a radial variation of the [C 2]/FIR ratio in ALESS 49.1 ($\alpha = 0.41 \pm 0.06$), while in ALESS 57.1, the data is consistent with being uniform ($\alpha = 0.05 \pm 0.05$). While the obscured *Chandra*-detected AGN in ALESS 57.1 (Wang et al. 2013) might be expected to suppress the [C 2] emission in the circumnuclear region, we do not detect any strong [C 2] suppression in ALESS 57.1 on 1-kpc scales. The difference in the [C 2]/FIR radial profiles in ALESS 49.1 and 57.1 is due to the larger scatter in [C 2]/FIR ratio for a given Σ_{SFR} in ALESS 57.1 (see Figure 5.7), which is a result of the complex [C 2] and 160- μm morphology (Figure 5.1). Note that the limited SNR of our data at $R \geq 2$ kpc prevents us to study the [C 2]/FIR radial dependence at larger radii.

5.4.4 Comparison with PDR models

The relative intensities of the [C 2], CO (3–2) and FIR emission from hot-dissociation regions (PDRs) depend on the ionizing FUV field strength G_0 and the gas density $n(\text{H})$, which determine the depth of the outer C^+ layer. We now use our resolved [C 2]/CO(3–2)/FIR observations to infer the G_0 and n using the PDR models from the PDRTOLBOX library (Kaufman

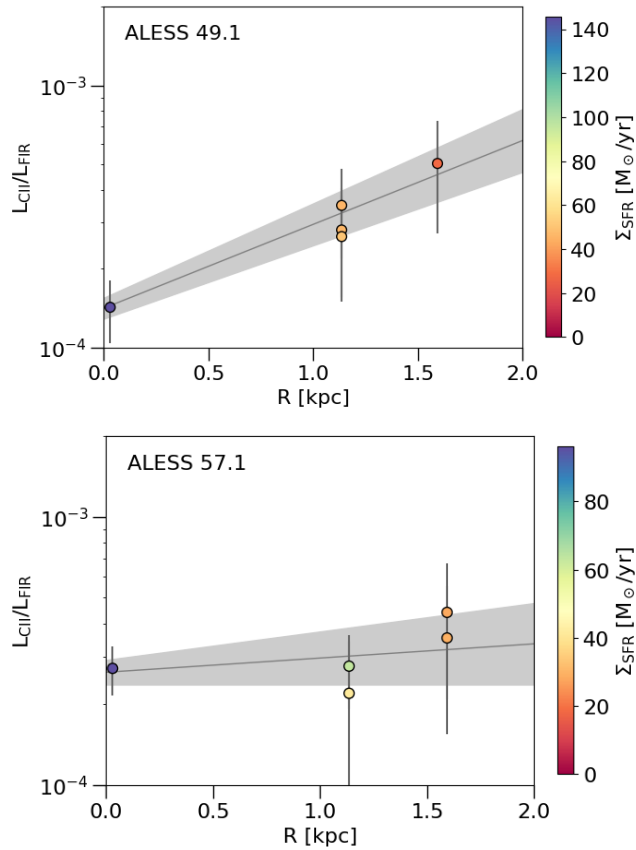


Figure 5.8: [C 2]/FIR deficit radial trends in ALESS 49.1 and 57.1, colour-coded by the star-formation rate surface density Σ_{SFR} ; each point corresponds to a separate resolution element. The lines and shaded regions indicate the best-fitting slopes and corresponding uncertainties, respectively. The radial distances R are measured from the $160\text{-}\mu\text{m}$ continuum surface brightness maximum.

Table 5.3: Comparison with PDRTOLBOX PDR models: observed [C 2]/CO(3–2) and [C 2]/FIR continuum ratios, along with inferred FUV field strength G_0 , density $n(\text{H})$ and PDR surface temperature T_{PDR} for ALESS 49.1 and 57.1. We consider both optically thin and thick [C 2] scenarios. The [C 2] luminosities are given before subtracting the contribution from non-PDR sources.

Source	ALESS 49.1	ALESS 57.1
[C 2]/FIR	$(3.3 \pm 1.5) \times 10^{-4}$	$(3.4 \pm 1.2) \times 10^{-4}$
[C 2]/CO(3–2)	310 ± 100	600 ± 240
[C 2] optically thin		
$\log G_0$	$4.1^{+0.3}_{-0.2}$	$4.1^{+0.9}_{-0.4}$
$\log n(\text{H})$ [cm ⁻³]	$4.2^{+0.5}_{-0.2}$	$3.6^{+0.5}_{-0.3}$
T_{gas} [K]	720 ± 200	670 ± 170
[C 2] optically thick		
$\log G_0$	$3.7^{+0.4}_{-0.3}$	$3.7^{+0.9}_{-0.4}$
$\log n(\text{H})$ [cm ⁻³]	$3.4^{+0.4}_{-0.2}$	$2.8^{+0.5}_{-0.2}$
T_{gas} [K]	430 ± 30	480 ± 90

et al. 2006; Pound & Wolfire 2008). We focus on the central regions of the source ($R \leq 2$ kpc) adopting the one/two-component Gaussian models from Section 5.3.2.

For a proper comparison, several corrections need to be applied. First, the [C 2] emission from the ionized ISM needs to be subtracted from the observed [C 2] signal. The contribution from the ionized gas can be estimated from [N 2] 122/205- μm lines, which have similar critical density for collisions with electrons ($300 \text{ cm}^{-3}/32 \text{ cm}^{-3}$) as the [C 2] line (50 cm^{-3} , Goldsmith et al. 2012), but ionization energy > 13.6 eV and hence traces only the ionized gas. Croxall et al. (2017) carried out a systematic study of the [N 2] 122/205 μm lines in a sample of 21 nearby star-forming galaxies, estimating the fraction of [C 2] in PDRs as $f_{[\text{CII}]}^{\text{PDR}} \geq 0.8$ for sources with $\Sigma_{\text{SFR}} \geq 10^{-2} \text{ M}_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$. At high redshift, Zhang et al. (2018b) used [N 2] 122- μm line observations in $z = 1 - 3$ DSFGs to derive 10–15 per cent ionized gas contribution to [C 2] luminosity, assuming Galactic diffuse gas N and C abundancies. We adopt a conservative estimate of $f_{[\text{CII}]}^{\text{PDR}} = 0.8$.

Second, PDRTOLBOX models are derived for a one-dimensional, semi-infinite slab, illuminated from the face side only. In the intensely star-forming DSFGs, we expect the clouds to be illuminated from multiple sides and the optical thickness of individual tracers needs to be considered. Namely, for optically thick emission, only the emission from the side of the cloud facing the observer is observed; while for the optically thin emission, the distant side of the cloud adds to the observed fluxes and the line intensities expected from PDR models need to be multiplied by a factor of 2 Kaufman et al. (1999). The 160- μm continuum is generally assumed to be optically thin. Based on the models of Narayanan & Krumholz (2014), CO (3–2) line is optically thick with a median optical depth ≥ 10 for $\Sigma_{\text{SFR}} = 10^{-1} - 10^3 \text{ M}_{\odot} \text{ yr}^{-1}$. The [C 2] emission is optically thin in most environments; although there is evidence for moderately optically thick [C 2] (optical depth ~ 1) in both Galactic PDRs (Graf et al. 2012; Sandell et al. 2015) and high-redshift sources (Gullberg et al. 2015). We consider both optically-thin and optically-thick [C 2] scenarios, adopting the former for the rest of this paper.

Figure 5.9 shows the contours in the G_0/n space for the central $R \leq 2$ kpc region of ALESS 49.1 and 57.1, with best-fitting values listed in Table 5.3. The combination of the three tracers provides orthogonal constraints on G_0 and n . In particular, G_0 is largely determined by the [C 2]/FIR ratio, and n by [C 2]/CO (3–2). Table 5.3 lists the inferred G_0 and

n values for the optically thin and optically thick [C 2] scenarios, along with the PDR surface temperature. For the optically-thin [C 2] case, the conditions in ALESS 49.1 and 57.1 are almost identical, with $\log G_0 \sim 4.1$ and $\log n \sim 4.0$, implying PDR surface temperature T_{PDR} of ~ 700 K. Increasing the fraction of [C 2] emission from the PDRs from 0.8 to 1.0 causes the inferred G_0 and n values to decrease by ≤ 0.25 dex. For the optically-thick [C 2] case, the inferred G_0 and n decrease almost 0.5 and 1.0 dex, respectively; T_{PDR} is reduced to 400–500 K.

The G_0 , n values in the central region of ALESS 49.1 and 57.1 are comparable to those inferred from unresolved SMG observations ($n = 10^2 - 10^4 \text{ cm}^{-3}$, $G_0 = 10^3 - 10^{4.5}$, Stacey et al. 2010; Danielson et al. 2013; Wardlow et al. 2017; Alaghband-Zadeh et al. 2013; Zhang et al. 2018b). Gullberg et al. (2015) found a larger scatter of FUV strength ($G_0 = 10^2 - 8 \times 10^3$) and density ($n = 10^2 - 10^5 \text{ cm}^{-3}$), although the effect of differential magnification might be substantial. For nearby star-forming galaxies, a comparison of observed spatially integrated [C 2], [O 1] 63- μm and FIR luminosities with the PDRTOOLBOX models was carried out by Malhotra et al. (2001) and Díaz-Santos et al. (2017). ALESS 49.1 and 57.1 are consistent with the high-density Malhotra et al. (2001) sources; however, G_0 and n in ALESS 49.1 and 57.1 are higher than in the most dense ultra-luminous infrared galaxies (ULIRGs) from the Díaz-Santos et al. (2017) sample, which have $G_0 \sim 10^3$, $n = 1 - 10^3 \text{ cm}^{-3}$. Note that the globally-averaged G_0 and n in ALESS 49.1 and 57.1 might be lower than those inferred from the $R \leq 2$ kpc region. On kpc-scales, G_0 and n in the central regions of ALESS 49.1 and 57.1 are more comparable to the resolved observations of central star-forming regions in nearby starburst galaxies NGC 6946 and NGC 1313 ($G_0 = 10^3 - 10^4$, $n = 10^{3.0} - 10^{3.5} \text{ cm}^{-3}$, Contursi et al. 2002).

What drives the strong FUV fields in ALESS 49.1 and 57.1: a central AGN, or star-formation? Although *Chandra* X-ray observations of ALESS 49.1 and 57.1 (Wang et al. 2013) revealed an obscured AGN in ALESS 57.1 (no emission from ALESS 49.1 was detected), it is unlikely that an obscured AGN would be driving a strong FUV field on few-kpc scales. On the other hand, the G_0 in the vicinity of H 2 regions is of the order $10^3 - 10^5$ (e.g. Tielens & Hollenbach 1985; Hollenbach & Tielens 1999), comparable to the values inferred from PDR models. Similarly, typical G_0 and n values for Galactic star-forming regions are of the order of $G_0 = 10^3 - 10^5$, $n = 10^3 - 10^6 \text{ cm}^{-3}$ (Stacey et al. 1991, 2010). We therefore conclude that the strong FUV field in ALESS 49.1 and 57.1 is due to star formation, rather than a central AGN.

5.4.5 Origin of the [CII]/FIR deficit

With estimates of G_0 and n in the central regions of ALESS 49.1 and 57.1, we now turn to the mechanism driving the [C 2]/FIR deficit. We focus on the thermal saturation model proposed by Muñoz & Oh (2016), and the reduction of the photoelectric heating of the gas by small dust grains (e.g. Bakes & Tielens 1994; Malhotra et al. 2001); we briefly discuss other potentially relevant mechanisms – AGN contribution and dust-bound HII regions – in Section 4.5.3. For a more exhaustive list of potential mechanisms behind the [C 2]/FIR deficit, we refer the reader to Smith et al. (2017).

Thermal saturation of the [CII] line

Muñoz & Oh (2016) have proposed the thermal saturation of the upper level of the C⁺ fine-structure transition as the main driver of the [C 2]/FIR deficit. In other words, when T_{gas} exceeds the C⁺ ionization temperature (92 K), the upper/lower level population ratio (and the [C 2] luminosity) depends only weakly on T_{gas} , while the FIR luminosity keeps on increasing.

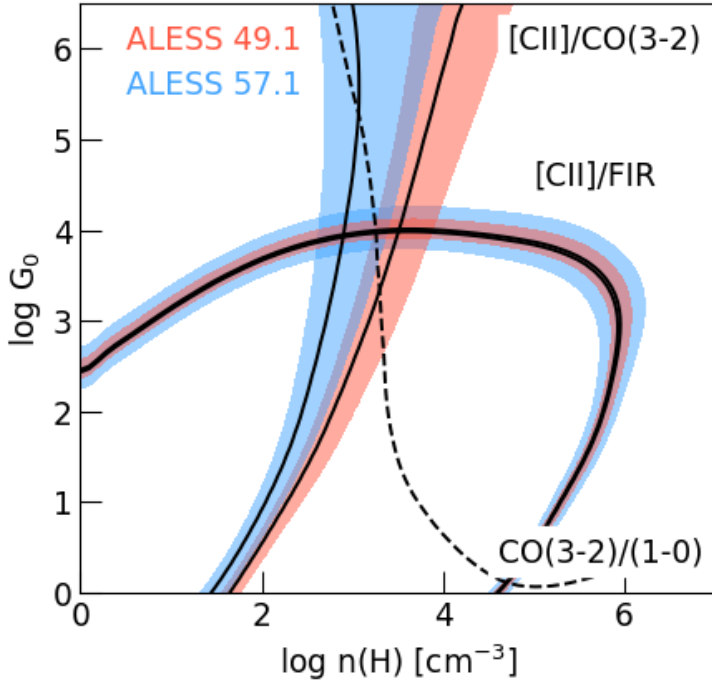


Figure 5.9: Constraints on the FUV field strength G_0 and density n for the central $R \leq 2$ kpc region derived from comparison with Kaufman et al. (2006) PDR models. For the $[\text{C } 2]/\text{FIR}/\text{CO}(3-2)$ emission, we adopt surface brightness profiles derived from the uv -plane fitting. The $[\text{C } 2]$ emission is assumed to be optically thin, with PDR contributing 80 per cent of the observed signal. The coloured areas indicate $1-\sigma$ confidence regions. For the central regions of ALESS 49.1 and 57.1, we infer $G_0 \sim 10^{3.5} - 10^{4.0}$ and $n = 10^{3.6} - 10^{4.2} \text{ cm}^{-3}$.

The PDRTOOLBOX models, which imply high FUV fields strength ($G_0 \sim 10^4$) and densities ($n = 10^{3.5} - 10^4$) and surface temperatures larger than 500 K (Table 5.3). The [C 2] transition is saturated in this regime. Following Muñoz & Oh (2016), the thermal cooling rate per Hydrogen atom via the [C 2] line depends on T_{gas} via

$$\Lambda_{[CII]} = 2.3 \times 10^{-6} k_B T_{[CII]} \frac{2}{2 + \exp(T_{CII}/T_{gas}) \frac{C}{H}}, \quad (5.4)$$

where k_B is the Boltzmann constant and $T_{[CII]}$ is the [C 2] ionization temperature. Following the equation (5.4), the [C 2] cooling rate increases by only ~ 40 per cent between $T_{gas}=100$ K and 500 K, whereas the L_{FIR} increases by a factor of few hundred, assuming T_{dust} scales proportionally with T_{gas} and $L_{FIR} \propto T_{dust}^{4+\beta}$, where we assumed dust opacity $\beta = 1.5$.

For a more direct comparison with Muñoz & Oh (2016) model, we compare the resolved [C 2]/FIR observations in ALESS 49.1 and 57.1 (Figure 5.7) to the predicted Σ_{SFR} -[C 2]/FIR slope. According to Muñoz & Oh (2016), $L_{[CII]}/L_{FIR}$ ratio scales as:

$$\frac{L_{[CII]}}{L_{FIR}} = 2.2 \times 10^{-3} \frac{f_{CII}}{0.13} \left(\frac{\Sigma_{FIR}}{10^{11} L_{\odot} \text{kpc}^{-2}} \right)^{-1/2}, \quad (5.5)$$

where f_{CII} is the fraction of gas emitting in [C 2] and C/H the relative abundances of Carbon/Hydrogen atoms. Fitting our datapoints with a power-law following the equation (5.5), we obtain a best-fitting slope of $\gamma = -0.53 \pm 0.12$. This is in agreement with the thermal-saturation model slope of $\gamma = -0.5$ (equation (5.5)).

We note that Díaz-Santos et al. (2017) discount the thermal saturation of the [C 2] line as a source of the [C 2]/FIR deficit in local star-forming galaxies. Namely, comparing the [O 1] 63 μm and [C 2] line ratios with a statistical equilibrium radiative transfer model, they obtain a scaling between dust and gas kinetic temperature $T_{gas} = 1.6 - 2.1 \times T_{dust}$. Given T_{dust} of 21–48 K, they find $T_{gas} \leq 92$ K, i.e. below the thermal-saturation regime. However, ALESS 49.1 and 57.1 show relatively high global $T_{dust} = 47^{+5}_{-9}/52^{+10}_{-6}$ K (Table 5.2). Given the conversion factors from Díaz-Santos et al. (2017) and evidence for increase in dust and gas temperature towards the centre of DSFGs (Calistro Rivera et al. 2018), T_{gas} in the central regions of ALESS 49.1 and 57.1 exceeds 92 K.

Suppression of the [CII] emission due to positive grain charging

In addition to the temperature saturation, another potentially important effect at the G_0 , n values inferred from our PDR analysis is the reduced photoelectric heating of the gas by electrons ejected from the small dust grains by the FUV photons (e.g. Bakes & Tielens 1994; Malhotra et al. 2001; Wolfire et al. 2003). At high G_0/n ratios, the grains become positively charged, thus raising the potential barrier for the electrons to escape. Qualitatively, a reduced photoelectric heating will manifest in moderate T_{gas}/T_{dust} ratios. Although ALESS 49.1 and 57.1 have elevated dust temperatures compared to other high-redshift DSFGs (Swinbank et al. 2014; da Cunha et al. 2015) and local ULIRGs (Díaz-Santos et al. 2017), the high PDR surface temperatures indicate that the gas is already heated to high temperature, at which point the [C 2] line becomes saturated.

Quantitatively, following Wolfire et al. (2003), the photoelectric heating rate per hydrogen atom is give as:

$$\Gamma_{\text{PE}} = \frac{1.1 \times 10^{-25} G' Z_d}{1 + 3.2 \times 10^{-2} [G' (T_{\text{gas}}/100 \text{ K})^{1/2} n_e^{-1} \phi_{\text{PAH}}]^{0.73}} \text{ erg s}^{-1}, \quad (5.6)$$

where $G' = 1.7 \times G_0$, Z_d is the dust-to-gas ratio (normalized to the Galactic value), n_e the electron density and ϕ_{PAH} a factor associated with the PAH molecules. The second term in the denominator corresponds to the positive grain charging. We follow Muñoz & Oh (2016) by adopting $n_e = 1.1 \times 10^{-4} n$, $\phi_{\text{PAH}} = 0.5$. Note that equation (5.6) assumes $T_{\text{gas}} \leq 1000 \text{ K}$, which is satisfied for both ALESS 49.1 and 57.1. While for the ALESS 49.1 and 57.1 values of G_0 , n the second term in the denominator corresponding to the reduction in photoelectric heating, becomes dominant, the numerator is also proportional to G_0 . Comparing a typical nearby star-forming galaxy with $G_0 = 10^2$, $n = 10^4 \text{ cm}^{-3}$, (c.f. Muñoz & Oh 2016) and ALESS 49.1 and 57.1 with $G_0 = 10^4$, $n = 10^4 \text{ cm}^{-3}$, the second term in the determinant increases from ~ 0.3 to ~ 18 , indicating a significant reduction in the gas heating due to grain charging. However, at the same time, the overall Γ_{PE} increases by a factor of ~ 6 .

Therefore, we attribute the pronounced [C 2]/FIR deficit in the central regions of ALESS 49.1 and 57.1 to the high gas temperature which results in a quantum-level saturation of the C^+ fine structure.

Other mechanisms for [CII]/FIR deficit

Finally, we briefly consider other proposed mechanisms for the [C 2] deficit.

AGNs can contribute to the [C 2] deficit, both by increasing the FIR luminosity and reduce the C^+ abundance and the [C 2] emission by ionizing the carbon atoms to higher ionization states (C^{2+} , C^{3+} etc.) via soft X-ray radiation (Langer & Pineda 2015). *Chandra* of ALESS 49.1 and 57.1 revealed an obscured AGN with an extinction-corrected X-ray luminosity of $\log L_{0.5-8.0\text{keV}} = 44.3$ and no X-ray emission in ALESS 49.1 (Wang et al. 2013). According to Langer & Pineda (2015) models, for $n \sim 10^3 \text{ cm}^{-3}$ (model closest to the conditions in ALESS 49.1 and 57.1), a 10 per cent decrease in the fraction of carbon in the C^+ state requires an X-ray flux of $f_X \approx 10^{3.5} \text{ erg cm}^{-2} \text{ s}^{-1}$. Assuming an X-ray flux dilutes with distance D as $1/4\pi D^2$, the AGN in ALESS 57.1 will affect only the innermost $\sim 100 \text{ pc}$ radius, well below the spatial resolution of our data. Consequently, we do not expect a significant AGN contribution to the observed [C 2] deficit.

Another potential explanation for the [C 2]/FIR deficit is the increased absorption of ionizing UV photons by the dust in dust-bounded H 2 regions, which would result in increased FIR and decreased [C 2] luminosity, respectively (Luhman et al. 2003). Abel et al. (2009) used radiative transfer models of dust-bounded H 2 region to qualitatively reproduce the [C 2]/FIR deficit trend. However, for the observed [C 2]/FIR values in ALESS 49.1 and 57.1, the Abel et al. (2009) models require densities of $n \leq 1 - 2 \times 10^3 \text{ cm}^{-3}$, i.e. much lower than those inferred from the PDR modelling. Furthermore, as already noted by Muñoz & Oh (2016), the dust drift time for high G_0 , n values becomes very short compared to O/B stars lifetime. We follow Draine (2011) to estimate a dust drift time for a cluster of 10^3 O/B stars, providing an ionizing photons flux $Q_0 = 10^{52} \text{ s}^{-1}$. Given the density of $10^{3.5} - 10^{4.0} \text{ cm}^{-3}$, the dust drift time becomes $t_{\text{drift}} = 1.0 - 1.5 \times 10^5 \text{ yr}$ (Figure 9 of Draine 2011). Even if the H 2 regions in ALESS 49.1 and 57.1 are originally dust-bound, given the duration of the starburst, we do not expect a significant fraction of the to be dust-bound at a given moment and hence do not expect the dust-bounded H 2 regions to dominate the [C 2]/FIR deficit in ALESS 49.1 and 57.1.

5.5 Conclusions

We have investigated the morphology and kinematics of the [C 2] 157.74- μm line emission and associated 160- μm rest-frame continuum in two $z \sim 3$ sources from the ALESS sample, based on the 0.15 arcsec ALMA Band 8 imaging. The morphology and [C 2] velocity field in both galaxies is consistent with an inclined rotating exponential disc. The [C 2] rotation curves show a flattening within the inner 2-3 kpc radius, indicative of a potential dominated by a baryonic disc.

Comparing the resolved maps of the [C 2] emission with those of CO (3–2) (Calistro Rivera et al. 2018), we found the [C 2] surface brightness distribution to be concentrated into a region a factor of 2–3 more compact the CO (3–2). In ALESS 49.1, we found evidence for a low surface-brightness, extended ($R_{1/2} \sim 8$ kpc) [C 2] component, accounting for up to 80 percent of the [C 2] brightness. Based on mock ALMA observations, we excluded the possibility that [C 2] and 160- μm continuum follow the same single-Gaussian surface brightness as the CO (3–2) emission.

We compared of the [C 2]/FIR and CO (3–2) observations to the PDRTOLBOX photo-dissociation regions models (Kaufman et al. 2006; Pound & Wolfire 2008). These indicate intense FUV radiation field ($G_0 \sim 10^4$) and moderately high gas densities ($n(\text{H}) = 10^{3.5} - 10^{4.0} \text{ cm}^{-3}$). These are comparable to the G_0 and n values found in the central regions of nearby starbursts (e.g. Contursi et al. 2002), as well as in other $z > 2$ SMGs (Stacey et al. 2010). We attribute the strong FUV field to massive the star-formation, rather than by an obscured AGN.

We tested the applicability of the Stacey et al. (2010) technique for estimating FIR source size from unresolved [C 2]/low- J CO / FIR observations to ALESS 49.1 and 57.1. The Stacey et al. (2010) method yields estimates a factor of 2.5–3.5 more compact than the FIR sizes measured from the uv -plane fitting; this bias causes the SFR surface-density to be overestimated by up to 1 dex, having a potentially significant impact on the interpretation of low-resolution observations.

Both ALESS 49.1 and 57.1 show a pronounced [C 2]/FIR deficit. The resolved [C 2]/FIR luminosity ratios fall below the empirical trend of Smith et al. (2017), indicating a change in physical conditions compared to the nearby star-forming galaxies. A comparison with PDR models indicated surface temperatures of 400–800 K; at such a high temperature, the occupancy of the upper fine-structure level of C^+ ions (and the [C 2] luminosity) saturates, while FIR luminosity increases sharply. The most direct interpretation is that the strong [C 2] deficit is a result of the [C 2] temperature saturation (Muñoz & Oh 2016). In addition, in the resolved [C 2]/FIR measurements in ALESS 49.1 and 57.1 scale with star-formation rate surface density $\Sigma_{\text{SFR}}^{-0.53 \pm 0.12}$, in agreement with the thermal-saturation scenario slope of -0.5 (Muñoz & Oh 2016). Although the photoelectric heating of the gas is reduced due to positive grain charging, for the G_0 , n values in ALESS 49.1 and 57.1, the thermal saturation is the main driving mechanism of the [C 2]/FIR deficit. This contrasts with the local star-forming galaxies, which are found to have gas temperatures below the C^+ ionization energy (e.g. Díaz-Santos et al. 2017).

With only two galaxies in our sample, it is difficult to generalize our conclusions to the entire population of dusty, star-forming galaxies. With ALMA now enabling routine observations of [C 2] emission at redshift 3 and beyond, and with a rapid increase of high-redshift sources with robust spectroscopic redshifts that are necessary for parallel [C 2]/CO observations, this study is a precursor to future multi-tracer, resolved studies of ISM at high redshift, and a necessary stepping stone to interpreting the [C 2] observations at very high redshift.

Acknowledgements

The authors thank Frank Israel and Desika Narayanan for helpful discussions about the [C 2]/CO extent. This paper makes use of the following ALMA data: ADS/JAO.ALMA#2013.1.00470.S, #2015.1.00019.S, #2015.1.00948.S and #2016.1.00754.S. ALMA is a partnership of ESO (representing its member states), NSF (USA) and NINS (Japan), together with NRC (Canada), MOST and ASIAA (Taiwan), and KASI (Republic of Korea), in cooperation with the Republic of Chile. The Joint ALMA Observatory is operated by ESO, AUI/NRAO and NAOJ. MR and JH acknowledge support of the VIDI research programme with project number 639.042.611, which is (partly) financed by the Netherlands Organisation for Scientific Research (NWO). IRS acknowledges support from the ERC Advanced Grant DUSTYGAL (321334) and STFC (ST/P000541/1). HD acknowledges financial support from the Spanish Ministry of Economy and Competitiveness (MINECO) under the 2014 Ramón y Cajal program MINECO RYC-2014-15686. JLW acknowledges support from an STFC Ernest Rutherford Fellowship (ST/P004784/1).

Bibliography

- Abel, N. P., Dudley, C., Fischer, J., Satyapal, S., & van Hoof, P. A. M. 2009, *ApJ*, 701, 1147
- Alaghband-Zadeh, S., Chapman, S. C., Swinbank, A. M., et al. 2013, *MNRAS*, 435, 1493
- ALMA Partnership, Vlahakis, C., Hunter, T. R., et al. 2015, *ApJl*, 808, L4
- Armus, L., Mazzarella, J. M., Evans, A. S., et al. 2009, *PASP*, 121, 559
- Bakes, E. L. O., & Tielens, A. G. G. M. 1994, *ApJ*, 427, 822
- Bevington, P. R. 1969, *Data reduction and error analysis for the physical sciences*
- Bothwell, M. S., Smail, I., Chapman, S. C., et al. 2013, *MNRAS*, 429, 3047
- Bouché, N., Carfantan, H., Schroetter, I., Michel-Dansac, L., & Contini, T. 2015, *AJ*, 150, doi:10.1088/0004-6256/150/3/92
- Brisbin, D., Ferkinhoff, C., Nikola, T., et al. 2015, *ApJ*, 799, 13
- Calistro Rivera, G., Hodge, J. A., Smail, I., et al. 2018, *ApJ*, 863, 56
- Carilli, C. L., & Walter, F. 2013, *ARA&A*, 51, 105
- Carniani, S., Maiolino, R., Amorin, R., et al. 2017, *ArXiv e-prints*, arXiv:1712.03985
- Casey, C. M., Narayanan, D., & Cooray, A. 2014, *Phys. Rep.*, 541, 45
- Chen, C.-C., Hodge, J. A., Smail, I., et al. 2017, *ApJ*, 846, doi:10.3847/1538-4357/aa863a
- Cicone, C., Maiolino, R., Gallerani, S., et al. 2015, *A&A*, 574, A14
- Contursi, A., Kaufman, M. J., Helou, G., et al. 2002, *AJ*, 124, 751
- Cooke, E. A., Smail, I., Swinbank, A. M., et al. 2018, *ApJ*, 861, 100
- Croxall, K. V., Smith, J. D., Pellegrini, E., et al. 2017, *ApJ*, 845, 96

- da Cunha, E., Charlot, S., & Elbaz, D. 2008, *MNRAS*, 388, 1595
- da Cunha, E., Groves, B., Walter, F., et al. 2013, *ApJ*, 766, doi:10.1088/0004-637X/766/1/13
- da Cunha, E., Walter, F., Smail, I. R., et al. 2015, *ApJ*, 806, 110
- Danielson, A. L. R., Swinbank, A. M., Smail, I., et al. 2013, *MNRAS*, 436, 2793
- . 2017, *ApJ*, 840, 78
- de Blok, W. J. G., Walter, F., Smith, J.-D. T., et al. 2016, *AJ*, 152, 51
- Decarli, R., Walter, F., Venemans, B. P., et al. 2018, *ApJ*, 854, doi:10.3847/1538-4357/aaa5aa
- Díaz-Santos, T., Armus, L., Charmandaris, V., et al. 2013, *ApJ*, 774, 68
- Díaz-Santos, T., Armus, L., Charmandaris, V., et al. 2017, *ApJ*, 846, 32
- Draine, B. T. 2011, *ApJ*, 732, 100
- Dye, S., Furlanetto, C., Swinbank, A. M., et al. 2015, *MNRAS*, 452, 2258
- Goldsmith, P. F., Langer, W. D., Pineda, J. L., & Velusamy, T. 2012, *The Astrophysical Journal Supplement Series*, 203, doi:10.1088/0067-0049/203/1/13
- Graciá-Carpio, J., Sturm, E., Hailey-Dunsheath, S., et al. 2011, *ApJ*, 728, L7
- Graf, U. U., Simon, R., Stutzki, J., et al. 2012, *A&A*, 542, L16
- Gullberg, B., De Breuck, C., Vieira, J. D., et al. 2015, *MNRAS*, 449, 2883
- Gullberg, B., Swinbank, A. M., Smail, I., et al. 2018, *ArXiv e-prints*, arXiv:1804.03663
- Herrera-Camus, R., Sturm, E., Graciá-Carpio, J., et al. 2018, *ArXiv e-prints*, arXiv:1803.04419
- Hodge, J. A., Carilli, C. L., Walter, F., et al. 2012, *ApJ*, 760, doi:10.1088/0004-637X/760/1/11
- Hodge, J. A., Riechers, D., Decarli, R., et al. 2015, *ApJ*, 798, L18
- Hodge, J. A., Karim, A., Smail, I., et al. 2013, *ApJ*, 768, 91
- Hodge, J. A., Swinbank, A. M., Simpson, J. M., et al. 2016, *ApJ*, 833, 103
- Hollenbach, D. J., & Tielens, A. G. G. M. 1999, *Reviews of Modern Physics*, 71, 173
- Huynh, M. T., Kimball, A. E., Norris, R. P., et al. 2014, *MNRAS*, 443, L54
- Huynh, M. T., Emonts, B. H. C., Kimball, A. E., et al. 2017, *MNRAS*, 467, 1222
- Ivison, R. J., Papadopoulos, P. P., Smail, I., et al. 2011, *MNRAS*, 412, 1913
- Ivison, R. J., Swinbank, A. M., Smail, I., et al. 2013, *ApJ*, 772, 137
- Kaufman, M. J., Wolfire, M. G., & Hollenbach, D. J. 2006, *ApJ*, 644, 283
- Kaufman, M. J., Wolfire, M. G., Hollenbach, D. J., & Luhman, M. L. 1999, *ApJ*, 527, 795
- Lagache, G., Cousin, M., & Chatzikos, M. 2018, *A&A*, 609, doi:10.1051/0004-6361/201732019

- Langer, W. D., & Pineda, J. L. 2015, *A&A*, 580, A5
- Luhman, M. L., Satyapal, S., Fischer, J., et al. 2003, *ApJ*, 594, 758
- . 1998, *ApJ*, 504, L11
- Madden, S. C., Geis, N., Genzel, R., et al. 1993, *ApJ*, 407, 579
- Malhotra, S., Helou, G., Stacey, G., et al. 1997, *ApJ*, 491, L27
- Malhotra, S., Kaufman, M. J., Hollenbach, D., et al. 2001, *ApJ*, 561, 766
- McMullin, J. P., Waters, B., Schiebel, D., Young, W., & Golap, K. 2007, in *Astronomical Data Analysis Software and Systems XVI ASP Conference Series*, Vol. 376, proceedings of the conference held 15-18 October 2006 in Tucson, Arizona, USA. Edited by Richard A. Shaw, Frank Hill and David J. Bell., p.127, Vol. 376, 127
- Muñoz, J. A., & Oh, S. P. 2016, *MNRAS*, 463, 2085
- Narayanan, D., & Krumholz, M. R. 2014, *MNRAS*, 442, 1411
- Offringa, A. R., & Smirnov, O. 2017, *MNRAS*, 471, 301
- Offringa, A. R., McKinley, B., Hurley-Walker, N., et al. 2014, *MNRAS*, 444, 606
- Olsen, K. P., Greve, T. R., Narayanan, D., et al. 2015, *ApJ*, 814, 76
- Oteo, I., Ivison, R. J., Dunne, L., et al. 2016, *ApJ*, 827, 34
- Pineda, J. L., Langer, W. D., Velusamy, T., & Goldsmith, P. F. 2013, *A&A*, 554, A103
- Planck Collaboration, Ade, P. A. R., Aghanim, N., et al. 2016, *A&A*, 594, A13
- Pound, M. W., & Wolfire, M. G. 2008, in *Astronomical Society of the Pacific Conference Series*, Vol. 394, *Astronomical Data Analysis Software and Systems XVII*, ed. R. W. Argyle, P. S. Bunclark, & J. R. Lewis, 654
- Riechers, D. A., Hodge, J., Walter, F., Carilli, C. L., & Bertoldi, F. 2011, *ApJ*, 739, L31
- Rybak, M., McKean, J. P., Vegetti, S., Andreani, P., & White, S. D. M. 2015a, *MNRAS*, 451, L40
- Rybak, M., Vegetti, S., McKean, J. P., Andreani, P., & White, S. D. M. 2015b, *MNRAS*, 453, L26
- Sandell, G., Mookerjee, B., Güsten, R., et al. 2015, *A&A*, 578, A41
- Serjeant, S. 2012, *MNRAS*, 424, 2429
- Smit, R., Bouwens, R. J., Carniani, S., et al. 2018, *Nature*, 553, 178
- Smith, J. D. T., Croxall, K., Draine, B., et al. 2017, *ApJ*, 834, 5
- Spilker, J. S., Aravena, M., Marrone, D. P., et al. 2015, *ApJ*, 811, 124
- Stacey, G. J., Geis, N., Genzel, R., et al. 1991, *ApJ*, 373, 423
- Stacey, G. J., Hailey-Dunsheath, S., Ferkinhoff, C., et al. 2010, *ApJ*, 724, 957

- Stefan, I. I., Carilli, C. L., Wagg, J., et al. 2015, *MNRAS*, 451, 1713
- Swinbank, A. M., Papadopoulos, P. P., Cox, P., et al. 2011, *ApJ*, 742, 11
- Swinbank, A. M., Simpson, J. M., Smail, I., et al. 2014, *MNRAS*, 438, 1267
- Tacconi, L. J., Genzel, R., Saintonge, A., et al. 2018, *ApJ*, 853, 179
- Taylor, G. B., Carilli, C. L., & Perley, R. A., eds. 1999, *Astronomical Society of the Pacific Conference Series*, Vol. 180, *Synthesis Imaging in Radio Astronomy II*
- Tielens, A. G. G. M., & Hollenbach, D. 1985, *ApJ*, 291, 722
- Vallini, L., Gallerani, S., Ferrara, A., Pallottini, A., & Yue, B. 2015, *ApJ*, 813, 36
- Valtchanov, I., Virdee, J., Ivison, R. J., et al. 2011, *MNRAS*, 415, 3473
- Walter, F., Carilli, C., Bertoldi, F., et al. 2004, *ApJ*, 615, L17
- Walter, F., Riechers, D., Cox, P., et al. 2009, *Nature*, 457, 699
- Wang, S. X., Brandt, W. N., Luo, B., et al. 2013, *ApJ*, 778, doi:10.1088/0004-637X/778/2/179
- Wardlow, J. L., Cooray, A., Osage, W., et al. 2017, *ApJ*, 837, doi:10.3847/1538-4357/837/1/12
- Wardlow, J. L., Simpson, J. M., Smail, I., et al. 2018, *MNRAS*, 479, 3879
- Weiß, A., Kovács, A., Coppin, K., et al. 2009, *ApJ*, 707, 1201
- Wolfire, M. G., McKee, C. F., Hollenbach, D., & Tielens, A. G. G. M. 2003, *ApJ*, 587, 278
- Wolfire, M. G., Tielens, A. G. G. M., & Hollenbach, D. 1990, *ApJ*, 358, 116
- Wright, E. L. 2006, *PASP*, 118, 1711
- Zanella, A., Daddi, E., Magdis, G., et al. 2018, *MNRAS*, 481, 1976
- Zhang, Z.-Y., Romano, D., Ivison, R. J., Papadopoulos, P. P., & Matteucci, F. 2018a, *Nature*, 558, 260
- Zhang, Z.-Y., Ivison, R. J., George, R. D., et al. 2018b, *MNRAS*, 481, 59

5.A Companion sources in LESS 49 field

Hodge et al. (2013) identified a nearby counterpart to ALESS 49.1 - ALESS 49.2. Detected at $4\text{-}\sigma$ confidence level in $870\ \mu\text{m}$ continuum, it is included in the “main” sample of ALMA counterparts of ALESS sources. With a reported position of J2000 03:31:24.47 -27° 50' 38.1”, ALESS 49.2 is located within the primary beam of our ALMA Band 8 observations. Hodge et al. (2013) observed ALESS 49.2 to have a $870\ \mu\text{m}$ continuum flux a factor of 3.3 lower than that of ALESS 49.1. ALESS 49.2 is undetected in Wardlow et al. (2018) ALMA Band 4 observations which cover the CO (3–2) line in ALESS 49.1, suggesting ALESS 49.2 is at a different redshift than ALESS 49.1.

We do not find any significant emission ($> 2\sigma_{rms}$) within a 1-arcsec radius of the position reported by Hodge et al. (2013). Therefore, we impose a 0.33 mJy upper limit on the ALESS 49.2 observed 620- μm continuum flux-density (at 3- σ level).

In addition to ALESS 49.2, Wardlow et al. (2018) identified several additional sources in the vicinity of ALESS 49.1. In particular, the ALESS 49.L source from Wardlow et al. (2018) is located at the same redshift as ALESS 49.1, based on a CO line detection. However, we do not detect any emission at ≥ 4 significance in either Band 8 continuum or [C 2] emission at the position of any of the Wardlow et al. (2018) sources.