THE INTERSTELLAR MEDIUM IN GRAVITATIONALLY LENSED DUSTY STAR-FORMING GALAXIES

by

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Dan Marrone
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“Shoot for the moon. Even if you miss, you’ll land among the stars,” the popular quote by Les Brown, was one of my favorite quotes when I was younger. My mom likes to joke that I took her and this quote literally when I decided to study astronomy. I would like to start by thanking my parents, Melanie and Scott, for encouraging me and supporting me throughout my life as I pursued my passions and my dreams.

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DEDICATION

To my family. I love you all so much.
TABLE OF CONTENTS

LIST OF FIGURES ................................................................. 8
LIST OF TABLES ................................................................. 10
ABSTRACT .................................................................................. 11

CHAPTER 1 Introduction .............................................................. 13
  1.1 Galaxies ............................................................................... 13
    1.1.1 The Birth of Extragalactic Astronomy ............................. 13
    1.1.2 Galaxy Formation ....................................................... 14
    1.1.3 Dusty Star-Forming Galaxies ....................................... 16
    1.1.4 The South Pole Telescope Survey ................................. 18
  1.2 Gravitational Lensing .......................................................... 19
    1.2.1 First Predictions and Observations ............................... 20
    1.2.2 Extragalactic Lensing ................................................ 21
  1.3 The Interstellar Medium ....................................................... 22
    1.3.1 Dust .......................................................................... 23
    1.3.2 Fine Structure Lines .................................................. 24

CHAPTER 2 Spatially Resolved [CII] Emission in SPT0346-52: A Hyper-
Starburst Galaxy Merger at $z \sim 5.7$ ........................................... 26
  2.1 Introduction ....................................................................... 26
  2.2 ALMA Observations .......................................................... 29
  2.3 Lensing Reconstruction ....................................................... 30
    2.3.1 Pixellated Lensing Reconstruction ............................... 32
    2.3.2 Reconstruction of SPT0346-52 ................................. 34
    2.3.3 Source Plane Resolution ........................................... 40
  2.4 Analysis ............................................................................. 41
    2.4.1 [CII] Deficit .............................................................. 41
    2.4.2 Kinematic Analysis .................................................... 46
  2.5 Discussion ......................................................................... 50
    2.5.1 Merging Galaxies ....................................................... 50
    2.5.2 Stability of Components .......................................... 53
TABLE OF CONTENTS – Continued

2.6 Summary and Conclusions ........................................... 58

CHAPTER 3 Multi-Phase ISM in the $z = 5.7$ Hyperluminous Starburst
SPT0346-52 ............................................................. 60
3.1 Introduction ........................................................... 60
3.2 ALMA Observations .................................................. 63
3.3 Lens Modeling ........................................................... 68
  3.3.1 Comparing Models ................................................ 72
  3.3.2 Lens Modeling Results ......................................... 74
3.4 CLOUDY Modeling ..................................................... 77
  3.4.1 CLOUDY Parameters ............................................ 77
  3.4.2 Cloudy Modeling Results ....................................... 81
3.5 Discussion .............................................................. 85
  3.5.1 Dust Temperatures ............................................... 87
  3.5.2 Line Deficits ...................................................... 89
  3.5.3 $[\text{C}]_{158}/[\text{N}]_{205}$ ......................................... 91
  3.5.4 $[\text{C}]_{158\mu m}/[\text{O}]_{146\mu m}$ ................................. 92
  3.5.5 Non-Detection of $[\text{N}]_{122\mu m}$ .............................. 94
  3.5.6 Non-Detection of $[\text{O}]_{63\mu m}$ ............................... 97
  3.5.7 Gas Mass Estimates .............................................. 99
3.6 Summary and Conclusions ........................................... 106

CHAPTER 4 The ISM in the $z = 6.9$ Interacting Galaxies of SPT0311-58 . 108
4.1 Introduction ........................................................... 108
4.2 ALMA Observations .................................................. 111
4.3 ISM Properties ........................................................ 120
  4.3.1 Ionization Parameter and Metallicity ......................... 122
  4.3.2 Density Constraints in Neutral Gas ......................... 125
4.4 Summary and Conclusions ........................................... 127

CHAPTER 5 Summary and Conclusions .................................... 130
5.1 SPT0346-52 ........................................................... 130
5.2 SPT0311-58 ........................................................... 133
5.3 Potential and Future Observations ................................ 134

APPENDIX A Using Visibility Data to Create the $[\text{C}]$ Spectrum .... 136
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>APPENDIX B Lens Modeling Details</td>
<td>138</td>
</tr>
<tr>
<td>APPENDIX C Spatially Resolved Best-Fit clou\textit{d}y Ratios</td>
<td>140</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>143</td>
</tr>
</tbody>
</table>
LIST OF FIGURES

2.1 High-resolution ALMA observation of SPT0346-52 .......................... 31
2.2 Spectrum of observed [CII] emission in SPT0346-52 .......................... 32
2.3 Triangle plot with the model lens parameters from reconstructing SPT0346-52 ................................................................. 35
2.4 Reconstruction of [CII]158µm emission in 50 km s$^{-1}$ channels ....... 37
2.5 Result of pixellated lensing reconstruction of SPT0346-52 ................. 39
2.6 Spectrum of reconstructed [CII] emission in SPT0346-52 ................. 40
2.7 [CII] to FIR luminosity ratio in SPT0346-52 ..................................... 44
2.8 L$_{[CII]}$/L$_{FIR}$ vs Σ$_{FIR}$ ........................................................... 47
2.9 Moments 1 and 2 of [CII] and Position-velocity diagrams in SPT0346-52 48
2.10 Separation of the two components in SPT0346-52 .......................... 49
2.11 Maps of Toomre Q disk stability parameter ................................... 56

3.1 Observed emission from SPT0346-52 ............................................ 66
3.2 Observed spectra of the targeted lines ........................................... 68
3.3 Triangle plot with the model lens parameters for SPT0346-52 computed for different continuum wavelength ................................. 73
3.4 Reconstructed source-plane emission ............................................. 75
3.5 Comparison of observed continuum and line ratios to CLOUDY best-fit galaxy-integrated ratios ................................................. 80
3.6 Comparison of observed continuum and line ratios to CLOUDY best-fit pixelated ratios ......................................................... 82
3.7 Best-fit spatially-resolved CLOUDY parameters .............................. 83
3.8 Modified blackbody fits to galaxy-integrated and pixel-by-pixel continuum flux values ............................................................. 88
3.9 Line luminosity/L$_{FIR}$ vs Σ$_{FIR}$ for the observed lines ....................... 90
3.10 Fraction of [CII]158µm emission originating from neutral gas, $f_{[CII],neutral}$, calculated from the [CII]158µm/[NII]205µm ratio ............. 93
3.11 [CII]158µm/[OI]146µm .............................................................. 95
3.12 Theoretical and calculated electron densities for SPT0346-52 ............. 96
3.13 Mass estimates for SPT0346-52 and other high-redshift sources, normalized by the molecular gas mass from CO measurements, vs L$_{FIR}$ 101
LIST OF FIGURES – Continued

4.1 Observed emission from SPT0311-58 ........................................ 116
4.2 Observed spectra from SPT0311-58 ............................................. 117
4.3 Observed spectra from SPT0311-58 in each component on the same vertical scale ................................................................. 119
4.4 Ionization parameter and metallicity ............................................. 126
4.5 $L_{\text{[CII]158}}/L_{\text{[OII]146}}$ versus $L_{\text{FIR}}$ ........................................... 128

B.1 Image-plane and source-plane maps ........................................... 139

C.1 Maps of observed and modeled ratios from CLOUDY ..................... 142
# LIST OF TABLES

| 2.1 | ALMA Band 7 Observations of SPT0346-52 | 30 |
| 2.2 | SPT0346-52 Lens Parameters | 36 |
| 2.3 | Kinematic Values of the Components of SPT0346-52 | 57 |
| 3.1 | ALMA Observations of SPT0346-52: Calibration | 64 |
| 3.2 | ALMA Observations of SPT0346-52: Results | 65 |
| 3.3 | SPT0346-52 Continuum Lens Modeling Results | 70 |
| 3.4 | SPT0346-52 Fluxes and Luminosities | 71 |
| 3.5 | Best-Fit Global cloudy Models$^a$ | 81 |
| 3.6 | Targeted Fine-Structure Lines | 86 |
| 3.7 | Summary of Mass Estimates | 100 |
| 4.1 | ALMA Observations of SPT0311-58: Calibration | 112 |
| 4.1 | ALMA Observations of SPT0311-58: Calibration | 113 |
| 4.2 | ALMA Observations of SPT0311-58: Results | 114 |
| 4.2 | ALMA Observations of SPT0311-58: Results | 115 |
| 4.3 | SPT0311-58 Flux Densities and Luminosities | 121 |
| 4.4 | High-z Reference Sample | 123 |
| C.1 | Data Used to Fit to cloudy Models | 141 |
ABSTRACT

In this dissertation, I characterize the interstellar medium (ISM) in two gravitationally lensed dusty star-forming galaxies (DSFGs) from the South Pole Telescope (SPT) survey using observations from the Atacama Large Millimeter/submillimeter Array (ALMA), the most intensely star-forming galaxy and the most distant galaxy from this sample. In Chapter 1, I provide context and background about galaxies, gravitational lensing, and the ISM.

In Chapter 2, I use high-resolution observations of [C\textsc{ii}]158 and continuum dust emission to study SPT0346-52, a gravitationally lensed system at \( z = 5.7 \). I use a pixelated, interferometric lens modeling code to “de-lens” the emission from SPT0346-52 and reconstruct its source-plane structure. With these reconstructions, I study the “[C\textsc{ii}]-deficit”, an observed phenomenon where the [C\textsc{ii}]158/L\textsc{ FIR} ratio falls as \( \Sigma_{\text{FIR}} \) increases. I then explore the kinematics of [C\textsc{ii}]158 in SPT0346-52 in detail using position-velocity diagrams and the Toomre Q stability parameter. This work was published in Litke et al. (2019).

In Chapter 3, I follow up on SPT0346-52 with ALMA observations of [N\textsc{ii}]205, [C\textsc{ii}]158, [O\textsc{i}]146, [N\textsc{ii}]122, [O\textsc{i}]63, and dust continuum in order to study the multi-phase ISM in this system. As in Chapter 2, I reconstruct the source-plane emission. I use the photoionization code CLOUDY to model the conditions of the ISM. I explore deficits in all of the lines observed. I study the neutral phase of the ISM, the electron density in the diffuse ionized phase, and I discuss the implications of the non-detection of [O\textsc{i}]63. This work was published in Litke et al. (2022).

In Chapter 4, I discuss on-going work using ALMA observations of [C\textsc{ii}]158,
[O\textsc{i}]146, [N\textsc{ii}]122, [O\textsc{iii}]88, and dust continuum to study the multi-phase ISM in the $z = 6.9$ interacting galaxies of SPT0311-58. I use different line and continuum ratios to determine the ionization parameter and metallicity, and constrain the density of the neutral gas phase.

In Chapter 5, I summarize the results of my work and the properties of these two systems, and discuss follow-up observations.
CHAPTER 1

Introduction

1.1 Galaxies

1.1.1 The Birth of Extragalactic Astronomy

Extragalactic astronomy has only existed for about a century. Before this subfield could take off, the existence of galaxies outside of our home galaxy, the Milky Way, had to be confirmed.

The debate over the existence of other galaxies, or “island universes” dates back to the late 1700s. The French astronomer Charles Messier was compiling a catalogue of astronomical objects so he could search for comets without confusing them with non-transient objects. He published these objects as a “Catalog of Nebulae and Star Clusters”. This catalogue included several “nebulae without stars”: diffuse cloud-like structures without resolvable stars (Messier, 1781). As telescopes improved, some of these nebulae proved to have spiral structure (Tempel, 1878; Dreyer, 1878) The question remained, were these “spiral nebulae” clouds within the Milky Way, or were they their own “island universes,” galaxies in their own right?

The argument reached a head on April 26, 1920, when astronomers Harlow Shapley and Heber Curtis faced off in the “Great Debate” at the Smithsonian Museum of Natural History (Shapley and Curtis, 1921). The largest difficulty in settling this debate was uncertainty over the scales involved. How big were the spiral nebulae? How far away were they?

The answer finally became available with Henrietta Leavitt’s discovery of the period-luminosity relation in Cepheid variable stars. Leavitt was cataloguing the
brightnesses of stars at the Harvard College Observatory. Looking at Cepheid variable stars in the Small Magellanic Cloud, she noticed that the brighter (more luminous) stars had longer periods over which they varied. Since the stars were all in the Small Magellanic Cloud, they were approximately the same distance from the Earth (Leavitt and Pickering, 1912). The periods of the Cepheid stars’ variabilities could be linked to their intrinsic brightnesses or luminosities, and therefore could be used as “standardizeable candles” to determine distances to these stars.

In 1925, Edwin Hubble used this period-luminosity relation to measure the distance to the Andromeda spiral nebula, Messier 31 (originally measured at 275 kpc, modern measurements are around 730 kpc; Hubble, 1929; Vilardell et al., 2007). This was too large to be part of the Milky Way. Therefore, Andromeda Nebula was in fact the Andromeda Galaxy. There are indeed galaxies beyond the Milky Way.

1.1.2 Galaxy Formation

Galaxies are made up of stars, gas and dust (the interstellar medium, or ISM), and dark matter. They can range from faint dwarf galaxies, with total luminosity \( \sim 10^3 \, L_\odot \), up to bright, massive galaxies with \( > 10^{12} \, L_\odot \). The stellar masses, star formation rates and histories, gas contents, dust contents, metallicities, and morphologies can vary greatly from galaxy to galaxy.

After the Big Bang, small density fluctuations formed the seeds that would eventually form into the large-scale structures, like galaxies, that we see today. Gravity caused regions with slight overdensities to collapse and become denser, while less-dense regions became voids. The densest of these regions became gravitationally bound and collapsed rather than expand with the rest of the universe (Wechsler and Tinker, 2018).

Before the first stars could form, the gas that had been formed in the Big Bang had to cool enough to collapse into stars. The first stars lived and died a few hundred
million years after the Big Bang, in minihalos with masses $\sim 10^6 \, M_\odot$ (Bromm et al., 2009). These stars, called Population III stars, formed out of primordial hydrogen and helium and were likely more massive than modern stars, with masses up to $300 \, M_\odot$ (Bromm et al., 2009). When the first stars died in supernova explosions, they heated and enriched the surrounding gas with metals.

Approximately 500 Myr ($z \sim 10 - 15$) after the Big Bang, the first galaxies formed (Bromm and Yoshida, 2011). By this point, the typical dark matter halos had grown to $\sim 10^8 \, M_\odot$. Galaxy-scale outflows, driven by stellar radiation pressure and supernovae, enriched the intergalactic medium (IGM), building up the metal and dust content. This enrichment would not have been uniform, with parts of the IGM being enriched while other parts remained close to primordial abundances (Bromm and Yoshida, 2011; Tornatore et al., 2007; Bertone et al., 2005).

Our understanding of the first stars and galaxies is based primarily on theoretical models and simulations. So far, the most distant galaxy that has been observed is GN-z11 at $z \approx 11$, just 420 Myr after the Big Bang (Oesch et al., 2016; Jiang et al., 2021). GN-z11 is already massive and actively forming stars, with stellar mass $\sim 10^9 \, M_\odot$. Future observations from telescopes such as the James Webb Space Telescope (JWST) will observe more of these first galaxies and drastically improve our understanding of them.

After the first galaxies formed, they began to heat the IGM and ionize the gas between galaxies. As young, hot stars formed and produced ionizing photons with energies $E > 13.6 \, eV$, the photons interacted with and ionized the surrounding neutral ISM to create H\textsc{ii} regions (Strömgren, 1939). Up to 90% of the light from the most massive early stars escaped to ionize the IGM, with the escape fraction decreasing in less massive stars (Alvarez et al., 2006; Wise, 2019). This Epoch of Reionization occurred at $z > 6$ (Bromm and Yoshida, 2011).

The star formation density over the history of the universe has not been constant.
From $z \approx 8$ to $z \approx 3$, the comoving cosmic star formation rate density rose steadily, then peaked at $z \approx 1.5 - 2$, 3.5 billion years after the Big Bang (Madau and Dickinson, 2014). Since this peak, the star formation rate density has gradually declined (Madau and Dickinson, 2014). Up to at least $z = 2$, there is a star-forming main sequence, a tight correlation between the star formation rate and the stellar mass (Gavazzi and Scodeggio, 1996; Madau and Dickinson, 2014). A small number of starburst galaxies lie above this relation, with enhanced star formation rates compared to their stellar masses. Gravitational instabilities can cause gas to accumulate in the central region of a galaxy, leading to enhanced star formation. These gravitational instabilities can be caused by interactions between galaxies (Di Matteo et al., 2007; Orlitova, 2020). Late stages of these interactions can also lead to the ignition of active galactic nuclei (AGN, or actively accreting supermassive black holes in the centers of galaxies; Ellison et al., 2008).

1.1.3 Dusty Star-Forming Galaxies

Only about half of the cosmic star formation can be observed at optical and ultraviolet wavelengths, where emission from young, hot stars can be more directly observed. The other half of the cosmic star formation is dust-obscured. The ultraviolet and optical light from young, hot stars is absorbed by surrounding dust, which reradiates the energy at infrared wavelengths (Casey et al., 2014).

DSFGs are sometimes called submillimeter galaxies (SMGs) because of the bright dust emission at submillimeter wavelengths. In the late 1990s, the Submillimeter Common-User Bolometer Array (SCUBA) instrument on the James Clerk Maxwell Telescope (JCMT) observed the first deep-field maps at 850$\mu$m, leading to the first sample of luminous, high-$z$ DSFGs (Smail et al., 1997; Barger et al., 1998; Hughes et al., 1998; Casey et al., 2014). These were some of the most luminous sources, with $L_{1.1}\mu m > 10^{12.5} \, L_\odot$, star formation rates $> 500 \, M_\odot \, yr^{-1}$, and a median redshift $z \approx 2.2$.
(Chapman et al., 2004, 2005). Subsequent surveys such as the South Pole Telescope found populations of gravitationally lensed dusty star-forming galaxies, with more galaxies at even higher redshifts (median \(z \approx 3.9\); Vieira et al., 2013; Strandet et al., 2016; Spilker et al., 2016; Reuter et al., 2020)

High-z DSFGs have a range of physical properties. Up to 50% have multiple counterparts, some of which may be components of merging systems (Bussmann et al., 2015). In addition, estimates of the fraction of DSFGs with active galactic nuclei (AGN, or actively accreting supermassive black holes) range from 15 – 30% (Laird et al., 2010; Georgantopoulos et al., 2011; Johnson et al., 2013; Wang et al., 2013b; Casey et al., 2014). More recently, most DSFGs have been found to host massive outflows (e.g., Spilker et al., 2020). DSFGs are thought to evolve into compact quiescent galaxies that are already in place by \(z \sim 2\) and eventually into giant elliptical galaxies found in the cores of galaxy clusters (Toft et al., 2014). One proposed evolutionary path is that gas-rich mergers induce a nuclear starburst. Then, the central supermassive black hole “turns on” as an AGN. Feedback from the AGN and possible galaxy-scale outflows “quench” the galaxy, stopping star formation and leaving a compact quiescent galaxy behind. These compact galaxies then merge together to eventually form the massive elliptical galaxies we see in the local universe (Toft et al., 2014).

In this work, I use “components” to describe parts of a system that are large enough, either physically (\(\gtrsim 1\) kpc; Hodge et al., 2016; Gullberg et al., 2018) or with high velocity dispersions and/or line widths (\(\gtrsim 200\) km/s; Pavesi et al., 2018; Dessauges-Zavadsky et al., 2019; Litke et al., 2019; Rosolowsky et al., 2021), to be individual galaxies that are interacting or merging. This is in contrast to clumps embedded within a gas disk, which have been observed in DSFGs (e.g., Hodge et al., 2012; Iono et al., 2016; Dannerbauer et al., 2017; Tadaki et al., 2018; Dessauges-Zavadsky et al., 2019; Rosolowsky et al., 2021; Spilker et al., 2022). For example,
while the clumps within each component of SPT0311-58 are more massive \((r \sim 1 \text{ kpc and } \sigma \sim 100 \text{ km/s}; \text{Spilker et al., 2022})\) than clumps observed at lower redshifts \((r \sim 0.1 \text{ kpc and } \sigma \lesssim 50 \text{ km/s}; \text{Genzel et al., 2011; Dessauges-Zavadsky et al., 2019; Rosolowsky et al., 2021}), they are embedded within larger components of SPT0311-58 (SPT0311-58 E and SPT0311-58 W).

### 1.1.4 The South Pole Telescope Survey

This work is focused on DSFGs discovered using the South Pole Telescope (SPT). SPT is a 10-meter millimeter-wave telescope at the geographic south pole in Antarctica (Carlstrom et al., 2011). The survey instrument was designed to observe diffuse, low contrast sources, such as the anisotropy in the Cosmic Microwave Background (CMB). In addition to galaxy clusters, the survey also found a sample of mm-bright sources. Based on the 1.4 mm to 2 mm flux ratio, the mm-bright sources were divided into a sample of synchotron-dominated sources (from AGN) and dust-dominated sources (DSFGs) (Vieira et al., 2010; Mocanu et al., 2013; Everett et al., 2020). The 2500 deg² SPT survey has yielded \(\sim 100\) DSFGs. Imaging with the Atacama Large Millimeter/submillimeter Array (ALMA) revealed that the majority of these sources are strongly gravitationally lensed. Hezaveh et al. (2013) and Spilker et al. (2016) performed gravitational lens modeling of the SPT DSFGs to determine their lens properties, source-plane properties, and magnifications.

Using 3 mm spectral scans looking for CO and [C\text{I}] transitions, Vieira et al. (2013), Weiß et al. (2013), Strandet et al. (2016) and Reuter et al. (2020) determined the redshifts of these gravitationally lensed DSFGs. In the final catalogue published by Reuter et al. (2020), there are 81 lensed DSFGs. This final sample only includes those with minimum flux density \(S_{870\mu m} > 25 \text{ mJy}\). This sample spans a large redshift range, from \(1.9 < z < 6.9\), when the universe was between 3.5 billion and 800 million years old. The sample is extremely star-forming, with median star formation rate
2300 ± 200M⊙/yr (Reuter et al., 2020).

The SPT survey yielded one of the largest samples of highly luminous DSFGs. It covers a wide range of redshifts and has a higher median redshift than other DSFG samples. The magnification from gravitational lensing makes these galaxies easier to detect and study. There are many interesting sources to follow up from the SPT sample of DSFGs, from maximally starbursting galaxies (Hezaveh et al., 2013) to massive dusty galaxies in the rarest and most massive dark matter haloes possible (Marrone et al., 2018).

1.2 Gravitational Lensing

Gravitational lensing is the effect where the path of light gets bent or deflected by a mass between the light source and the observer (Einstein, 1911, 1915). It can result in a shift in the apparent position of the source, magnification of the source, image distortion, and/or multiple images (Blandford and Narayan, 1992). The magnification is advantageous as it allows us to observe fainter objects than would be detectable without the aid of gravitational lensing. However, the image distortions and multiple images can make it difficult to interpret the physical conditions of the gravitationally lensed sources.

Gravitational lensing produces beautiful images, from multiply imaged quasars like the Einstein Cross (Huchra et al., 1985) and the Cloverleaf (Magain et al., 1988), to long arcs and arclets found in images of galaxy clusters (Lynds and Petrosian, 1986; Soucail et al., 1987a,b), to nearly perfect circles called Einstein rings when the background source is directly behind the foreground lens galaxy (Hewitt et al., 1988). Lensing has influenced a wide variety of astrophysics fields, including tests of general relativity, calculation of the Hubble parameter and the cosmology that describes our universe, mass profiles for galaxies and galaxy clusters, understanding dark matter, and much, much more (Blandford and Narayan, 1992).
1.2.1 First Predictions and Observations

The idea that light can be deflected due to gravity dates back to the late 1700s and early 1800s. Using Newtonian gravity and the particle nature of light, scientists such as Henry Cavendish and Johann George von Soldner predicted that the sun should deflect light from background stars by

$$\theta_{\text{Newton}} = \frac{2GM}{Dc^2} \approx 0.85,$$

where $G$ is the gravitational constant, $c$ is the speed of light, $M$ is the mass of the lens, and $D$ is the distance of closest approach between the light ray and the mass (in this case, the radius of the sun; Cervantes-Cota et al., 2019).

In 1911, before his General Theory of Relativity was fully developed, Einstein predicted that the sun was massive enough to deflect light. His prediction was the same as the earlier estimates and did not take into account the curvature of space-time, $0.83 \,\text{arcsec}$ (Einstein, 1911; Cervantes-Cota et al., 2019). By 1915, the General Theory of Relativity was fully developed. With the General Relativity framework, the deflection by a mass was updated to $1.7 \,\text{arcsec}$ (Einstein, 1915).

After Einstein’s first (incorrect) prediction was published, there were several expeditions attempting to measure the deflection of light from stars by the sun by observing the apparent positions of stars during a solar eclipse and comparing to their positions at other times. However, due to poor weather conditions (1912), arrests and confiscation of equipment by Russia during World War I (1914, 1916), and data left unpublished for unknown reasons (1918), no one was able to confirm or dispute Einstein’s theory for several years (Cervantes-Cota et al., 2019). Finally, in 1919, a pair of expeditions to Sobral in northern Brazil and Príncipe off the west coast of Africa measured mean deflections of $1.98 \pm 0.12$ and $1.61 \pm 0.30$, respectively (Dyson et al., 1920). This was consistent with Einstein’s prediction and was one of the first experimental confirmations of General Relativity.
1.2.2 Extragalactic Lensing

The possibility that galaxies could act as gravitational lenses was first suggested by Zwicky (1937a,c). This was advantageous over detecting gravitational lensing by individual stars because, as Fritz Zwicky realized, the greater mass in a galaxy would cause larger lensing deflections that would be easier to observe. He also realized the possibility of using gravitational lensing as an astrophysical tool to measure the masses of galaxies and galaxy clusters (Zwicky, 1937b).

After the initial gravitational lensing calculations, eclipse observations, and thought experiments, gravitational lensing stagnated as a field of study for several decades. Walsh et al. (1979) observed the first multiply-imaged quasar, Q0957+561, using the Kitt Peak 84” telescope (with additional follow up from the Steward Observatory 90” telescope and the Very Large Array; Cervantes-Cota et al., 2019). After that gravitational lensing had its renaissance. Like Q0957+561, the lensed quasars identified over the next few years were serendipitously discovered before more systematic searches for lensed sources began (Cervantes-Cota et al., 2019).

A few years later, the first luminous blue arcs of galaxies gravitationally lensed by galaxy clusters were discovered in Abell 370 (Lynds and Petrosian, 1986; Soucail et al., 1987a). At first, they were not sure what this 20” arc of constant surface brightness was, and thought it could be the result of galaxy-galaxy interactions or star formation otherwise related to the cluster. Paczynski (1987) was among the first to suggest this arc could be a lensed image of a background galaxy. This hypothesis was confirmed by Soucail et al. (1987b) when they found the redshift of the arc was different than that of the galaxy cluster.

Around this same time, astronomers began to model the lensing configurations they observed. Soucail et al. (1987b) used lens modeling to support their assertion that the arc in Abell 370 was gravitationally lensed by the galaxy cluster. The first gravitationally lensed quasar, Q0957+561, was also a popular target of lens
modeling. Q0957+561 varies; Schild and Cholfin (1986) was able to measure the time delay in these variabilities between the two images. This time delay was included in lens modeling by Falco et al. (1991) and was eventually used with lens modeling to estimate the Hubble parameter, $H_0$ (Falco et al., 1997). Since then, lens modeling has come a long way, allowing for more precise measurements of $H_0$ (Wong et al., 2020), aiding in the search for dark matter subhalos (Hezaveh et al., 2016), and helping us understand the structures of galaxies in the early universe (e.g., Spilker et al., 2016; Rizzo et al., 2021).

1.3 The Interstellar Medium

My work focuses on the interstellar medium (ISM), the gas and dust that lie between the stars. The ISM is mostly made up of hydrogen, with $\sim 90\%$ of atoms being hydrogen, $\sim 10\%$ helium, and $\sim 1\%$ everything else (Ferrière, 2001). There are different phases of the ISM with a wide range of physical conditions. By volume, most of the ISM is in low density phases. However, the ISM is also very clumpy and full of interstellar clouds. Most of the mass in the ISM lies in clouds of neutral atomic gas, and most molecular gas lives in giant molecular clouds (Hollenbach and Tielens, 1999).

Stars form in cold ($T \sim 10 - 50$ K), dense ($n \sim 10^3 - 10^6$ cm$^{-3}$) molecular cloud cores (Hollenbach and Tielens, 1997, 1999; Draine, 2011). As the stars evolve and die, they enrich the ISM with newly formed metals (anything heavier than helium), increasing the metallicity of the gas which in turn becomes the basis for a new generation of stars. Near sites of active star formation are H$\upiota$ regions, where the gas is fully ionized by FUV radiation produced by young, hot stars, with $T \sim 10000$ K and electron densities up to $n_e < 10^4$ cm$^{-3}$ (Hollenbach and Tielens, 1997, 1999; Draine, 2011). Adjacent to these H$\upiota$ regions is the warm neutral medium ($n \sim 0.6$ cm$^{-3}$ and $T \sim 5000$ K; Hollenbach and Tielens, 1997, 1999; Draine, 2011), where the neutral
gas is heated by interstellar dust reradiating the FUV energy from the nearby stars (Hollenbach and Tielens, 1997, 1999). The conditions within the ISM evolve over time and are closely related to the star formation within a galaxy.

1.3.1 Dust

An important component of the ISM is dust. By mass, dust makes up \( \sim 1\% \) of the ISM. Dust grains are formed in the outer layers of evolved stars. For example, dust grains can form in the winds of asymptotic giant branch (AGB) stars or in nova or supernova ejecta. Dust can then grow by capturing more atoms and molecules as gases cool below a critical temperature where solids can form and can condense (Dopita and Sutherland, 2003). The sizes of dust grains can range from individual polycyclic aromatic hydrocarbon (PAH) molecules up to 1000 Å (Hollenbach and Tielens, 1997, 1999).

Dust is heated by UV radiation from young, hot stars. This heat is reradiated at infrared (IR) wavelengths. Emission from the dust is observed as a modified blackbody continuum. A blackbody continuum results from thermal radiation, and the wavelength where the intensity of light peaks is inversely proportional to the temperature of the object. The spectrum at a given frequency, \( \nu \), is given by

\[
B(\nu, T) = \frac{2\hbar \nu^3}{c^2} \frac{1}{\exp\left(\frac{\hbar \nu}{k_B T}\right) - 1},
\]

where \( h \) is the Planck constant, \( k_B \) is the Boltzmann constant, and \( c \) is the speed of light. It depends on the temperature of the radiating object, \( T \). The dust will be warmer in actively star-forming regions and colder in the ambient ISM.

Dust is very important to the overall heat balance of the ISM. UV light from young, hot stars adds energy to dust grains and dislodges electrons through the photoelectric effect. These electrons can then collisionally excite the gas. Photoelectric heating in neutral gas is dominated by small dust grains. When dust has a higher
grain charge, the photoelectric heating becomes less efficient.

Dust absorbs UV and optical light from young, hot stars and reradiates that heat at infrared wavelengths. Therefore, traditional star formation rate measures that use UV and optical light can severely underestimate the total star formation rate. Instead, the dust continuum emission can be used to measure the dust-obscured star formation rate, where the star formation rate is proportional to the total infrared luminosity (Kennicutt, 1998).

1.3.2 Fine Structure Lines

Atoms have specific energy levels in which their electrons can be found. However, within these energy levels there are multiple spin states that have the same or nearly the same energy depending on how the spin angular momentum and orbital angular momentum combine. For a given transition, there will be a degeneracy of \( g = 2J + 1 \), where \( J \) is the total angular momentum. Due to spin-orbit coupling, these degenerate total angular momenta have slightly different energies, on order \( \sim 10^{-2} \) eV, which corresponds to FIR emission (Draine, 2003). The transitions between these energy levels produce fine structure lines.

Fine structure lines can be ideal for studying various phases of the ISM. They are often (but not always) optically thin, so they allow observations of gas from deeper into clouds. They can be very bright, emitting up to 1% of the total IR luminosity of the galaxy in the cases of [C\text{II}]158 and [O\text{I}]63, the dominant coolants of atomic gas in the ISM (Dopita and Sutherland, 2003; Hollenbach and Tielens, 1997, 1999). The atoms are excited via collisions with electrons or Hydrogen atoms. The gas densities are low enough that the electron will de-excite before another collision can excite it again, causing the atom to release energy and radiate a photon (Dopita and Sutherland, 2003).

Fine structure lines provide a powerful tool for studying multiple phases of the
ISM. [Cu]158 is one of the brightest cooling lines and traces both neutral clouds and warm ionized regions (Hollenbach and Tielens, 1999). As one of the brightest cooling lines, [Cu]158 is an excellent general gas tracer and allows for detailed kinematic analysis at high redshift (see Chapter 2). Lines such as [Nii]122 and [Nii]205 are produced in warm, diffuse ionized gas (Hollenbach and Tielens, 1999). Some lines trace only neutral gas (e.g., [Oi]146 and [Oi]63; Hollenbach and Tielens, 1999), while other lines trace more highly ionized gas where the energies of the photons are high enough to ionize or doubly ionize different atoms (e.g., [Oiii]88; Cormier et al., 2019).

Combinations of lines can also provide diagnostic tools to help us understand the ISM. Because the [Nii] lines are collisionally excited but have different critical densities (the density at which the collisional deexcitation rate is equal to the spontaneous decay rate; Stacey, 2011), the [Nii]122/[Nii]205 can be used as diagnostics of the electron density (see Chapter 3; Dopita and Sutherland, 2003). In addition, observations of [Nii]205 can help disentangle the relative contribution of the ionized and neutral gas phases to the total [Cu]158 emission (Chapter 3). [Cu]158 can also be combined with [Oi]146 to provide constraints on the neutral gas in galaxies (Chapters 3 and 4). Other ratios such as [Oiii]88/[Nii]122 can help us learn more about the ionization states and metallicities in the ISM (Chapter 4).

Throughout this dissertation, I will use the various lines and diagnostic line ratios listed above to understand the ISM in two remarkable dust star-forming galaxies.
CHAPTER 2

Spatially Resolved [C\text{II}] Emission in SPT0346-52: A Hyper-Starburst Galaxy
Merger at $z \sim 5.7$

SPT0346-52 is one of the most luminous and intensely star-forming galaxies in the universe, with $L_{\text{FIR}} > 10^{13} \, L_{\odot}$ and $\Sigma_{\text{SFR}} \approx 4200 \, M_{\odot} \, \text{yr}^{-1} \, \text{kpc}^{-2}$. In this paper, we present $\sim 0\farcs15$ ALMA observations of the [C\text{II}]$158\mu$m emission line in this $z = 5.7$ dusty star-forming galaxy. We use a pixellated lensing reconstruction code to spatially and kinematically resolve the source-plane [C\text{II}] and rest-frame 158$\mu$m dust continuum structure at $\sim 700$ pc ($\sim 0\farcs12$) resolution. We discuss the [C\text{II}] deficit with a pixellated study of the $L_{\text{[CII]}}/L_{\text{FIR}}$ ratio in the source plane. We find that individual pixels within the galaxy follow the same trend found using unresolved observations of other galaxies, indicating that the deficit arises on scales $\lesssim 700$ pc. The lensing reconstruction reveals two spatially and kinematically separated components ($\sim 1$ kpc and $\sim 500$ km $s^{-1}$ apart) connected by a bridge of gas. Both components are found to be globally unstable, with Toomre Q instability parameters $\ll 1$ everywhere. We argue that SPT0346-52 is undergoing a major merger, which is likely driving the intense and compact star formation.

2.1 Introduction

Dusty star-forming galaxies (DSFGs) are among the most infrared-luminous ($L_{\text{FIR}} > 10^{12} \, L_{\odot}$, where $L_{\text{FIR}}$ is the luminosity integrated from 42.5 – 122.5$\mu$m, Helou et al., 1988) and intensely star-forming ($\Sigma_{\text{SFR}} \sim 1000 \, M_{\odot} \, \text{yr}^{-1} \, \text{kpc}^{-2}$) galaxies in the universe (Greve et al., 2012; Casey et al., 2014; Ma et al., 2015). The origin of DSFGs is heavily debated (Sanders et al., 1988; Engel et al., 2010; Narayanan et al., 2010;
Hayward et al., 2012, 2013; Chen et al., 2015; Oteo et al., 2016). It has been theorized that strong starbursts like DSFGs will eventually form the massive elliptical galaxies seen in the centers of galaxy clusters at $z < 1.5$ (Thomas et al., 2005, 2010; Kodama et al., 2007; Kriek et al., 2008; Zirm et al., 2008; Gabor and Davé, 2012; Hartley et al., 2013; Toft et al., 2014).

Recent surveys with the 2500 deg$^2$ South Pole Telescope (SPT; Vieira et al., 2010; Carlstrom et al., 2011; Mocanu et al., 2013) have greatly expanded the number of known, bright, strongly lensed DSFGs up to $z \sim 7$ (Strandet et al., 2017; Marrone et al., 2018). One of the most extreme DSFGs discovered by SPT, with the highest $L_{\text{FIR}}$ and $\Sigma_{\text{SFR}}$ in the SPT sample, is SPT-S J034640-5204.9 (hereafter SPT0346-52). SPT0346-52 has been studied at radio, infrared, optical, and X-ray wavelengths (Vieira et al., 2013; Weiß et al., 2013; Hezaveh et al., 2013; Gullberg et al., 2015; Ma et al., 2015; Spilker et al., 2015; Ma et al., 2016; Strandet et al., 2016; Aravena et al., 2016; Spilker et al., 2016).

SPT0346-52 is a gravitationally lensed galaxy at $z = 5.6559$ (Weiß et al., 2013), with lensing magnification $\mu = 5.6 \pm 0.1$ (Spilker et al., 2016). It has an apparent $L_{\text{FIR}} = 1.23 \times 10^{14} \, L_\odot$ (Spilker et al., 2015) and specific star formation rate $s\text{SFR} > 15.7 \, \text{Gyr}^{-1}$ (Ma et al., 2015). This galaxy’s star formation rate density, $\Sigma_{\text{SFR}}$, is $4200 \, M_\odot \, \text{yr}^{-1} \, \text{kpc}^{-2}$, one of the highest of any known galaxy (Hezaveh et al., 2013; Spilker et al., 2015; Ma et al., 2015, 2016).

Hezaveh et al. (2013) and Spilker et al. (2016) performed gravitational lensing reconstructions of the 860$\mu$m continuum emission in SPT0346-52. This work was continued in Spilker et al. (2015), which reconstructed the CO(2-1) line in 200 km s$^{-1}$ channels. This lensing reconstruction showed that gas with velocities blueward of $-100$ km s$^{-1}$ was spatially offset from the rest of the emission, but it was unable to distinguish between a merging system of galaxies or a rotation-dominated system due to insufficient spatial resolution ($\gtrsim 0''.5$).
Ma et al. (2016) explored the origin of the high luminosity surface density and star formation rate and found that the infrared luminosity is star-formation dominated, with negligible contributions from a central active galactic nucleus (AGN).

In this paper, we use ALMA Band 7 observations of \([\text{C} \II]158\mu\text{m}\) (hereafter \([\text{C} \II]\)), a fine-structure line of singly ionized carbon, combined with an interferometric lensing reconstruction tool developed by Hezaveh et al. (2016), to study the structure of SPT0346-52. \([\text{C} \II]158\) is an ideal tracer of the gas in the interstellar medium (ISM) of galaxies. At 11.26 eV, neutral carbon has a lower ionization potential than neutral hydrogen, so \([\text{C} \II]\) can be found in many different phases of the ISM and trace regions inaccessible to observations of ionized hydrogen emission. \([\text{C} \II]\) is the dominant cooling line in far-UV heated gas (Hollenbach et al., 1991), making it an ideal line with which to study the structure of SPT0346-52. By studying the structure of this galaxy in \([\text{C} \II]\) we can begin to understand what drives the intense star formation rates observed.

The ratio of the \([\text{C} \II]\) line luminosity to the far infrared (FIR) continuum luminosity has been observed to decrease as the FIR luminosity increases (e.g., Malhotra et al., 1997; Luhman et al., 1998, 2003; Díaz-Santos et al., 2013; Gullberg et al., 2015), forming the so-called “\([\text{C} \II]\) deficit.” Several different mechanisms to produce the observed \([\text{C} \II]\) deficit with respect to \(L_{\text{FIR}}\) have been proposed. These include charged dust grains in high UV radiation fields, self absorption of \([\text{C} \II]\) or optically thick \([\text{C} \II]\), saturated \([\text{C} \II]\) emission in very high density photodissociation regions (PDRs), dust-bounded photoionization regions, and star formation rates driven by gas surface densities (Malhotra et al., 1997; Luhman et al., 1998, 2003; Muñoz and Oh, 2016; Narayanan and Krumholz, 2017). Pinpointing the origin of this deficit has been difficult, especially since the deficit is not always observed in DSFGs (e.g., Wagg et al., 2010; De Breuck et al., 2014). Spatially resolved studies of the \([\text{C} \II]\) deficit have recently become possible at high redshift (e.g., Rawle et al., 2014; Oteo et al.,
2016) and should be able to provide a more comprehensive look at the gas conditions associated with the deficit. The analysis in this paper allows for a spatially resolved study of the [CII] deficit in SPT0346-52.

The [CII] observations from ALMA are described in Section 2.2. Section 2.3 describes the lensing reconstruction code used and the source-plane reconstruction of SPT0346-52. The [CII] deficit and a kinematic analysis of the results are described in Section 2.4 and further discussed in Section 2.5. A summary and conclusions are provided in Section 2.6. Throughout this paper, we adopt the cosmology from Planck Collaboration et al. (2016), with \( \Omega_m = 0.309, \Omega_\Lambda = 0.691, \) and \( H_0 = 67.7 \text{ km s}^{-1}. \) At \( z = 5.6559, 1'' = 6.035 \text{ kpc} \) (Wright, 2006).

### 2.2 ALMA Observations

ALMA Band 7 observations of SPT0346-52 were carried out on 2014 September 02 and 2015 June 28 (project ID: 2013.1.01231, PI: Marrone). SPT0346-52 was observed twice at different resolutions, with \( \sim 5 \) minutes on source in both observations. The 2014 September 02 observation used 34 antennae with baselines up to 1.1km. For the 2015 June 28 observation, 41 antennae were used with baselines up to 1.6km, yielding higher resolution. The reference frequency (first local oscillator frequency) was 291.53GHz. J0334-4008 was used as both the flux calibrator and the phase calibrator on both days. More information about the observations is available in Table 2.1.

The data were processed using the Common Astronomy Software Applications package (CASA; McMullin et al., 2007) pipeline version 4.2.2. Some additional flagging was carried out before processing the data with the pipeline. Images were made using the clean algorithm within CASA, with Briggs weighting (robust=0.5). The continuum was subtracted from the line cube using uvcontsub (fitorder=1). The [CII] data were binned to 50 km s\(^{-1}\) channels. The observed 158\( \mu \text{m} \) dust emission
Table 2.1. ALMA Band 7 Observations of SPT0346-52

<table>
<thead>
<tr>
<th>Date</th>
<th># of Ant.</th>
<th>Resolution (arcsec)</th>
<th>PWV (mm)</th>
<th>$t_{\text{int}}$ (min)</th>
<th>Noise Level (mJy/beam)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2014-Sep-02</td>
<td>34</td>
<td>0.26 × 0.23</td>
<td>0.944</td>
<td>5.3</td>
<td>0.44</td>
</tr>
<tr>
<td>2015-Jun-28</td>
<td>41</td>
<td>0.19 × 0.17</td>
<td>1.315</td>
<td>5.2</td>
<td>0.54</td>
</tr>
</tbody>
</table>

$^a$Precipitable water vapor at zenith

$^b$On-source integration time

$^c$Root-mean-square noise level in continuum image

and integrated [C\text{II}] emission are shown in Figure 2.1.

The observed [C\text{II}] spectrum is shown in Figure 2.2. It shows a profile with two peaks, one red-shifted and one blue-shifted relative to the [C\text{II}] rest frequency. This spectrum is obtained using the observed complex visibilities rather than cleaned images of the [C\text{II}] line. The method used to create the spectrum is described further in Appendix A.

2.3 Lensing Reconstruction

Gravitational lensing is a useful phenomenon for observing faint emission. Lensing conserves surface brightness of lensed background sources but it increases their apparent sizes, resulting in greater observed flux. However, strong lensing produces multiple distorted images of background sources and studying the intrinsic properties of lensed objects requires correcting for the lensing distortion.
Figure 2.1: High-resolution ALMA observation of SPT0346-52. The image shows the velocity-integrated $[\text{CII}]$ line. The continuum is shown overlaid as white contours. The synthesized beam ($0''.17 \times 0''.19$) is illustrated as the blue ellipse in the lower left corner.
Figure 2.2: Spectrum of observed [CII] emission in SPT0346-52. The spectrum was obtained using the observed visibilities and the model continuum visibilities as described in Section A.

2.3.1 Pixellated Lensing Reconstruction

To determine the structure of SPT0346-52, we use the pixellated lensing reconstruction code ripples. This code is described in detail in Hezaveh et al. (2016), with the general framework of using pixellated sources described in Warren and Dye (2003) and Suyu et al. (2006). ripples models the interferometric observations of lensed sources. It models the mass distribution in the lensing galaxy and the background source emission while accounting for observational effects such as those due to the primary beam.

Using a pixellated source reconstruction is advantageous as it does not assume a specific source structure (i.e., the source is not constrained to follow, for example, a Gaussian or Sérsic surface brightness profile). Instead, it has the flexibility to model more complex source structures, especially when high-resolution data are available,
because of the large parameter space of the source pixels and the less constraining priors. Using an inherently interferometric code such asripples also allows us to use all of the data available from an observing session with an interferometer like ALMA.

The model visibilities can be written as a linear matrix equation,

\[ V = F(BLS). \] (2.1)

Light from the background source, \( S \), is first lensed by the foreground galaxy. Pixels in the image (lensed) plane are mapped back to the source (de-lensed) plane for a given set of lens parameters. The lensing operation is a matrix represented by \( L \) in Equation 2.1, and depends on the mass distribution of the lensing galaxy. The lensed emission is then modified by the primary beam of the telescope (represented by the matrix \( B \)). Finally, we take a Fourier transform of the sky emission, \( F \) to obtain the complex visibilities of interferometric observations, \( V \). The model visibilities are compared to the observed visibilities via a \( \chi^2 \) goodness-of-fit test. A Markov Chain Monte Carlo (MCMC) method is used to solve for the lens galaxy mass distribution parameters.

In addition to the lens parameters, there is a regularization term, \( \lambda \). The regularization term acts to smooth the source and minimize large gradients between adjacent pixels in the source plane. This prevents over-fitting of the data, or fitting to the noise in the source plane image. \( \lambda \) is determined by

\[ N_s - \lambda \text{Tr}([FL + \hat{C}_s]^{-1}\hat{C}_s^{-1}) - \lambda S^T\hat{C}_sS = 0, \] (2.2)

where \( N_s \) is the number of source pixels and \( C_s \) is the source covariance matrix. \( \lambda \) scales an arbitrarily normalized source covariance matrix, \( \hat{C}_s \). It is determined for a fixed lens model, rather than being simultaneously fit for with the lens parameters. We fit for \( \lambda \), then run the MCMC withripples. These two steps are repeated until the chains have converged around a most-likely set of parameters.
After modeling the mass distribution of the lensing galaxy, we obtain a pixellated map of the source-plane emission, a model image, and model complex visibilities.

2.3.2 Reconstruction of SPT0346-52

We model the lensing galaxy as a singular isothermal ellipsoid at $z = 0.9$ with an external shear component. The initial parameters are taken from previous lensing reconstructions of SPT0346-52 by Hezaveh et al. (2013) and Spilker et al. (2015). The best-fit model was determined by fitting the 158µm continuum data because the continuum has a much higher signal-to-noise ratio than the individual line channels. Figure 2.3 shows a probability density plot of the lens parameters with the results of the MCMC. The determined lens parameters are given in Table 2.2.

The best-fit model was then applied to the [CII] line in each 50 km s$^{-1}$ channel. This channel width was chosen to be wide enough to have high signal-to-noise to be able to reconstruct the source in each channel, while being narrow enough to study kinematic features in SPT0346-52. The source regularization, $\lambda$, for the [CII] line was fixed for all 50 km s$^{-1}$ channels. The original image, model image, and model source are shown for each channel in Figure 2.4.

Hezaveh et al. (2013) reconstructed the 860µm continuum of SPT0346-52 only using short baselines, assuming a symmetric Gaussian source profile. Spilker et al. (2015) reconstructed the CO(2-1) line emission using the code visilens (Spilker et al., 2016). They used four 200 km s$^{-1}$ channels and assumed a symmetric Gaussian source-plane structure for each channel. Channels blueward of $-100$ km s$^{-1}$ were spatially offset from redder emission, with the same orientation and velocity ranges obtained with the reconstruction of the [CII] line. The $-400$ km s$^{-1}$ and $+200$ km s$^{-1}$ channels from the parametric reconstruction of CO(2-1) in Spilker et al. (2016) show disks with similar size and orientation as the two components in the [CII] pixellated reconstruction from this work (see Figure 2.4).
Figure 2.3: Triangle plot with the model lens parameters from reconstructing SPT0346-52. $M$ is measured in $M_\odot$ and is the mass enclosed within 10 kpc. $e_x$ and $e_y$ are the $x$- and $y$-components of lens galaxy’s ellipticity. $x$ and $y$ are the offset of the lens center in arcseconds. $\gamma_x$ and $\gamma_y$ are the $x$- and $y$-components of shear.
Table 2.2. SPT0346-52 Lens Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>log Mass(\text{[M_\odot]})</td>
<td>11.43 ± 0.02</td>
</tr>
<tr>
<td>Ellipticity x-Component, (e_x)</td>
<td>-0.16 ± 0.02</td>
</tr>
<tr>
<td>Ellipticity y-Component, (e_y)</td>
<td>0.49 ± 0.06</td>
</tr>
<tr>
<td>Ellipticity, (e^{a,c})</td>
<td>0.52 ± 0.06</td>
</tr>
<tr>
<td>Position Angle, (\phi_e) (E of N)(^{b,c})</td>
<td>72 ± 6°</td>
</tr>
<tr>
<td>Lens x Position, (x)</td>
<td>0(^\prime)076 ± 0(^\prime)014</td>
</tr>
<tr>
<td>Lens y Position, (y)</td>
<td>0(^\prime)31 ± 0(^\prime)01</td>
</tr>
<tr>
<td>Shear x-Component, (\gamma_x)</td>
<td>0.035 ± 0.022</td>
</tr>
<tr>
<td>Shear y-Component, (\gamma_y)</td>
<td>-0.093 ± 0.015</td>
</tr>
<tr>
<td>Shear Amplitude, (\gamma^{a,c})</td>
<td>0.10 ± 0.02</td>
</tr>
<tr>
<td>Shear Position Angle, (\phi_\gamma) (E of N)(^{b,c})</td>
<td>111 ± 12°</td>
</tr>
</tbody>
</table>

\(^a\alpha = \sqrt{\alpha_x^2 + \alpha_y^2}\), where \(\alpha = e\) or \(\alpha = \gamma\)

\(^b\phi_\alpha = \arctan (-\alpha_y/\alpha_x)\), where \(\alpha = e\) or \(\alpha = \gamma\)

\(^c\)Derived from best-fit parameters
Figure 2.4: Reconstruction of [C\textsc{ii}]158\textmu m emission in 50 km s$^{-1}$ channels. Left 3-panel column: blue velocities. Right 3-panel column: red velocities. Within each column: Left: observed [C\textsc{ii}] from ALMA. Center: model sky emission. Right: reconstructed source with lensing caustic. Lensed images are 5\textarcmin on a side. The source plane images are 8.5 kpc a side. The light blue ellipses in the corners of the source-plane panels show the effective resolution where the emission is brightest in each channel. The data and model sky emission have one color scale, and images of the reconstructed source have another color scale. These color scales are the same across all channels.
We combined the reconstructed channels from Figure 2.4 into a map of the [C\textsc{ii}] emission (Figure 2.5). The top image shows the reconstructed continuum emission, while the bottom image shows the velocity-integrated reconstructed [C\textsc{ii}] line. There are two lobes in the [C\textsc{ii}] emission, with the lower left component much brighter than the upper right component. The continuum emission, arising mostly from dust, is more regular and is roughly elliptical. It is located near the center of the [C\textsc{ii}] emission, between the two components and is less extended than the [C\textsc{ii}] emission. The dust continuum emission has been found to be more compact than the [C\textsc{ii}] emission in other high-z galaxies. Gullberg et al. (2018) measured [C\textsc{ii}]-emitting regions that are 1.6× more extended than the regions with dust continuum emission in four $z \sim 4.5$ DSFGs. Wang et al. (2013a) found dust continuum in $1.2 - 2.3$ kpc regions and [C\textsc{ii}] emission in $1.7 - 3.5$ kpc regions in $z \sim 6$ quasars with vigorous star formation in the central region of the quasar host galaxies. Oteo et al. (2016) found similar sizes in the dust continuum and [C\textsc{ii}] emission regions of SGP38326. An offset between the brightest [C\textsc{ii}] emission and the center of the dust emission, as is seen in the source-plane reconstruction of SPT0346-52, was also observed in the Seyfert 2 galaxy NGC1068 (Herrera-Camus et al., 2018a). We also find the dust continuum emission to be smoother than the [C\textsc{ii}] emission. Smooth dust continuum emission with clumpy [C\textsc{ii}] emission was also seen by Oteo et al. (2016) in SGP38326, a pair of interacting dusty starbursts.

Figure 2.6 shows a spectrum of the reconstructed [C\textsc{ii}] emission. The spectrum was obtained by summing the flux from the pixels in the source plane reconstruction, while excluding pixels near the edges of the source plane. There are two clear peaks in the spectrum with similar maximum fluxes. A two-component Gaussian was fit to the spectrum; the results are overlaid on Figure 2.6. The blue component is centered at $-287 \pm 22$ km s$^{-1}$ and has a FWHM of $337 \pm 22$ km s$^{-1}$. The red component is centered at $+158 \pm 22$ km s$^{-1}$ with a FWHM of $319 \pm 15$ km s$^{-1}$. Similar velocity
Figure 2.5: Result of pixellated lensing reconstruction of SPT0346-52. Top: map of continuum emission at 158 µm. Bottom: map of integrated [CII] emission. The resolution varies across the source depending on the location relative to the caustics (white lines). The blue, green, and purple ellipses in the corner indicate the 1σ size of the 2D Gaussian fit to determine the effective resolution in the reconstruction at the locations of the dots in the maps of the same color. To see more of how the resolution varies across the source plane, see Figure 2.4. Colorbar units are mJy/pixel.
Figure 2.6: Spectrum of reconstructed $[\text{C}\text{ii}]$ emission in SPT0346-52. The solid black line shows the two component Gaussian fit to the spectrum, with the individual components shown in red and blue dashed lines. The two components are centered at $-287$ km s$^{-1}$ and $+158$ km s$^{-1}$ relative to $z = 5.6559$. The purple dashed line shows the spectrum obtained from the (lensed) visibilities in Figure 2.2.

structure to that seen in the source-plane spectrum was also observed by Spilker et al. (2015), Aravena et al. (2016), Dong et al. (2019), and Apostolovski et al. (2019).

2.3.3 Source Plane Resolution

In order to determine the resolution in the source plane, we created a set of mock visibilities for a point source in the source plane that was lensed by the best-fit lens model. Ripples was then applied to the mock visibilities to reconstruct the source and a 2D Gaussian was fit to the reconstructed source. This Gaussian is the effective resolution. This process was repeated with the location of the point source varying throughout the source plane to understand the variation in resolution across the source. We find that in regions away from the central diamond caustic the effective
resolution is $0\prime.13 \times 0\prime.15$, while closer to the diamond caustic the effective resolution decreases to $0\prime.12 \times 0\prime.12$. Example effective resolution ellipses are shown in blue in Figure 2.5.

2.4 Analysis

2.4.1 [CII] Deficit

[CII] is usually the brightest coolant line of the ISM. While it can be emitted in a variety of ISM conditions, it is primarily produced in warm, diffuse gas at the edges of photodissociation regions (PDRs) being heated by an external FUV radiation field, such as a star-forming region or AGN (Hollenbach et al., 1991; Malhotra et al., 1997; Luhman et al., 1998; Pineda et al., 2010). Pavesi et al. (2018) calculated that $\sim 85\%$ of [CII] emission in a $z = 5.7$ DSFG comes from PDRs. One of the more interesting aspects of the [CII] line is the so-called “[CII] deficit”, in which the $L_{\text{[CII]}}/L_{\text{FIR}}$ ratio has been found to decrease at high $L_{\text{FIR}}$, though this is not always the case. The deficit is often associated with AGN activity, though not all AGN have a [CII] deficit (Sargsyan et al., 2012). Farrah et al. (2013) also showed that the deficit is stronger in merging systems, with no clear dependence on the presence of an AGN. The deficit was found to be strongest in AGN with the highest central starlight intensities, rather than those with the highest X-ray luminosities at low redshift (Smith et al., 2017). This is further supported by Lagache et al. (2018), who found that the [CII] deficit is correlated with the interstellar radiation field in their simulations. In resolved [CII] studies of the Orion Nebula in our galaxy and other DSFGs, the [CII] deficit has been shown to be strongest in regions with higher star formation rates (Goicoechea et al., 2015; Oteo et al., 2016).

Several mechanisms have been suggested as a cause for the [CII] deficit. The [CII] line may be optically thick or self-absorbed by foreground gas. Enhanced IR emission, from intense star formation or an AGN, can also lead to a deficit (Malhotra...
et al., 1997; Luhman et al., 1998). More recently, Narayanan and Krumholz (2017) proposed that increased surface densities in clouds and increased star formation rates cause a rise in the fraction of gas that is CO-dominated, rather than [CII]-dominated, leading to a [CII] deficit. In addition, Díaz-Santos et al. (2017) found a correlation between the UV flux to gas density ratio, $G/n_H$, and $\Sigma_{\text{IR}}$. They found a critical surface density, $\Sigma_{\text{IR}}^* \approx 5 \times 10^{10}$ L$_\odot$ kpc$^{-2}$, below which $G/n_H$ remains constant. Above $\Sigma_{\text{IR}}^*$, they found that $G/n_H$ increases. They argued that the relation between $G/n_H$ and $\Sigma_{\text{IR}}$ links kpc-scale galaxy properties to those of individual PDRs. Herrera-Camus et al. (2018a) also found a critical surface density, $\Sigma_{\text{FIR}} \gtrsim 10^{11}$ L$_\odot$, above which the $L_{\text{[CII]}}/L_{\text{FIR}}$ ratio decreases, but with increased scatter. The [CII] deficit has also been found to correlate directly with $G/n_H$ (e.g., Malhotra et al., 1997).

Using the pixellated lensing reconstruction, we have resolved maps of the source-plane continuum and [CII] emission. This allows us to obtain a resolved map of the $L_{\text{[CII]}}/L_{\text{FIR}}$ ratio and probe the [CII] deficit to smaller scales than has previously been possible at high redshift.

In order to study the [CII] deficit, we assume that the 158$\mu$m continuum flux density, $F_{\text{cont}}$, traces the $L_{\text{FIR}}$ ratio. The measured continuum flux in each pixel, $F_{\text{cont},i}$, is scaled proportional to the total $L_{\text{FIR}}$, using $L_{\text{FIR}}$ from Gullberg et al. (2015) and corrected for lensing using the magnification from Spilker et al. (2016), such that

$$L_{\text{FIR},i} = F_{\text{cont},i} \left( \frac{L_{\text{FIR}}}{\Sigma F_{\text{cont}}} \right).$$

(2.3)

This method assumes a constant flux density-to-luminosity ratio, and thus a constant dust temperature. We tested the effect of this assumption by determining the total FIR luminosity for a range of dust temperatures measured in DSFGs from the SPT sample ($22 < T_d < 57$). $L_{\text{FIR}}$ was calculated by integrating the spectral energy distribution (SED; modeled by a modified black body, see Greve et al. 2012) from $42.5 - 122.5\mu$m and scaling the SED to go through the flux of SPT0346-52 at 158$\mu$m.
Resulting $L_{\text{FIR}}$ values were within a factor of $\sim 2$ of the luminosity measured by Gullberg et al. (2015), so the variation caused by variable dust temperatures in the galaxy is within a factor of $\sim 2$.

A map of the $L_{\text{[CII]}}/L_{\text{FIR}}$ ratio is shown in Figure 2.7. Typical values of the $L_{\text{[CII]}}/L_{\text{FIR}}$ ratio in the center of SPT0346-52 are around $\sim 1 \times 10^{-4}$. This value is consistent with other ultra-luminous infrared galaxies (ULIRGs) and DSFGs that have the [CII] deficit (e.g., Maiolino et al., 2005; Iono et al., 2006; Oteo et al., 2016; Mazzucchelli et al., 2017; Decarli et al., 2017). The higher values of $L_{\text{[CII]}}/L_{\text{FIR}}$ at the edges of the galaxy are due to the low amounts of continuum emission in those regions. Oteo et al. (2016) found a similar mapped distribution in a pair of interacting DSFGs and suggested it was due to the different morphology of the [CII] emission compared to the dust continuum emission. As with SPT0346-52, the sources studied by Oteo et al. (2016) do not show evidence for AGN activity (Oteo et al., 2016). The uniformity of the $L_{\text{[CII]}}/L_{\text{FIR}}$ ratio is similar to the merging system observed by Neri et al. (2014).

Figure 2.8 shows the $L_{\text{[CII]}}/L_{\text{FIR}}$ vs $\Sigma_{\text{FIR}}$ relation for SPT0346-52, pixels from the lensing reconstruction, other high-z sources, and ULIRGs from the GOALS survey (Díaz-Santos et al., 2013). As noted by Spilker et al. (2016), the $L_{\text{[CII]}}/L_{\text{FIR}}$ vs $\Sigma_{\text{FIR}}$ relation continues to higher values of $\Sigma_{\text{FIR}}$ for high-z sources. The tight relation continues to hold true at smaller physical scales (the purple diamonds and green shaded region in Figure 2.8 are individual pixels in resolved [CII] observations from this work and Oteo et al. 2016), with a similar scatter as previous, galaxy-averaged studies at high redshift.

The spatially resolved [CII] deficit was recently explored in nearby galaxies. Smith et al. (2017) measured $L_{\text{[CII]}}/L_{\text{TIR}}$ at $0.2 - 1.6$ kpc scales in the KINGFISH sample and found that the $L_{\text{[CII]}}/L_{\text{TIR}}$ vs $\Sigma_{\text{SFR}}$ relation continues at lower values of $\Sigma_{\text{SFR}}$. The relation between $L_{\text{[CII]}}/L_{\text{TIR}}$ and $\Sigma_{\text{SFR}}$ found by Smith et al. (2017) is in good
Figure 2.7: [CII] to FIR luminosity ratio in SPT0346-52. The center region, where the continuum emission is strongest, shows relatively uniform values for $L_{\text{CII}}/L_{\text{FIR}}$ in the center, $\sim 1 \times 10^{-4}$. The white contour traces the strongest region of continuum emission. The larger values at the edges of the galaxy are due to the falling continuum emission.
agreement with the star formation rate density and $L_{[\text{CII}]}/L_{\text{FIR}}$ ratio in SPT0346-52. This relation, and the similar $L_{[\text{CII}]}/L_{\text{FIR}}$ vs $\Sigma_{\text{FIR}}$ trend explored in this work, spans many orders of magnitude. It holds true both for spatially resolved regions and galaxy-averaged values at high and low redshift. The $[\text{CII}]$ deficit appears to come from local conditions in the ISM because it continues to hold over smaller physical areas. Gullberg et al. (2018) reached the same conclusion in their resolved study of $[\text{CII}]$ emission in four $z \sim 4.5$ DSFGs.

Muñoz and Oh (2016) argue that the $[\text{CII}]$ deficit is the result of thermal saturation of the $[\text{CII}]$ emission line. The relation of $L_{[\text{CII}]}/L_{\text{FIR}}$ vs $\Sigma_{\text{IR}}$ from Muñoz and Oh (2016) is plotted in Figure 2.8 for $f_{[\text{CII}]} \approx 0.13$ as a black dash-dotted line. $f_{[\text{CII}]}$ is proportional to $L_{[\text{CII}]}/L_{\text{FIR}}$, and $f_{[\text{CII}]} \approx 0.13$ is the fraction of the total gas in a galaxy traced by $[\text{CII}]$ for a typical DSFG. However, if we calculate $f_{[\text{CII}]}$ (Equation 5 from Muñoz and Oh 2016) for SPT0346-52 using $\alpha_{\text{CO}} = 2.2$, using $L'_{\text{CO}(2-1)}$ from Spilker et al. (2015) and assuming $L'_{\text{CO}(1-0)} = L'_{\text{CO}(2-1)}$, we find that $f_{[\text{CII}]} = 0.21$. This moves the relation from Muñoz and Oh (2016) above the majority of the pixels in the reconstruction of SPT0346-52 in Figure 2.8 (grey dash-dot line). It should be noted that the other lines shown in Figure 2.8 are empirical fits to the data.

Herrera-Camus et al. (2018a) looked at the $L_{[\text{CII}]}/L_{\text{FIR}}$ ratio in the SHINING sample of nearby galaxies, with spatially resolved information for 25 of their galaxies. In Herrera-Camus et al. (2018b), they use a pair of toy models to explore the origin of the $[\text{CII}]$ deficit, one with the ISM modeled as having OB stars and molecular gas clouds closely related, and the other with OB associations and neutral gas clouds randomly distributed throughout the ISM. In the former case, the $[\text{CII}]$ intensity only weakly depends on $G_0$ (because the ionization parameter reaches a limit, $U \approx 0.01$) and $n_\text{H}$ (because the density of the neutral gas exceeds the critical density for collisional excitation of $[\text{CII}]$), and in the latter case, the $[\text{CII}]$ intensity is nearly independent of $G_0$ (because photoelectric heating efficiency decreases), while the FIR intensity is
proportional to $G_0$ in both scenarios. They conclude that the combination of both scenarios best replicates the observed [Cii] deficit, including a critical luminosity surface density of $\Sigma_{\text{FIR}} \approx 10^{10} L_\odot \text{kpc}^{-2}$ above which the $L_{\text{[Cii]}}/L_{\text{FIR}}$ ratio begins to decline.

2.4.2 Kinematic Analysis

In addition to the [Cii] emission map shown in Figure 2.5, we calculate moment 1 (intensity-weighted average velocity, shown in the top left panel of Figure 2.9) and moment 2 (intensity-weighted velocity dispersion, top right panel of Figure 2.9) of the reconstructed line. The velocity dispersions in the center of the system reach very high values ($\sigma > 200 \text{ km s}^{-1}$). Extracting the velocities along the major axis of SPT0346-52 (dashed line in Figure 2.9, top right panel) reveals two spatially distinct velocity components. This is shown in the position-velocity diagram in the middle panel of Figure 2.9.

In order to separate the two velocity components seen in Figure 2.9, we fit the spectrum of each pixel with two Gaussian components. Each Gaussian is assigned to the appropriate galaxy component based on its velocity. The shape of the velocity-integrated [Cii] emission in each of the two spatial components is fitted with an elliptical gaussian distribution. The centers and elliptical full-width half-maximum shapes of these components are shown in Figure 2.10. The spatial distribution of the gas bridge, outlined in purple in Figure 2.10, is determined by selecting pixels with emission at velocities intermediate to the two main galaxy components.
Figure 2.8: $L_{[\text{CII}]}/L_{\text{FIR}}$ vs $\Sigma_{\text{FIR}}$. The magenta star shows the galaxy-summed value for SPT0346-52 from this work. The purple diamonds show the individual pixels from the lensing reconstruction. The size of the diamonds is weighted by the continuum signal-to-noise. The right panel zooms in on the region from the left panel with the pixels from the SPT0346-52 reconstruction (light blue box). The green squares are the resolved DSFGs (SGP 38326) from Oteo et al. (2016), while the green shaded region outlines the parameter space occupied by their individual pixels. The turquoise shaded squares represent spaxels from a spatially resolved survey of FIR lines in the $z \sim 0$ SHINING sample (Herrera-Camus et al., 2018a). The pink shaded region represents binned pixels from a spatially resolved study of the [CII] deficit in the KINGFISH galaxy sample (Smith et al., 2017). The blue triangles are SPT DSFGs (Gullberg et al., 2015). The black points are low-redshift star-forming galaxies and ULIRGs from the GOALS survey (Díaz-Santos et al., 2013). The light blue points represent global values from nearby galaxies in the SHINING survey (Herrera-Camus et al., 2018a). The steel blue points are additional nearby galaxies (Farrah et al., 2013; Brauher et al., 2008). The dark blue points are $z > 6$ quasars from Decarli et al. (2018) and Izumi et al. (2018). The grey points are additional high-redshift objects from the literature (Walter et al., 2009; Carniani et al., 2013; Riechers, 2013; Wang et al., 2013a; De Breuck et al., 2014; Neri et al., 2014; Riechers et al., 2014; Yun et al., 2015; Díaz-Santos et al., 2016; Pavesi et al., 2018; Hashimoto et al., 2019a). The grey circles represent the $L_{[\text{CII}]}/L_{\text{FIR}}$ ratio in the cores (measured within the continuum spectrum) and annuli (measured between the continuum and [CII] apertures) for three DSFGs at $z \sim 4.5$ in Gullberg et al. (2018). The solid grey lines connect core of a given DSFG to the annulus of that DSFG. The core values have higher $\Sigma_{\text{FIR}}$ and lower $L_{[\text{CII}]}/L_{\text{FIR}}$ than their annulus counterparts. The grey solid line represents the relation found by Díaz-Santos et al. (2013) and extended by Spilker et al. (2016). The black dash-dot line represents the relation from Muñoz and Oh (2016) saturation of the [CII] line for $f_{[\text{CII}]} = 0.13$, the value for typical DSFGs. The grey dash-dot line represents the relation from Muñoz and Oh (2016) for $f_{[\text{CII}]} = 0.21$, the value calculated for SPT0346-52. The solid line is the relation found by Díaz-Santos et al. (2017). The dotted line is the relation fit by Smith et al. (2017) $\Sigma_{SFR}$ values were converted to $\Sigma_{\text{FIR}}$ following Murphy et al. (2011) and Greve et al. (2012). The dashed line is the fit from Lutz et al. (2016).
Figure 2.9: Top: Moments 1 and 2 of [C\textsc{ii}] in SPT0346-52. Middle: Position-velocity diagram of the major axis of SPT0346-52. The velocities were extracted along the dashed line shown in the moment 2 map. There are two spatially and kinematically components. Bottom: Position-velocity diagram of the bridge connecting the two components of SPT0346-52. The velocities were extracted along the dotted line shown in the moment 2 map, with positions 0 kpc marked by the black x’s. The units on the colorbars in the position-velocity diagrams are Jy/pixel.
Figure 2.10: Separation of the two components in SPT0346-52. The blue and red ellipses outline the FWHM size of the blue and red components, and the centers are marked with an x. The amplitudes of the red and blue components of the Gaussian fits are shown as the red and blue images. The darker region in the center shows where the components overlap. The purple line outlines the pixels containing the “bridge” connecting the two components. Contours of the continuum emission are overlaid in white for reference.
2.5 Discussion

2.5.1 Merging Galaxies

Estimates of the fraction of DSFGs that have multiple components or are merging are varied. For example, from continuum emission only Spilker et al. (2016) found only 13% of lensed DSFGs from the SPT sample showed strong evidence of having multiple components, while Bussmann et al. (2015) found 69% of DSFGs with multiple components. If only the intensity-weighted velocity (moment 1) map (see Figure 2.9) were considered when studying the kinematics of SPT0346-52, this system could appear to be a symmetric, rotating disk. However, only $\sim 40\% - 80\%$ of merging systems show asymmetric kinematics in their star-forming gas (Hung et al., 2016), so symmetric gas kinematics is not a definitive way to determine that a galaxy is not a merging system.

The lensing reconstruction of SPT0346-52 reveals two separated components (see Figure 2.9). The centers of these components are separated by $\sim 1$ kpc and $\sim 500$ kms$^{-1}$. There is a significant decrease in emission at velocities between the center velocities of the two components, as shown in Figure 2.6. Both of these components are larger than the effective resolution in this region of the reconstructed source plane, and they are separated by $\sim 2 - 3$ resolution elements. Therefore, these two components are more likely to represent two separate structures, rather than a barely-resolved rotating disk.

The two components overlap in the middle of the system, near the peak of the continuum emission. This region of overlap has a more complex velocity structure and higher velocity dispersions (Figure 2.9, top panel). Because the overlap region is where there is the most dust continuum emission, the star formation is likely occurring most intensely in that region, as has been observed in other merging systems such as The Antennae Galaxies (Mirabel et al., 1998; Karl et al., 2010). Teyssier
et al. (2010) also found that merger-induced star formation is relatively concentrated near the center of merging systems in their hydrodynamic simulations.

In addition to the red and blue components, a position-velocity slice through the more complex velocity structure reveals a bridge of gas connecting the two components. The extraction line is indicated by the dotted line in the moment 2 map in Figure 2.9, and the position-velocity diagram through this slice is shown in the bottom panel of Figure 2.9. The location of this bridge feature is also indicated by the purple contour in Figure 2.10. This structure resembles simulated tidal tails and observed tidal tails, such as in Arp105 (Bournaud et al., 2004), as well as the south tail in the The Antennae (NGC 4038/9, Gordon et al., 2001) in position-velocity diagrams. Decarli et al. (2017) also found [CII] emission connecting a quasar host galaxy, PJ308-21, and a companion galaxy, though on much larger scales (25 kpc and 1000 km s$^{-1}$) than what is observed in SPT0346-52.

Both components of SPT0346-52 have large velocity dispersions (> 200 km s$^{-1}$, determined by the Gaussian fits to the spectra in each pixel). These large turbulent motions can help stabilize disks against gravitational fragmentation (e.g., Westmoquette et al., 2012; Rangwala et al., 2015), see Section 2.5.2.

Several other merging DSFGs have been observed. For example, Neri et al. (2014) observed [CII] emission in HDF850.1 ($z = 5.185$) and found two components, one red-shifted and one blue-shifted, and separated by 2 kpc with radii $\sim 1$ kpc. These components are similar in size to the components observed in SPT0346-52. Neri et al. (2014) explored the idea that HDF 850.1 was a rotating disk, but concluded that they observed a merger-driven starburst. Rawle et al. (2014) also observed a late-stage merging DSFG at $z > 5$ (HLS0918) with up to four components separated by < 4 kpc. Engel et al. (2010) concluded using CO observations that most bright DSFGs with $L_{IR} > 5 \times 10^{12}$ $L_{\odot}$ are major mergers. This is consistent with the conclusion drawn from studies of stellar structures (e.g., Chen et al., 2015). At
Hashimoto et al. (2019a) concluded that the Lyman-break galaxy B14-65666 was a merger-induced starburst galaxy based on the velocity gradient in the [C\text{II}] line and a two-component spectrum, whose spatial positions are consistent with two [C\text{II}] knots and UV emission peaks. Cosmological hydrodynamic galaxy formation simulations by Narayanan et al. (2015) have shown that many DSFGs have multiple components, though the intense star formation may be driven by stellar feedback rather than major mergers.

Mergers can trigger intense star formation activity without producing an obvious AGN in DSFGs (Wang et al., 2013b). Though many ULIRGs, which have similar L\text{IR} as DSFGs and enhanced star formation, have AGN activity that heats the dust and causes their high values of L\text{FIR}, Younger et al. (2009) found that star formation alone can produce warm IR colors and produce UV radiation that is reradiated by hot dust. About 63% of luminous infrared galaxies (LIRGs) have multiple components (Haan et al., 2011; Engel et al., 2011). Merging ULIRGs, which have higher FIR luminosities than LIRGs and have FIR luminosities more similar to that of SPT0346-52, have small nuclear separations (average 1.2 kpc) and are in later merging systems (Haan et al., 2011). Similarly, SPT0346-52 could be a late-stage merger.

Pavesi et al. (2018) recently observed [C\text{II}] in a DSFG similar to SPT0346-52 at z = 5.667, COSMOS (FIR-)Red Line Emitter (CRLE), with SFR = 1500 M\odot yr\textsuperscript{-1} and a diameter of 2.7 kpc. They determined that CRLE is an intermediate stage merger. CRLE has a gas depletion time scale of 45 Myr. For SPT0346-52, we calculate a gas depletion timescale of 31 ± 10 Myr by dividing the gas mass from Spilker et al. (2015) by the star formation rate from Ma et al. (2015), similar to the depletion timescale calculated by Aravena et al. (2016) for this system.

An alternative explanation for the kinematic morphology in SPT0346-52 is that it is a rotating galaxy with a clumpy gas disk. Clumpy, rotating disks have been observed in DSFGs (e.g., Hodge et al., 2012; Iono et al., 2016; Dannerbauer et al.,
However, Hodge et al. (2016) searched for \( \sim 1 \) kpc clumps (comparable to the sizes of the clumps in GN20 and the components in SPT0346-52) in luminous DSFGs and found no significant evidence for clumping in most cases. Gullberg et al. (2018) looked at [CII] in four \( z \sim 4.5 \) DSFGs. They found three that showed a smooth morphology, while the fourth could be a clumpy disk, though they cannot rule out the possibility of it being a smooth disk. The data explored by Gullberg et al. (2018) and Hodge et al. (2016) did not have enough signal-to-noise to definitively show that the observed clumps were real, rather than noise fluctuations. The data presented in this work have a higher signal-to-noise ratio, allowing a more confident classification of this system as a merger rather than a clumpy, rotating disk.

### 2.5.2 Stability of Components

The Toomre Q parameter describes the stability of rotating disk against gravitational collapse. It is given by

\[
Q = c_s \kappa \frac{1}{\pi G \Sigma_{\text{gas}}},
\]

where \( c_s \) is the sound speed, \( \kappa \) is the epicyclic frequency, and \( \Sigma_{\text{gas}} \) is the gas surface density (Toomre, 1964). In a system dominated by turbulent pressure, rather than thermal pressure, this becomes

\[
Q = \sqrt{c_s^2 + \sigma_T^2} \kappa \frac{1}{\pi G \Sigma_{\text{gas}}},
\]

where \( \sigma_T \) is the turbulent velocity dispersion. In the limit of high turbulence, \( \sqrt{c_s^2 + \sigma_T^2} \sim \sigma_T \) (Hayward and Hopkins, 2017). The gas is stable against gravitational collapse if \( Q > 1 \) and unstable for \( Q < 1 \), though observations of galaxies and simulations of thick disks place this threshold at \( Q \sim 0.7 \) (Kennicutt, 1989; Kim and Ostriker, 2007).
The sound speed and turbulent linewidth are difficult to measure directly, so the gas velocity dispersion, $\sigma_r$, is often used instead. In cosmological simulations from the FIRE (Feedback In Realistic Environments) suite, Su et al. (2017) found that stellar feedback, which would be an important factor in a rapidly star-forming system like SPT0346-52, increases the turbulent velocity dispersion by a factor of 2-3. Using the velocity dispersion instead of the sound speed and true turbulent velocity dispersion likely provides an upper limit to $Q$ (Prieto and Escala, 2016). Because the observed velocity dispersion ($\sigma_r$) can include ordered motion such as rotation or outflows it tends to overestimate $\sigma_T$ (Su et al., 2017).

The epicyclic frequency, $\kappa$, is $a\Omega$, where $\Omega$ is the rotational frequency and $a$ is a constant. For a flat rotation curve, $a = 1$. In general, $1 < a < 2$. Swinbank et al. (2015) and Oteo et al. (2016) used an intermediary value of $a = \sqrt{3}$; we use the same substitution here. The rotational frequency can be described as $\Omega = \nu_r/r$. Then, $\kappa = a\Omega \approx \sqrt{3}\nu_r/r$.

With the above substitutions, we calculate the Toomre $Q$ stability parameter using

$$Q \approx \frac{\sigma_r \sqrt{3}\nu_r}{r \pi G \Sigma_{\text{gas}}}.$$  \hspace{1cm} (2.6)

While we do not assume that the components of SPT0346-52 are disks, past spatially resolved calculations of $Q$ have found $Q < 1$ locally where there are star-forming regions and giant molecular clouds in other systems, even when the global disk has $Q > 1$ (i.e., Fisher et al., 2017; Genzel et al., 2011; Martig et al., 2009). The $Q$ parameter can therefore be used to find local instabilities independent of the global stability/instability of a system.

To calculate the gas surface density, $\Sigma_{\text{gas}}$, we assume the [C\text{II}] emission traces the gas. The total gas mass, $M_g = 1.5 \times 10^{11} \, M_\odot$, taken from Spilker et al. (2015), is divided among the pixels according to their [C\text{II}] luminosity. To convert to surface density, the gas mass in each pixel is divided by the area of the pixel.
The surface density is then given by

$$\Sigma_{\text{gas},i} \approx M_g \frac{S_i}{\sum_i S_i A_i}$$

where $S_i$ is the integral of the Gaussian component in each pixel for each component from Section 2.4.2, $\sum_i S_i$ is the total [CII] flux density, and $A_i$ is the area of a pixel.

The value of $\sigma_r$ used in Equation 2.6 is the standard deviation determined in the Gaussian line fitting described in Section 2.4.2. To calculate $v_r$, we first created velocity fields for the two spatial/velocity components using the mean velocity determined by the two-Gaussian line fitting described in Section 2.4.2. These velocity fields were then fit using the 2D tilted ring modeling in 3D-Barolo (Di Teodoro and Fraternali, 2015). These model velocity fields are used as the values of $v_r$ throughout both components. The position, $r$, is defined relative to the center of each component, indicated by red crosses in Figure 2.10.

A map of the Toomre Q stability parameter is shown in Figure 2.11. The individual pixels in the blue component have a [CII] intensity-weighted mean of $\bar{Q} = 0.03$ and a maximum value of $Q_{\text{max}} = 0.13$. The individual pixels in the red component have $\bar{Q} = 0.02$ and $Q_{\text{max}} = 0.06$. All values of $Q$ are well less than one, indicating that the system (separated into individual components) is unstable to gravitational collapse. As mentioned above, using $\sigma_r$ instead of $\sigma_T$ or $c_s$ gives the upper limit for $Q$. Thus, the result that $Q \ll 1$ everywhere and the disks are gravitationally unstable does not depend on this substitution.

We also calculated values of $Q$ that would be measured for SPT0346-52 if we could not spatially resolve its structure, as is typical of high-redshift galaxies observed to date. We also consider the unresolved estimates for the red and blue components alone. These values, along with the maximum rotational velocity, $V_{\text{max}}$, the mean velocity dispersion, $\bar{\sigma}$, and the radius of each component, $R$, are given in Table 2.3. The values of $Q$ are low compared to previous studies of DSFGs. For example, Oteo et al. (2016) calculated $Q \sim 0.22$ and $Q \sim 0.35$ for an interacting pair of DSFGs
Figure 2.11: Maps of Toomre Q disk stability parameter. Left: blue component. The blue component pixels have [C\text{II}] intensity-weighted mean $\bar{Q} = 0.03$ and maximum $Q_{\text{max}} = 0.13$. Right: red component. The red component pixels have $\bar{Q} = 0.02$ and $Q_{\text{max}} = 0.06$. $Q \ll 1$ throughout the galaxy indicates that it is unstable against gravitational collapse, consistent with rapid star formation throughout both disks.

at $z = 4.425$, and Swinbank et al. (2015) found $Q \sim 0.3$ in SDP.81. De Breuck et al. (2014) found a higher average in ALESS 73.1, a $z=4.76$ DSFG, with average $Q = 0.58$, though with $Q < 1$ at all radii. In Arp220, $Q < 1$ only in the inner part of the disk, where the most intense star formation is occurring (Scoville et al., 1997). The values of Q in SPT0346-52 are consistent with studies of star-forming galaxies, where giant star-forming clumps and local overdensities were found to be unstable against fragmentation (Genzel et al., 2011; Westmoquette et al., 2012; Martig et al., 2009). Where $Q > 1$ in Seyfert galaxies and ULIRGs, the disks cannot fragment and form stars (Sani et al., 2012; Tacconi et al., 1999). The low values of Q throughout SPT0346-52 indicate that the components are very unstable against collapse, which is fully consistent with the observed high star formation rate.
Table 2.3. Kinematic Values of the Components of SPT0346-52

<table>
<thead>
<tr>
<th>Source</th>
<th>$V_c$</th>
<th>$V_{\text{max}}$</th>
<th>$\bar{\sigma}$</th>
<th>$R$</th>
<th>$Q$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(km s$^{-1}$)</td>
<td>(km s$^{-1}$)</td>
<td>(km s$^{-1}$)</td>
<td>kpc</td>
<td></td>
</tr>
<tr>
<td>Both</td>
<td>263</td>
<td>307</td>
<td>1.6</td>
<td>0.30</td>
<td></td>
</tr>
<tr>
<td>Blue</td>
<td>-309</td>
<td>95</td>
<td>301</td>
<td>0.95</td>
<td>0.11</td>
</tr>
<tr>
<td>Red</td>
<td>158</td>
<td>30</td>
<td>313</td>
<td>0.94</td>
<td>0.05</td>
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</tbody>
</table>

The Future of SPT0346-52

While mergers can trigger the onset of an AGN (e.g., Wang et al., 2013b), SPT0346-52 has negligible AGN activity (Ma et al., 2016). However, many DSFGs and merging systems do have AGN (e.g., Rawle et al., 2014; Carniani et al., 2013; Westmoquette et al., 2012; Engel et al., 2011; Younger et al., 2009, 2008). At $z = 3.351$, Marsan et al. (2015) found an AGN in an ultra-massive and compact galaxy at $z = 3.35$ whose stars formed in an intense starburst $300 - 500$ Myr prior. It is possible SPT0346-52 currently has an AGN that is so heavily obscured that X-ray emission is not visible. SPT0346-52 may also host an AGN in the future.

DSFGs are thought to evolve to form the red sequence by $z = 2$. The stars in this red sequence would form in an intense, short, dissipative burst of star formation at $z > 4$ within a compact, $r_e \approx 1$ kpc, region (Kriek et al., 2008). This effective radius is similar to that of SPT0346-52. The models by Narayanan et al. (2015) suggest that by $z \sim 0$ DSFGs (like SPT0346-52) will reside in massive dark matter (DM) halos with $M_{DM} \approx 10^{14}$ M$_\odot$, though not all of the intense star formation is driven by major mergers. These studies are in agreement with that of Cattaneo et al. (2013), who found that most $2 < z < 4$ star-forming galaxies with $M_* > 10^{10}$ M$_\odot$
evolve into the most massive galaxies on the red sequence and had a phase of intense star formation at \( z > 2 \). Similarly, angular clustering analyses of \( z > 2 \) blank-field DSFGs have suggested that DSFGs evolve into present day halos with masses of \( 10^{13} - 10^{14} \, M_\odot \) (e.g., Chen et al., 2016; Wilkinson et al., 2017). Oteo et al. (2016) observed a pair of interacting DSFGs at \( z = 4.425 \). The system observed by Oteo et al. (2016) is at an earlier merger stage than SPT0346-52. They concluded that this system is likely the progenitor of a massive, red, elliptical galaxy. At \( z = 2.3 \), Fu et al. (2013) studied two interacting massive starburst galaxies, separated by 19 kpc and connected by a tidal tail or bridge. They similarly conclude that this system will deplete its gas reservoir in 200 Myr and merge to form an elliptical galaxy with \( M_* \sim 4 \times 10^{11} \, M_\odot \).

SPT0346-52 is currently undergoing a phase of intense star formation. It may deplete its gas reservoir in \( \sim 30 \) Myr (Aravena et al., 2016; Spilker et al., 2015; Narayanan et al., 2015; Fu et al., 2013) and evolve into a red sequence galaxy.

### 2.6 Summary and Conclusions

In this paper, we presented a pixellated lensing reconstruction of high-resolution [CII] emission observed with ALMA towards the \( z = 5.7 \) dusty star-forming galaxy SPT0346-52. With this reconstruction, we mapped the integrated [CII] emission and dust continuum at rest-frame 158 \( \mu \)m in the (unlensed) source plane. We spatially resolved the \( L_{\text{[CII]}}/L_{\text{FIR}} \) ratio in SPT0346-52 and showed that the \( L_{\text{[CII]}}/L_{\text{FIR}} \) vs \( \Sigma_{\text{FIR}} \) relation continues at smaller spatial scales.

We also obtained source-plane velocity information on SPT0346-52, including a demagnified spectrum and moment maps. The reconstruction revealed two spatially and kinematically separated components, one red-shifted and one blue-shifted relative to the [CII] rest frequency. These components are connected by a bridge of gas. Each individual component is extremely unstable, with Toomre Q stability
parameter $Q \ll 1$ throughout both components.

These components are in the process of merging. This merger is likely driving the intense star formation observed in SPT0346-52. SPT0346-52 may have an AGN in its future and evolve into a massive red sequence galaxy.
SPT0346-52 \((z = 5.7)\) is the most intensely star-forming galaxy discovered by the South Pole Telescope, with \(\Sigma_{\text{SFR}} \sim 4200 \, M_\odot \, \text{yr}^{-1} \, \text{kpc}^{-2}\). In this paper, we expand on previous spatially-resolved studies, using ALMA observations of dust continuum, \([\text{N}\,\text{II}]_{205\mu m}, [\text{C}\,\text{II}]_{158\mu m}, [\text{O}\,\text{I}]_{146\mu m}\), and undetected \([\text{N}\,\text{II}]_{122\mu m}\) and \([\text{O}\,\text{I}]_{63\mu m}\) emission to study the multi-phase interstellar medium (ISM) in SPT0346-52. We use pixelated, visibility-based lens modeling to reconstruct the source-plane emission. We also model the source-plane emission using the photoionization code CLOUDY and find a supersolar metallicity system. We calculate \(T_{\text{dust}} = 48.3 \, \text{K}\) and \(\lambda_{\text{peak}} = 80\mu m\), and see line deficits in all five lines. The ionized gas is less dense than comparable galaxies, with \(n_e < 36 \, \text{cm}^{-3}\), while \(\sim 20\%\) of the \([\text{C}\,\text{II}]_{158}\) emission originates from the ionized phase of the ISM. We also calculate the masses of several phases of the ISM. We find that molecular gas dominates the mass of the ISM in SPT0346-52, with the molecular gas mass \(\sim 4 \times\) higher than the neutral atomic gas mass and \(\sim 100 \times\) higher than the ionized gas mass.

3.1 Introduction

The interstellar medium (ISM) of high-redshift galaxies is difficult to study directly due to cosmological dimming and angular resolution limitations. Observations of rest-frame optical and ultraviolet wavelengths also suffer from significant dust extinction, and some phases of the ISM lack suitable tracers at these wavelengths. However, for very distant objects, far-infrared (FIR) continuum and line emission
that is normally obscured by the Earth’s atmosphere redshifts into the submillimeter window. The angular resolution and sensitivity afforded by the Atacama Large Millimeter/submillimeter Array (ALMA) is providing new opportunities to explore the physical conditions in early galaxies through their rest-frame FIR emission.

Many recent high-redshift studies (e.g., Gullberg et al., 2015; Le Fèvre et al., 2020; Béthermin et al., 2020) have focused on the the 158 μm fine structure line of singly-ionized carbon (hereafter, [CII]158μm) because it is one of the brightest cooling lines of the ISM (Hollenbach et al., 1991). However, this line can be difficult to interpret because it can originate from both ionized gas and neutral gas in photo-dissociation regions (PDRs). The 122 and 205 μm lines of ionized nitrogen ([NII]) arise from the ionized phase of the ISM because nitrogen has a higher ionization energy than hydrogen. Since [NII]122μm and [NII]205μm trace the ionized ISM, comparing [CII]158μm to [NII]205μm emission makes it possible to determine what fraction of the [CII]158μm emission originates from PDRs, with values typically in the 60 – 90% range (e.g., Pavesi et al., 2016; Díaz-Santos et al., 2017; Herrera-Camus et al., 2018a; Cormier et al., 2019). [OI]63μm and [OI]146μm, on the other hand, originate from warm, neutral gas (Tielens and Hollenbach, 1985; Hollenbach et al., 1991). Where there is more [OI]146μm emission compared to the [CII]158μm emission, we would expect more dense, neutral gas in those regions (De Breuck et al., 2019).

Recently, (mostly) spatially unresolved multi-line surveys of high-z galaxies, including [NII]205μm, [CII]158μm, [OI]146μm, and [NII]122μm, have been conducted in individual systems. Novak et al. (2019) and De Breuck et al. (2019) found highly enriched ISM, with approximately solar metallicities, in J1342+0928 and SPT0418-47. De Breuck et al. (2019) and Lee et al. (2021) also found evidence for a dense gas-dominated ISM using the ratio of [OI]146μm to [CII]158μm in the first detections of [OI]146μm at z > 1. Rybak et al. (2020) also recently published the first [OII]63μm
detection at $z > 3$ in a dusty galaxy at $z \sim 6$ and determined that $[\text{O}i]63\mu\text{m}$ was the main neutral gas coolant in G09.83808.

In this paper, we focus on the $z = 5.656$ gravitationally lensed dusty star-forming galaxy (DSFG) SPT-SJ034640-5204.9 (hereafter SPT0346-52; Weiß et al., 2013; Vieira et al., 2013). SPT0346-52 is the most intensely star-forming galaxy from the 2500 deg$^2$ South Pole Telescope survey (SPT; Vieira et al., 2010; Carlstrom et al., 2011; Everett et al., 2020), with apparent $L_{\text{FIR}} = 1.1 \times 10^{14}L_\odot$ (Spilker et al., 2015; Reuter et al., 2020) and intrinsic star formation rate density $\Sigma_{\text{SFR}} = 4200 \text{ M}_\odot\text{yr}^{-1}\text{kpc}^{-2}$ (Hezaveh et al., 2013; Ma et al., 2015, 2016; Spilker et al., 2015), where $L_{\text{FIR}}$ is the emission from 42.5 – 122.5$\mu\text{m}$ (Helou et al., 1988). Based on Chandra observations, Ma et al. (2016) determined that the high $L_{\text{FIR}}$ is dominated by star formation with negligible contribution from an active galactic nucleus (AGN).

Litke et al. (2019) performed pixelated, interferometric lens modeling of $[\text{C}ii]158\mu\text{m}$ emission in SPT0346-52. The gas in SPT0346-52 was found to be globally unstable, with Toomre Q instability parameters $\ll 1$ throughout the system. In addition, they found two components separated by $\sim 1$ kpc and $\sim 500$ km/s that appear to be merging, which is likely driving the intense star formation in SPT0346-52. More recently, Jones et al. (2019) have suggested that a rotating disk galaxy is a better explanation for a water absorption line.

In this paper, we extend the work of Litke et al. (2019), expanding their $[\text{C}ii]158\mu\text{m}$ analysis to a survey of fine-structure lines. Using $[\text{N}ii]205\mu\text{m}$, $[\text{C}ii]158\mu\text{m}$, $[\text{O}i]146\mu\text{m}$, $[\text{N}ii]122\mu\text{m}$, $[\text{O}i]63\mu\text{m}$, and the underlying dust continuum emission, we conduct a multi-phase study of the ISM in SPT0346-52. This represents one of the first multi-line, spatially resolved studies of the ISM at high-$z$.

We describe ALMA observations of the five fine-structure lines in Section 3.2. The lensing reconstruction process and results are discussed in Section 3.3. In Section 3.4, we describe the CLOUDY modeling of the ISM in SPT0346-52. We describe the
results and various line and continuum diagnostics in Section 3.5, and summarize the results in Section 3.6. We adopt the cosmology of Planck Collaboration et al. (2016) ($\Omega_m = 0.309$, $\Omega_\Lambda = 0.691$, and $H_0 = 67.7$ km/s). At $z = 5.656$, $1'' = 6.035$ kpc.

### 3.2 ALMA Observations

SPT0346-52 was observed in ALMA Bands 6, 7, and 9 from September 2014 through September 2018 (project IDs: 2013.1.01231, 2015.1.01580, 2016.1.01565; PI: Marrone). $[\text{C}^\text{II}]_{158}\mu\text{m}$, $[\text{N}^\text{II}]_{122}\mu\text{m}$, and $[\text{O}^\text{I}]_{63}\mu\text{m}$ were all observed on multiple dates at different resolutions, while $[\text{N}^\text{II}]_{205}\mu\text{m}$ and $[\text{O}^\text{I}]_{146}\mu\text{m}$ were each observed once. Details of these observations, including dates, observing frequencies, flux and phase calibrators, and resolutions, are listed in Tables 3.1 and 3.2.

The data were processed using various pipeline versions of the Common Astronomy Software Applications package (CASA; McMullin et al., 2007; Petry and CASA Development Team, 2012). $[\text{C}^\text{II}]_{158}\mu\text{m}$, $[\text{N}^\text{II}]_{205}\mu\text{m}$, and $[\text{O}^\text{I}]_{146}\mu\text{m}$ were all processed using CASA pipeline version 4.2.2. $[\text{N}^\text{II}]_{122}\mu\text{m}$ was processed with CASA pipeline version 4.7.1, and $[\text{O}^\text{I}]_{63}\mu\text{m}$ was processed with CASA pipeline version 5.4.0. These were the accepted pipeline versions for the cycles in which each dataset was observed.

Continuum images at all five frequencies were created with the task tclean in CASA version 5.4.0, using Briggs weighting (robust=0.5) and the automainthreash masking option. The continuum images are shown in the top row of Figure 3.1 and as contours in the bottom row. For the line emission, the continuum was subtracted from the line cube using the CASA task uvcontsub with a first order polynomial representing the continuum.

The line emission was imaged in the same manner as the continuum, but tapered to $300k\lambda$ and integrated from -300 to +300 km/s. (Figure 3.1, bottom row). This
Table 3.1. ALMA Observations of SPT0346-52: Calibration

<table>
<thead>
<tr>
<th>Line</th>
<th>Date</th>
<th>Frequency$^a$ (GHz)</th>
<th>Flux Calibrator</th>
<th>Phase Calibrator</th>
<th>Project ID$^b$</th>
</tr>
</thead>
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<tr>
<td></td>
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<tr>
<td><strong>Band 6</strong></td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>[N\text{ii}]$205\mu$m</td>
<td>2015 Aug 30</td>
<td>227.518</td>
<td>J0334-4008</td>
<td>J0334-4008</td>
<td>2013.1.01231</td>
</tr>
<tr>
<td>[N\text{ii}]$122\mu$m</td>
<td>2016 Jun 30</td>
<td>364.434</td>
<td>Ceres</td>
<td>J0253-5441</td>
<td>2015.1.01580</td>
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<tr>
<td>[C\text{ii}]+158\mu$m</td>
<td>2014 Sep 2</td>
<td>291.533</td>
<td>J0334-4008</td>
<td>J0334-4008</td>
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</tr>
<tr>
<td>[N\text{ii}]+158\mu$m</td>
<td>2015 Jun 28</td>
<td>291.536</td>
<td>J0334-4008</td>
<td>J0334-4008</td>
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</tr>
<tr>
<td>[O\text{i}]+146\mu$m</td>
<td>2014 Sep 2</td>
<td>304.136</td>
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<td>J0253-5441</td>
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<td>J0522-3627</td>
<td>J0210-5101</td>
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$^a$First local oscillator frequency

$^b$PI: Marrone
Table 3.2. ALMA Observations of SPT0346-52: Results

<table>
<thead>
<tr>
<th>Line</th>
<th>Date</th>
<th># Ant.</th>
<th>Resolution (arcsec)</th>
<th>PWV $^a$ (mm)</th>
<th>$t^b_{\text{int}}$ (min)</th>
<th>Noise Level $^c$ (mJy/beam)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Band 6</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>[NII]205$\mu$m</td>
<td>2015 Aug 30</td>
<td>35</td>
<td>0.19 × 0.25</td>
<td>1.4</td>
<td>44.3</td>
<td>0.10</td>
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<td>Band 7</td>
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<tr>
<td>[CII]158$\mu$m</td>
<td>2014 Sep 2</td>
<td>34</td>
<td>0.22 × 0.26</td>
<td>0.9</td>
<td>5.3</td>
<td>0.25</td>
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<tr>
<td>[OII]146$\mu$m</td>
<td>2014 Sep 2</td>
<td>34</td>
<td>0.22 × 0.27</td>
<td>0.9</td>
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<td>0.20</td>
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<td>[NII]122$\mu$m</td>
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<td>40</td>
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<tr>
<td>[OII]63$\mu$m</td>
<td>2018 Aug 17</td>
<td>46</td>
<td>0.23 × 0.33</td>
<td>0.4</td>
<td>19.2</td>
<td>1.7</td>
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</table>

$^a$Precipitable water vapor at zenith

$^b$On-source integration time

$^c$Root-mean-square noise level in continuum image
Figure 3.1: Observed emission from SPT0346-52. Top: Continuum images. Bottom: Line images with continuum contours. Continuum images were untapered and used Briggs weighting (robust=0.5). Line Images were made integrating from $-300$ to $+300$ km/s with Briggs weighting (robust=0.5) and tapered to $300\,k\lambda$. The contours represent the observed continuum emission at 10, 30, and $50\,\sigma$. From left to right: $205\,\mu m$, $158\,\mu m$, $146\,\mu m$, $122\,\mu m$, and $63\,\mu m$. 
tapering was also used in the lensing reconstructions.

To evaluate the overall significance of our line detections, we construct source-integrated spectra from the visibility data. Because SPT0346-52 is gravitationally lensed, we use the spatial structure of the continuum emission to provide a spatial template for the line emission (see the Appendix of Litke et al. (2019)). Visibilities of the line emission are weighted by a gravitational lensing model of the continuum emission to emphasize the visibilities that best sample the source structure, yielding a channelized flux density \( F_\nu \) determined by

\[
F_\nu = \frac{\sum_i \tilde{v}_{\nu,i} |\tilde{m}_i|^2}{\sum_i |\tilde{m}_i|^2}.
\]

(3.1)

Here, \( \tilde{v}_{\nu,i} \) is the complex line data visibility and \( \tilde{m}_i \) is the complex model visibility for that data set. The model visibilities are obtained from our lensing reconstructions, described in Section 3.3. The observed spectrum for each line is shown in Figure 3.2. To obtain the uncertainties, visibilities were randomly drawn from the distribution of visibilities for each channel and each line 500 times. The random spectra were then calculated using Equation 3.1. The uncertainties were then determined by taking the standard deviation of the 500 random noise trials.

\[\text{[NII]}122\mu\text{m}\] is not significantly detected in our observations. \[\text{[NII]}122\mu\text{m}\] is redshifted to 369.5 GHz, where the atmospheric transmission declines due to a strong atmospheric O\(_2\) line at 368.5 GHz. \[\text{[OI]}63\mu\text{m}\] is also not significantly detected in our observations. This line is redshifted to 712.9 GHz, the high-frequency end of ALMA Band 9, where a strong atmospheric O\(_2\) line at 715.4 GHz and the 752 GHz water line that separates the 650 and 850 GHz atmospheric windows (Bands 9 and 10) combine to produce a sharp decline in atmospheric transmission toward higher frequency (bluer velocity). To obtain the upper limits for \[\text{[NII]}122\mu\text{m}\] and \[\text{[OI]}63\mu\text{m}\] listed in Table 3.4, the 1\(\sigma\) uncertainty on a single 600 km/s channel was calculated using the method described above. This value was multiplied by 3 to obtain the
Figure 3.2: Observed spectra of the targeted lines. Top row (left to right): [N\text{II}]205\,\mu m, [C\text{II}]158\,\mu m, [O\text{I}]146\,\mu m. Bottom row (left and center): [N\text{II}]122\,\mu m, [O\text{I}]63\,\mu m. The rightmost bottom panel shows all five spectra overlaid on the same vertical scale. The grey regions in the [N\text{II}]122\,\mu m and [O\text{I}]63\,\mu m spectra represent velocities between spectral windows. The spectra were obtained using observed and model visibilities, as described in the appendix of Litke et al. (2019). Typical uncertainties are plotted in the upper left corners of the [N\text{II}]205\,\mu m, [C\text{II}]158\,\mu m, [O\text{I}]145\,\mu m, [N\text{II}]122\,\mu m, and [O\text{I}]63\,\mu m spectra.

3\sigma upper limit. It was then divided by $\mu = 5.6$ (Spilker et al., 2016) to correct for magnification from gravitational lensing. The non-detections of [N\text{II}]122\,\mu m and [O\text{I}]63\,\mu m are discussed in Sections 3.5.5 and 3.5.6, respectively.

### 3.3 Lens Modeling

Gravitational lensing is a powerful tool for studying galaxies at high redshift. Because lensing spreads the source emission over a larger solid angle on the sky while preserving the surface brightness, resolving detail in the lensed galaxy can be done with a more compact array configuration than is possible in unlensed sources, and
more compact arrays have better surface brightness sensitivity. However, the image distortion introduced by the gravitational lensing makes it difficult to study the spatially-resolved physical structure of the galaxy in a straight-forward manner.

In order to study the source-plane structure of SPT0346-52, we turn to lensing reconstruction models. We use a pixelated, interferometric lensing reconstruction code, RIPPLES (Hezaveh et al., 2016). Additional information in the general framework for pixelated lens modeling is described by Warren and Dye (2003) and Suyu et al. (2006). RIPPLES uses a Markov Chain Monte Carlo (MCMC) method to model the mass distribution of the foreground galaxy as well as the background source emission. It also takes into account observational effects from the primary beam. In addition, a regularization factor is introduced that minimizes large gradients between adjacent pixels, which prevents overfitting of the data.

As mentioned above, RIPPLES models the complex visibilities observed by ALMA directly, rather than modeling CLEAN images. By modeling the complex visibilities, we use all of the data available from the ALMA observations. Because RIPPLES is a pixelated code, we do not assume a source-plane structure, and can model more complex structures.
Table 3.3. SPT0346-52 Continuum Lens Modeling Results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>205µm</th>
<th>158µm</th>
<th>146µm</th>
<th>122µm</th>
<th>63µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>logMass([M_\odot])</td>
<td>11.46 ± 0.01</td>
<td>11.46 ± 0.01</td>
<td>11.46 ± 0.02</td>
<td>11.50 ± 0.01</td>
<td>11.47 ± 0.02</td>
</tr>
<tr>
<td>Ellipticity x-Component, (e_x)</td>
<td>-0.17 ± 0.01</td>
<td>-0.17 ± 0.01</td>
<td>-0.18 ± 0.02</td>
<td>-0.16 ± 0.01</td>
<td>-0.16 ± 0.01</td>
</tr>
<tr>
<td>Ellipticity y-Component, (e_y)</td>
<td>+0.43 ± 0.03</td>
<td>+0.41 ± 0.04</td>
<td>+0.39 ± 0.07</td>
<td>+0.22 ± 0.01</td>
<td>+0.39 ± 0.09</td>
</tr>
<tr>
<td>Ellipticity, (e^{a,c})</td>
<td>0.45</td>
<td>0.45</td>
<td>0.42</td>
<td>0.25</td>
<td>0.45</td>
</tr>
<tr>
<td>Position Angle, (\phi_e) (E of N)(^{b,c})</td>
<td>69°</td>
<td>68°</td>
<td>65°</td>
<td>55°</td>
<td>68°</td>
</tr>
<tr>
<td>Shear x-Component, (\gamma_x)</td>
<td>+0.06 ± 0.01</td>
<td>+0.06 ± 0.01</td>
<td>+0.09 ± 0.02</td>
<td>+0.15 ± 0.01</td>
<td>+0.07 ± 0.03</td>
</tr>
<tr>
<td>Shear y-Component, (\gamma_y)</td>
<td>-0.10 ± 0.01</td>
<td>-0.11 ± 0.01</td>
<td>-0.10 ± 0.01</td>
<td>-0.08 ± 0.01</td>
<td>-0.10 ± 0.01</td>
</tr>
<tr>
<td>Shear Amplitude, (\gamma^{a,c})</td>
<td>0.12</td>
<td>0.12</td>
<td>0.13</td>
<td>0.17</td>
<td>0.12</td>
</tr>
<tr>
<td>Shear Position Angle, (\phi_\gamma) (E of N)(^{b,c})</td>
<td>120°</td>
<td>120°</td>
<td>127°</td>
<td>115°</td>
<td>119°</td>
</tr>
<tr>
<td>Lens x Position, (x)</td>
<td>0(^{\prime})04 ± 0(^{\prime})01</td>
<td>0(^{\prime})08 ± 0(^{\prime})01</td>
<td>0(^{\prime})00 ± 0(^{\prime})01</td>
<td>0(^{\prime})01 ± 0(^{\prime})01</td>
<td>0(^{\prime})05 ± 0(^{\prime})01</td>
</tr>
<tr>
<td>Lens y Position, (y)</td>
<td>0(^{\prime})38 ± 0(^{\prime})01</td>
<td>0(^{\prime})32 ± 0(^{\prime})01</td>
<td>0(^{\prime})40 ± 0(^{\prime})01</td>
<td>0(^{\prime})39 ± 0(^{\prime})01</td>
<td>0(^{\prime})35 ± 0(^{\prime})01</td>
</tr>
</tbody>
</table>

\(^a\alpha = \sqrt{\alpha_x^2 + \alpha_y^2}\), where \(\alpha = e\) or \(\alpha = \gamma\)

\(^b\phi_\alpha = \arctan (-\alpha_y/\alpha_x)\), where \(\alpha = e\) or \(\alpha = \gamma\)

\(^c\)Derived from best-fit parameters
Table 3.4. SPT0346-52 Fluxes and Luminosities

<table>
<thead>
<tr>
<th>Parameter</th>
<th>205μm</th>
<th>158μm</th>
<th>146μm</th>
<th>122μm</th>
<th>63μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuum Flux (mJy)</td>
<td>6.8 ± 1.1</td>
<td>11.9 ± 1.2</td>
<td>13.2 ± 1.3</td>
<td>24.9 ± 2.5</td>
<td>28.1 ± 2.8</td>
</tr>
<tr>
<td>Line Luminosity (10^8 L⊙)</td>
<td>1.2 ± 0.2</td>
<td>34 ± 5</td>
<td>3.2 ± 0.5</td>
<td>&lt; 3.5^a</td>
<td>&lt; 53^a</td>
</tr>
</tbody>
</table>

^a3σ upper limit from observations, corrected for lensing
We model the ALMA observations using the same procedure as Litke et al. (2019). The mass distribution of the foreground lensing galaxy is modeled as a singular isothermal ellipsoid (SIE) at $z = 0.9$ with an external shear component. Previous lens modeling of SPT0346-52 by Hezaveh et al. (2013), Spilker et al. (2015), and Litke et al. (2019) were used to obtain the initial parameters. The 205$\mu$m, 158$\mu$m, 146$\mu$m, 122$\mu$m, and 63$\mu$m rest-frame continuum data were all fit independently. The best-fit lens model derived from each continuum data set was then applied to the corresponding line data corresponding to that continuum. For example, the 158$\mu$m model was applied to the [CII] 158$\mu$m line data, while the 205$\mu$m model was applied to the [NII] 205$\mu$m line data. The lines were integrated from -300 km/s to +300 km/s for the reconstructions. Table 3.3 gives the best-fit lensing parameters for all five models, while Table 3.4 gives the source-plane continuum fluxes and line luminosities. The parameter covariance plot from the MCMC for all five continuum sets is shown in Figure 3.3.

### 3.3.1 Comparing Models

As seen in Figure 3.3, the five continuum models do not have identical lens parameters, though they are very similar in most parameters. In order to explore the effect of the differing models on the source-plane reconstructions, we applied each model to each of the other continuum data sets. We then reconstructed the source-plane continuum emission. The derived continuum fluxes were consistent, independent of the model used. The differences between the best-fit models are within the errors of the MCMC fit and most likely result from degeneracies between the ellipticity and shear parameters. These differences do not affect our results in the source-plane.

---

1The exception lies with the lens x and y positions. These positions are measured relative to the phase-centers of observations. The variation in the modeled positions of the lens from different datasets are consistent with the variation seen in the position of the astrometric test sources.
Figure 3.3: Triangle plot with the model lens parameters for SPT0346-52 computed for different continuum wavelengths. Red: 205 µm continuum model. Orange: 158 µm continuum model. Green: 146 µm continuum model. Blue: 122 µm continuum model. Purple: 63 µm continuum model. $M$ is the lens mass enclosed within 10 kpc and is measured in $M_\odot$. $e_x$ and $e_y$ are the two components of the lens galaxy’s ellipticity, while $\gamma_x$ and $\gamma_y$ are the two components of the shear. $x$ and $y$ are the offset of the lens center from the phase center in arcseconds.
To find the uncertainty on the flux in each pixel, we created 500 sets of random visibilities from the distribution of uncertainties in the visibilities. We then reconstructed these 500 random noise data sets and took the standard deviation in each pixel. The total error used is the standard deviation of the random noise reconstructions added in quadrature with 10% of the flux.

In order to determine the effective resolution of the reconstructed maps, we follow the method used by Litke et al. (2019). We define the effective resolution as the inferred source-plane size when reconstructing a lensed point source at that source-plane position. This effective resolution will vary depending on the position of the source relative to the caustic in the source-plane, as well as the signal-to-noise of the input data. For each set of visibilities, we create a point source with the flux and position of the emission at that wavelength. We then apply the corresponding lens model in Table 3.3 to these point sources to create a lensed set of visibilities. Next, we make source-plane reconstructions of these lensed point sources using ripple. Finally, we fit a 2D-Gaussian to the reconstructed image to find the effective resolution.

It is simpler to compare the different line and continuum reconstructions if they have comparable resolutions. Therefore, we tapered the visibilities in each data set to 300kλ before performing the reconstructions. The resolutions are shown as colored ellipses in the lower left corner of the continuum and Moment 0 maps in Figure 3.4. The effective resolution is \( \sim 0.08 \times 0.15 \), which gives us \( \sim 700 \) pc resolution. The models, residuals, and error maps are shown in Figure B.1 in Appendix B.

### 3.3.2 Lens Modeling Results

Figure 3.4 shows the reconstructed continuum maps and the Moment 0 (integrated flux) maps of the line reconstructions. The continuum maps mostly show similar morphologies, but with different fluxes. As expected, the 63\( \mu \)m continuum emission is
Figure 3.4: Reconstructed source-plane emission. From left to right: 205\(\mu\)m, 158\(\mu\)m, 146\(\mu\)m, 122\(\mu\)m, and 63\(\mu\)m. Top: continuum maps of the source-plane. Colorbar units are mJy. Bottom Row: Moment 0 maps (velocity-integrated line flux). Colorbar units are mJy km/s. The ellipses represent the typical resolution where there is emission in the source-plane. The black x’s mark the center of the source plane. A representative caustic is shown as black lines in the upper right corner (the 63\(\mu\)m continuum map). All source-plane images are 8kpc per side.
the brightest and the 205μm emission is the weakest. We see differing morphologies in the line emission. The [CII]158μm and [NII]205μm lines show their brightest emission offset from the [OI]146μm emission. Because the Earth’s atmosphere limits access to these lines except at the highest redshifts, the sources with spatially resolved maps of FIR fine structure lines are mostly very nearby galaxies. Parkin et al. (2013) and Herrera-Camus et al. (2018a) found in M51 and NGC1068, respectively, that the [CII]158μm and [NII] lines had similar morphologies. A similar offset between [OI]146μm and [CII]158μm emission was seen by Herrera-Camus et al. (2018a) in NGC1068. In their maps, the brightest [OI]146μm emission was associated with the central AGN in NGC1068, while the [CII]158μm emission was associated with the peak in CO emission. Parkin et al. (2013) also found that the [OI]63μm and [OI]146μm emission peaked in the center of M51, most likely associated with the central AGN, offset from where [CII]158μm and [NII]122μm emission were strongest. In the SMC, [OI]63μm emission was associated with Hα emission and therefore recent massive star formation (Jameson et al., 2018). As seen in these other systems, the [OI]146μm and [OI]63μm emission has been associated with regions where one would expect dust heating, whether the dust is being heated by star formation or a central AGN. For SPT0346-52, the [OI]146μm emission is concentrated closer to where the dust continuum is strongest. As any potential AGN contribution to the IR emission in SPT0346-52 is negligible (Ma et al., 2016), the [OI]146μm emission appears to coincide with the most intense star formation.

Litke et al. (2019) determined that the intense star-formation in SPT0346-52 was driven by a major merger of two components. These components are centered at -310 and +160 km/s and have similar widths (≈ 300 km/s). The center of these two components lies near -75 km/s. The merger status was determined using position-velocity diagrams of the [CII]158μm emission, which is the highest signal-to-noise line of those explored here. Litke et al. (2019) used higher resolution reconstructions
than are shown in this work, where we decrease the resolution of the \([\text{Cu}]158\mu\text{m}\) reconstruction to match that of the lowest resolution lines. More recently, Jones et al. (2019) claimed SPT0346-52 is better described as a disk galaxy with a molecular outflow, based on visual inspection of the image-plane structure. However, the candidate H$_2$O outflow Jones et al. (2019) detected is kinematically similar to the blue-shifted component found by Litke et al. (2019). The mass loading factor of the possible outflow in SPT0346-52 is well below unity, unlike other outflows with mass loading factors near or greater than unity. Spilker et al. (2020) do not see broad wings in [Cu]158\mu m that would be indicative of outflows in any DSFGs with confirmed molecular outflows traced by blue-shifted OH absorption. Thus, SPT0346-52 is unlikely to host outflow activity. The disk structure described by Jones et al. (2019) may also have resulted from a recent major merger (e.g., Hopkins et al., 2009).

3.4 CLOUDY Modeling

In order to understand the physical conditions that explain our observations, we turn to the photoionization code CLOUDY (version 17.01; Ferland et al., 2017). CLOUDY simulates the microphysics within a cloud of gas and dust that is heated by a central source. It predicts the physical conditions throughout the cloud, including temperatures, densities, and metallicities, while also computing a predicted observed spectrum.

3.4.1 CLOUDY Parameters

We model our system as an open, or slab-like, geometry. We adopt an inner radius (the distance between the central heating source and the inner face of the cloud) of 100 pc. This distance is chosen to be smaller than the size of an individual pixel.

We use the ISM gas-phase elemental abundances and grain size distributions included with CLOUDY, which represents the average warm and cold phase abundances
of the ISM in the Milky Way (Cowie and Songaila, 1986; Savage and Sembach, 1996). We also include polycyclic aromatic hydrocarbons (PAHs) in the simulation. Small grains such as PAHs are an important contributor of grain heating mechanisms and FUV radiative transfer effects (Hollenbach and Tielens, 1999). For the equation of state of the ISM, we assume constant pressure. The components balanced to achieve constant pressure gas are

\[ P_{\text{tot}} = P_{\text{gas}} + P_{\text{turb}} + P_{\text{lines}} + \Delta P_{\text{rad}}, \]  

(3.2)

where \( P_{\text{gas}} \) is thermal gas pressure, \( P_{\text{turb}} \) is the turbulent pressure, \( P_{\text{lines}} \) is radiation pressure due to trapped emission lines, and \( \Delta P_{\text{rad}} \) is pressure from the attenuation of the incident radiation field. In order to simplify the model, we do not include a magnetic field component. Following Cormier et al. (2019), we assume a constant microturbulent velocity of 1.5 km/s. This is consistent with the microturbulent velocities of individual PDRs (Kaufman et al., 1999; Tielens and Hollenbach, 1985).

The gas cloud is heated by a single-burst stellar population. The starburst spectral energy distribution (SED) was compiled by Byler et al. (2017) for use in CLOUDY using the Flexible Stellar Population Synthesis code (Conroy et al., 2009; Conroy and Gunn, 2010). We use the ionizing spectrum from Byler et al. (2017) produced by the MESA Isochrones and Stellar Tracks (MIST; Choi et al., 2016; Dotter, 2016). The MIST stellar evolution tracks differ from other models in that they include stellar rotation, which results in harder ionizing spectra and higher luminosities (Byler et al., 2017). Byler et al. (2017) compared nebular emission ionized by MIST models to Padova (for low-mass stars; Bertelli et al., 1994; Girardi et al., 2000; Marigo et al., 2008) and Geneva (for high-mass stars; Schaller et al., 1992; Meynet and Maeder, 2000) evolutionary tracks (Levesque et al., 2010), and found that the MIST models can match observed line ratios better as the starburst ages past a few Myr. We fix the stellar metallicity to \( \log \frac{Z}{Z_\odot} = 0 \) and the age to the stellar age calculated by Ma et al. (2015) using SED fitting, \( \sim 30 \) Myr. Allowing the stellar metallicity to
scale with the gas metallicity did not change our results. The input starburst SED sets the shape of the ionizing spectrum in CLOUDY. The intensity of the ionizing radiation is determined by the ionization parameter, described below.

We also include the cosmic microwave background (CMB) at \( z = 5.7 \) and cosmic rays to contribute to the gas heating. The CMB spectrum was then subtracted from the modeled continuum SED before comparing to the observations, which are measurements of excess above the CMB spectrum.

We create a grid of models varying the ionization parameter \( (U) \), Hydrogen density \( (n_H) \) at the face of the cloud, and gas metallicity \( (Z) \). The ionization parameter is defined as the ratio of hydrogen-ionizing photons to the total hydrogen density, or more specifically

\[
U \equiv \frac{Q(H)}{4\pi r_0^2 n_H c},
\]

where \( r_0 \) is distance between center of starburst and inner surface of cloud (100 pc), \( n_H \) is the total hydrogen density, \( Q(H) \) is the number of hydrogen-ionizing photons, and \( c \) is the speed of light. We vary \( \log U \) from -4.5 to -0.5 in steps of 0.25. The total hydrogen density includes molecular, atomic, and ionized hydrogen components. \( n_H \) is defined at the inner face of the cloud for the grid values \( 0.5 \leq \log n_H \leq 3.5 \) in steps of 0.25. We vary the gas metallicity from \( -2.0 \leq \log Z/Z_\odot \leq 2.0 \) in steps of 0.25. We stop the CLOUDY simulation at visual extinction \( A_V = 100 \), following Abel et al. (2009).

To find the best-fit model, we compare the CLOUDY outputs to a combination of continuum ratios \( (\log 63\mu m/122\mu m, \log 63\mu m/146\mu m, \log 63\mu m/158\mu m, \log 63\mu m/205\mu m) \), line ratios \( (\log[C\text{II}]158\mu m/[N\text{II}]205\mu m, \log[C\text{II}]158\mu m/[O\text{I}]146\mu m) \), and a line-to-continuum ratio \( (\log[O\text{I}]146\mu m/146\mu m) \) to constrain the relative contributions of gas and dust. The best-fit model is chosen to be the model with the lowest reduced chi-squared value, \( \chi_r^2 \). Continuum values are in mJy and line values are in \( L_\odot \). \([O\text{I}]146\mu m/146\mu m \) has units \( 10^7 L_\odot / \text{mJy} \). The factor of \( 10^7 \) is used so the
Figure 3.5: Comparison of observed continuum and line ratios to CLOUDY best-fit galaxy-integrated ratios. From left to right: log $63\mu m/122\mu m$, log $63\mu m/146\mu m$, log $63\mu m/158\mu m$, log $63\mu m/205\mu m$, log $[O\,I]146\mu m/146\mu m$, log$[C\,II]158\mu m/[N\,II]205\mu m$, log$[C\,II]158\mu m/[O\,I]146\mu m$. Black circles represent the observed ratios and associated uncertainties. Purple squares represent the best-fit ratios from the CLOUDY modeling and associated uncertainties.

The line-to-continuum ratio is the same order of magnitude as the continuum ratios and line ratios. Table C.1 in Appendix C lists the values used to compare to the CLOUDY models. We consider both spatially-resolved and galaxy-integrated emission models.

We tested whether the inclusion of the continuum ratios affected our results. When the continuum ratios were not included, the line ratios were still well-fit, but the continuum ratios from CLOUDY did not match our observations. The ionization parameter was the variable most sensitive to the inclusion of the continuum ratios. This is consistent with previous CLOUDY modeling, where Abel et al. (2009) found the $60\mu m/100\mu m$ continuum ratio was strongly dependent on the ionization parameter.
Table 3.5. Best-Fit Global cloudy Models

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>log $U$</td>
<td>$-2.75^{+1.3}_{-0.1}$</td>
</tr>
<tr>
<td>log $n_H [cm^{-3}]$</td>
<td>$1.75^{+0.1}_{-1.1}$</td>
</tr>
<tr>
<td>log $Z/Z_{⊙}$</td>
<td>$0.75^{+0.5}_{-0.1}$</td>
</tr>
<tr>
<td>$\chi_r^2$</td>
<td>6.6</td>
</tr>
</tbody>
</table>

aThe likelihood distribution is calculated by summing $e^{-\chi^2}$. The best-fit value is the peak of the likelihood distribution, and the uncertainties are where the likelihood distribution is within 1σ of the peak.

3.4.2 Cloudy Modeling Results

Figure 3.5 shows the observed continuum and line ratios with their associated errors, as well as the ratios calculated for the best-fit cloudy model for SPT0346-52. Table 3.5 lists the best-fit starburst age, $U$, $n_H$, and $Z$ values, as well as $\chi_r^2$, for the best-fit models for the global fits shown in Figure 3.5. Overall, the best-fit models agree with the observed global line and continuum ratios in SPT0346-52.

It is a crude approximation to model an entire galaxy as a single PDR. Indeed, Katz et al. (2019) found in their simulations of emission lines in high-z galaxies that
Figure 3.6: Comparison of observed continuum and line ratios to CLOUDY best-fit pixelated ratios. From left to right: log 63\(\mu\)m/122\(\mu\)m, log63\(\mu\)m/146\(\mu\)m, log 63\(\mu\)m/158\(\mu\)m, log 63\(\mu\)m/205\(\mu\)m, log[O\,\text{I}]146\(\mu\)m/146\(\mu\)m, log[C\,\text{II}]158\(\mu\)m/[N\,\text{II}]205\(\mu\)m, log[C\,\text{II}]158\(\mu\)m/[O\,\text{I}]146\(\mu\)m. Black circles represent the means of the observed pixel ratios, and the errorbars represent the maximum and minimum observed ratios. Purple squares represent the means of the best-fit pixel ratios from the CLOUDY modeling, with the maximum and minimum best-fit ratios.
there can be very large ranges in metallicity and ionization parameter across a single galaxy. In the case of SPT0346-52, we have spatially-resolved information about the line and continuum emission and can explore the distribution of properties across the galaxy by fitting our models on a pixel-by-pixel basis. We use the same technique as was used for the galaxy-integrated fits for each pixel. Figure 3.6 shows the range of values observed and in the best-fit models, as well as the mean values, for each set of continuum and line ratios, while Figure 3.7 shows the best-fit $U$, $n_H$, and $Z$ values in each pixel. For maps of the observed continuum and line ratios, as well as the best-fit model ratios, see Figure C.1 in Appendix C.

As with the fits to the global line and continuum ratios, the range of ratios in the pixellated best-fit models mostly agree with the range of ratios observed. The modeled $\frac{[\text{C} \text{II}]158\mu m}{[\text{N} \text{II}]205\mu m}$ ratios have higher maximum values than the observed ratios, though their average values are more similar. We also see a higher average $\frac{[\text{C} \text{II}]158\mu m}{[\text{O} \text{I}]146\mu m}$ model ratio than observed, as we did with the galaxy-integrated fit. This may result from the CLOUDY model not probing far enough from
the ionizing source to fully recover line emission from the neutral gas component of the ISM.

The best-fit ionization parameters are around \( \log U = -2.75 \) and are relatively uniform. These values are comparable to those found for the DSFG SPT0418-47 (using \([\text{N} \text{II}]205, [\text{C} \text{II}]158, [\text{O} \text{I}]146, [\text{N} \text{II}]122, \) and \([\text{O} \text{III}]88; \) De Breuck et al., 2019). A popular technique is to report the intensity of the FUV, \( G \), relative to the interstellar radiation field, \( G_0 \), instead of the ionization parameter. To compare our \( U \) values to models using \( G \), we turn to Figure 1 of Abel et al. (2009); for a starburst SED, \( \log U \approx \log G - 6 \) and \( \log U = -2.75 \) corresponds to \( G = 10^{3.25} G_0 \). Rybak et al. (2019) and Rybak et al. (2020) found \( \log G/G_0 \approx 4 \) for \( z \approx 3 \) DSFGs and the \( z = 6 \) DSFG G09.83808, respectively, while Novak et al. (2019) found \( \log G/G_0 > 3 \) for the \( z = 7.5 \) quasar host galaxy J1342+0928. SPT0346-52 has a lower ionization parameter and FUV field strength compared to other high-z DSFGs.

We find densities around \( \log n_\text{H} \sim 2 \) throughout this system. This is lower than the inferred densities of the DSFGs SPT0418-47 at \( z = 4.225 \) (log \( n \sim 4.3; \) De Breuck et al., 2019) and G09.83808 at \( z = 6.027 \) (log \( n \sim 4; \) Rybak et al., 2020).

From the cloudy modeling, SPT0346-52 appears to have a supersolar metallicity (\( \log Z/Z_\odot = 0.75 \)). This is higher than other high-z sources that have been found to have metallicities near solar (\( \log Z/Z_\odot \sim 0.1 \) for quasar-host galaxy J1342+0928 at \( z = 7.54 \) and \( -0.5 < \log Z/Z_\odot < 0.1 \) for DSFG SPT0418-47) using \([\text{O} \text{III}]88/[\text{N} \text{II}]122 \) (Novak et al., 2019; De Breuck et al., 2019). However, the \([\text{O} \text{III}]88/[\text{N} \text{II}]122 \) metallicity diagnostic is highly dependent on the ionization parameter (Pereira-Santaella et al., 2017). Using the mass-metallicity relation of elliptical galaxies, Tan et al. (2014) found the metallicity of DSFGs in the protocluster GN20 (\( z = 4.05 \)) to be \( \log Z/Z_\odot \sim 0.5 \pm 0.2 \). The gas to dust ratio, \( \delta_{GDR} \), has been observed to be approximately inversely proportional to the metallicity in galaxies (e.g., Magdis et al., 2012; Leroy et al., 2011). Leroy et al. (2011) determined the relation between the gas to dust
ratio, and metallicity to be \( \log \delta = (9.4 \pm 1.1) - (0.85 \pm 0.13) \times (12 + \log([\text{O}/\text{H}])) \). Using the gas and dust masses from Aravena et al. (2016), \( \delta_{\text{GDR}} = 41 \pm 13 \) in SPT0346-52, giving us \( \log Z/Z_\odot = 0.7 \pm 0.3 \), consistent with the CLOUDY value.

### 3.5 Discussion

In this section, we explore various diagnostics of the different phases of the ISM in SPT0346-52. We begin with dust emission, then move on to line deficits and the electron density. We then explore the prevalence of ionized versus neutral gas and the non-detection of [O\text{i}]63. Finally, we look into several gas mass estimates for different phases of the ISM. For reference, Table 3.6 lists the transitions explored and their excitation properties. While SPT0346-52 has negligible AGN contribution to its \( L_{\text{FIR}} \), it is possible there is a highly dust-obscured AGN that prevents X-ray emission from being observed (Ma et al., 2016). DSFGs can contain AGN; for example, Wang et al. (2013a) found \( 17^{+16}_{-6}\% \) of DSFGs in the ALESS (ALMA LABOCA E-CDF-S Submm Survey) sample contain AGN. SPT0346-52 may also evolve to contain an AGN (e.g., Toft et al., 2014). We therefore consider both DSFGs and quasar-host galaxies for comparison.
<table>
<thead>
<tr>
<th>Line</th>
<th>Transition</th>
<th>$\nu_0$ (GHz)$^a$</th>
<th>$E_{\text{ion}}$ (eV)</th>
<th>$T_e$ (K)</th>
<th>$n_{\text{crit}, H}$ (cm$^{-3}$)$^b$</th>
<th>$n_{\text{crit}, e}$ (cm$^{-3}$)$^b$</th>
<th>$A$ (s$^{-1}$)$^a$</th>
<th>$g_u$</th>
</tr>
</thead>
<tbody>
<tr>
<td>[NII]205 μm</td>
<td>$^3P_2-^3P_0$</td>
<td>1461</td>
<td>70</td>
<td>1453</td>
<td>$1.76 \times 10^2$</td>
<td>$1.76 \times 10^{-6}$</td>
<td>8</td>
<td>3</td>
</tr>
<tr>
<td>[Cu]158 μm</td>
<td>$^2P_3-^2P_1$</td>
<td>1901</td>
<td>91</td>
<td>1126</td>
<td>$4.83 \times 10^1$</td>
<td>$4.83 \times 10^{-4}$</td>
<td>44</td>
<td>4</td>
</tr>
<tr>
<td>[O]146 μm</td>
<td>$^3P_0-^3P_1$</td>
<td>2000</td>
<td>-</td>
<td>327</td>
<td>$7.65 \times 10^2$</td>
<td>$7.65 \times 10^{-1}$</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>[NII]122 μm</td>
<td>$^3P_2-^3P_1$</td>
<td>2459</td>
<td>188</td>
<td>1453</td>
<td>$3.86 \times 10^2$</td>
<td>$3.86 \times 10^{-5}$</td>
<td>310</td>
<td>5</td>
</tr>
<tr>
<td>[O]63 μm</td>
<td>$^3P_1-^3P_2$</td>
<td>4745</td>
<td>228</td>
<td>-</td>
<td>$3.14 \times 10^4$</td>
<td>$3.14 \times 10^{-7}$</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Note. — The first two columns list the targeted lines and the fine structure transition that emits that line. $\nu_0$ is the emitted frequency of the line. $E_{\text{ion}}$ is the ionization energy needed to remove an electron. $T_e$ is the excitation temperature needed to populate the transition level. $n_{\text{crit}, H}$ is the critical density for collisions with hydrogen at $T = 100$ K. $n_{\text{crit}, e}$ is the critical density for collisions with electrons at $T = 10000$ K. $A$ is the Einstein A coefficient. $g_u$ is the statistical weight of the upper level.

$^a$Stacey (2011)

$^b$Cormier et al. (2019)
3.5.1 Dust Temperatures

We characterize the FIR continuum and dust temperatures throughout the source-plane using a modified blackbody function. We use the form from Spilker et al. (2016),

\[ S_{\nu} \propto (B_{\nu}(T_D) - B_{\nu}(T_{CMB}))(1 - e^{-\tau_{\nu}}). \]  

(3.4)

\( B_{\nu}(T) \) is the Planck function at rest-frame frequency \( \nu \) and temperature \( T \). The blackbody is modified by the dust optical depth, \( \tau_{\nu} \), which at long wavelengths can be parameterized by \( \tau_{\nu} = (\nu/\nu_0)^\beta = (\lambda_0/\lambda)^\beta \). In this parameterization, the optical depth reaches unity at wavelength \( \lambda_0 \), which together with \( T_D \) determines the peak wavelength and the width of the peak of the dust emission. The slope of the Rayleigh-Jeans tail of dust emission is \( \beta \). Typically, \( \beta \sim 1.5 - 2 \) and \( \lambda_0 \sim 100 - 200 \mu m \) in the rest-frame (e.g., Casey et al., 2014).

This modified blackbody is used to fit for the dust temperature in each pixel of the source-plane reconstruction, as well as the global dust temperature. Five continuum bands (63\( \mu m \), 122\( \mu m \), 146\( \mu m \), 158\( \mu m \), and 205\( \mu m \)) are used to fit the SEDs. Because of the limited number of photometric points available for these fits, we follow Greve et al. (2012) by fixing \( \beta = 2.0 \) and \( \lambda_0 = 100\mu m \). There are two free parameters in each SED fit, the dust temperature, \( T_D \), and the normalization.

The top panel of Figure 3.8 shows the global SED fit (black line) to the continuum (colored stars). For SPT0346-52, we calculate \( T_D = 48.3 \pm 4.0 \) K. The grey lines show the best-fit SEDs for the individual pixels. The best-fit dust temperatures are shown in the bottom center panel of Figure 3.8, while the right panel shows the error on the best-fit dust temperatures in each pixel. The left panel shows the FIR surface density (\( \Sigma_{\text{FIR}} \)). \( L_{\text{FIR}} \) is calculated here as the integral of the best-fit modified blackbody SED from 42.5 - 122.5\( \mu m \) (Helou et al., 1988). To get \( \Sigma_{\text{FIR}} \), we divide by the source-plane pixel area in kpc\(^2\). Dust temperature values in individual pixels have a mean \( T_D = 56 \) K.
Figure 3.8: Top: Modified blackbody fits to galaxy-integrated (black) and pixel-by-pixel (grey) continuum flux values. The colored stars are the measured global continuum flux values. The best-fit SED has a temperature of $T_D = 48.3\, K$. Bottom left: $\Sigma_{\text{FIR}}$, in $L_\odot/\text{kpc}^2$ across the source. Bottom center: Dust temperature throughout the system. Bottom right: Error in dust temperature. The mapped $T_D$ values are the temperatures from the best-fit modified blackbody SEDs in each pixel. $\Sigma_{\text{FIR}}$ is calculated by integrating the best-fit modified blackbody SED in each pixel from $42.5 - 122.5\mu$m and dividing by the pixel area.
Dust temperatures can vary significantly depending on the fitting form used (e.g., Hayward et al., 2012). Casey et al. (2014) show how, for a given $\lambda_{\text{peak}}$, the dust temperature can vary by up to 40 K depending on what assumptions are made about the opacity, as well as the value of $\beta$ used. The dust temperatures we calculate are lower than that calculated by Reuter et al. (2020) using Equation 3.4 ($T_D = 79\pm15$ K for SPT0346-52). However, this temperature difference is a result of the fitting procedures used in this work and by Reuter et al. (2020). Reuter et al. (2020) use the relation between $T_D$ and $\lambda_0$ found by Spilker et al. (2016). Using this relation tends to increase the fitted dust temperature by $\sim 20\%$ (Reuter et al., 2020). Jones et al. (2020) also calculated $T_D = 79 \pm 0.5$ K for SPT0346-52, using a modified blackbody distribution with effects from the CMB. The small uncertainty is largely due to the unrealistically small photometric errors claimed for the data used in the fit, many of which are well below 1%. Using the model from Jones et al. (2020) and the data from this paper, we calculate $T_D = 71 \pm 3$ K. Apostolovski et al. (2019) calculated $T_D = 29 \pm 1$ K for SPT0346-52 by using a radiative transfer model. The significant difference from the results of the continuum SED fits presented above undoubtedly results from the difference in methodology and the impact of including CO excitation as a constraint on the dust temperature.

3.5.2 Line Deficits

A commonly observed phenomenon is the so-called “[CII] deficit”, where $L_{[\text{CII}]}/L_{\text{FIR}}$ falls as $\Sigma_{\text{FIR}}$ increases (e.g., Luhman et al., 1998; Sargsyan et al., 2012; Farrah et al., 2013; Oteo et al., 2016; Spilker et al., 2016; Gullberg et al., 2018). Here, we explore possible deficits in other FIR lines that trace different components of the ISM. Figure 3.9 shows the line-to-FIR luminosity ratios versus $\Sigma_{\text{FIR}}$ for the five lines in this work. In SPT0346-52, we see deficits, i.e., apparent trends with $\Sigma_{\text{FIR}}$, in all five lines. Additionally, we see spatially-resolved deficits (apparent trends with $\Sigma_{\text{FIR}}$ in
Figure 3.9: Line luminosity/L\textsubscript{FIR} vs Σ\textsubscript{FIR} for the observed lines. From top to bottom: [N\textsc{ii}]205\,\mu m, [C\textsc{ii}]158\,\mu m, [O\textsc{i}]146\,\mu m, [N\textsc{ii}]122\,\mu m, [O\textsc{i}]63\,\mu m. The right column shows the same as the left column, but focused on the regions where our pixels lie (the parameter space indicated by light purple boxes in the right column). Colored diamonds are individual pixels, while the colored stars are the global value for each line. For [N\textsc{ii}]122\,\mu m and [O\textsc{i}]63\,\mu m, the upper limits are shown. Brown triangles are galaxies from SPT (Gullberg et al., 2015; De Breuck et al., 2019; Cunningham et al., 2020; Reuter et al., 2020). Grey dots are galaxy-integrated values from SHINING (Herrera-Camus et al., 2018a) and black are from GOALS (Díaz-Santos et al., 2017; Lutz et al., 2016; Lu et al., 2017b). Tan dots are a selection of high-z line detections: J1342+0928 (Venemans et al., 2017; Bañados et al., 2019; Novak et al., 2019), SPT0311-58 (Marrone et al., 2018), PJ231-20 (Pensabene et al., 2021), HFLS3 (Riechers, 2013), PJ308-21 (Decarli et al., 2019; Pensabene et al., 2021), G09.83808 (Zavala et al., 2018; Rybak et al., 2020), J2310+1855 (Shao et al., 2019; Li et al., 2020), BR1202-0725 (Decarli et al., 2014; Lu et al., 2017b; Lee et al., 2019, 2021), SMMJ02399 (Weiß et al., 2007; Ivison et al., 2010; Ferkinhoff et al., 2011), Cloverleaf (Weiß et al., 2003; Ferkinhoff et al., 2011), SDP.11 (Lamarche et al., 2018), and MIPS J1428 (Iono et al., 2006; Hailey-Dunsheath et al., 2010).
individual pixels) in all three detected lines.

Graciá-Carpio et al. (2011) found deficits in [C\textsc{ii}]158\,\mu m, [N\textsc{ii}]122\,\mu m, [O\textsc{i}]146\,\mu m and [O\textsc{i}]63\,\mu m, concluding that line deficits occurred in both ionized and neutral gas in galaxies with a variety of redshifts and optical classifications. They explained the deficits as resulting from an increase in the ionization parameter at $L_{\text{FIR}}/M_{\text{H}_2} > 80 \, L_\odot/M_\odot$ as highly compressed, more efficient star formation leads to enhanced ionization parameters. Zhao et al. (2016) found that there was only a [N\textsc{ii}]205 deficit in LIRGs that had warm ($f_{70}/f_{160} > 0.6$) colors. SPT0346-52 falls into this warm-color regime and does indeed exhibit an [N\textsc{ii}]205 deficit. On the other hand, several individual sources, ranging from $z = 1.5$ main sequence galaxies to $z = 6$ quasar host galaxies, did not show lower [O\textsc{i}]146\,\mu m/$L_{\text{FIR}}$ (Li et al., 2020) and [O\textsc{i}]63\,\mu m/$L_{\text{FIR}}$ ratios (Wagg et al., 2020; Coppin et al., 2012; Sturm et al., 2010). In the spatially resolved SHINING galaxies, a sample of nearby galaxies that includes star-forming galaxies, AGN host galaxies, and LIRGs, Herrera-Camus et al. (2018a) found the trend of decreasing line/$L_{\text{FIR}}$ strongest for singly ionized lines like [N\textsc{ii}]122\,\mu m and [C\textsc{ii}]158\,\mu m and weakest for neutral [O\textsc{i}]146\,\mu m and [O\textsc{i}]63\,\mu m.

### 3.5.3 [C\textsc{ii}]158/[N\textsc{ii}]205

Carbon has an ionization potential of 11.26 eV, which is slightly lower than that of hydrogen. This makes interpretation of [C\textsc{ii}]158\,\mu m emission difficult because it can originate from both ionized and neutral regions of the ISM. By comparing the [C\textsc{ii}]158\,\mu m to the [N\textsc{ii}]205\,\mu m emission, which arises only in ionized regions, we can infer how the [C\textsc{ii}]158\,\mu m emission is divided between neutral and ionized gas.

We can calculate the fraction of [C\textsc{ii}]158\,\mu m emission originating from neutral gas by comparing the observed [C\textsc{ii}]158\,\mu m/[N\textsc{ii}]205\,\mu m ratio to the expected ratio. From Abdullah et al. (2017),

$$R_{\text{ion}} = \frac{I_{[C\textsc{ii}]}}{I_{[N\textsc{ii}]}} = \frac{N_{[C\textsc{ii}]u}}{N_{[N\textsc{ii}]u}} \times \frac{E_{[C\textsc{ii}]ul}}{E_{[N\textsc{ii}]ul}} \times \frac{A_{[C\textsc{ii}]ul}}{A_{[N\textsc{ii}]ul}},$$  \hspace{1cm} (3.5)
where $R_{\text{ion}}$ is the expected line intensity ratio, $I$ is the expected line intensity of the transition, $N$ is the upper-level population, $E$ is the energy of the transition, and $A$ is the Einstein coefficient for that transition. This relation assumes the ionic abundance ratio, $[\text{Cu}]_{158\mu m}/[\text{N} \text{II}]_{205\mu m}$ is equal to the elemental abundance ratio, $C/N$. $R_{\text{ion}}$ also depends on $n_e$. As seen in Table 3.6, $[\text{Cu}]_{158\mu m}$ and $[\text{N} \text{II}]_{205\mu m}$ have similar critical electron densities (50 cm$^{-3}$ and 48 cm$^{-3}$). Therefore, if we compute the expected $[\text{Cu}]_{158\mu m}/[\text{N} \text{II}]_{205\mu m}$ ratio, there is little density dependence.

Croxall et al. (2017) calculated $R_{\text{ion}} = 4.0$ using collision rates from Tayal (2008) ($[\text{Cu}]_{158}$) and Tayal (2011) ($[\text{N} \text{II}]_{205}$) and assuming Galactic gas-phase abundances for both elements, while Díaz-Santos et al. (2017) used $R_{\text{ion}} \simeq 3.0 \pm 0.5$, based on photoionization models by Oberst et al. (2006). We adopt an intermediate value of $R_{\text{ion}} = 3.5$. With this expected $[\text{Cu}]_{158\mu m}/[\text{N} \text{II}]_{205\mu m}$ ratio, we can calculate the fraction of $[\text{Cu}]_{158\mu m}$ from neutral gas, $f_{[\text{Cu}],\text{neutral}}$, using

$$f_{[\text{Cu}],\text{neutral}} = \frac{[\text{Cu}]_{158\mu m} - R_{\text{ion}} \times [\text{N} \text{II}]_{205\mu m}}{[\text{Cu}]_{158\mu m}}. \quad (3.6)$$

For SPT0346-52, we calculate $f_{[\text{Cu}],\text{neutral}} = 0.84 \pm 0.04$. Nearby galaxies ranging from low-metallicity dwarf galaxies (Cormier et al., 2019) to star-forming galaxies (Sutter et al., 2019; Herrera-Camus et al., 2018a) and (U)LIRGs (Díaz-Santos et al., 2017) have $f_{[\text{Cu}],\text{neutral}} \sim 60 - 90\%$. As shown in Figure 3.10, SPT0346-52 has a more comparable $f_{[\text{Cu}],\text{neutral}}$ to what has been observed in other high-z sources and DSFGs ($f_{[\text{Cu}],\text{neutral}} \sim 85\%$, e.g., Li et al., 2020; De Breuck et al., 2019; Pavesi et al., 2018; Zhang et al., 2018). This fraction has been observed to be higher in active star-forming regions (Herrera-Camus et al., 2018a) and LIRGs with warmer $S_{63}/S_{158}$ colors (Díaz-Santos et al., 2017) like SPT0346-52.

3.5.4 $[\text{Cu}]_{158\mu m}/[\text{O} \text{I}]_{146\mu m}$

$[\text{Cu}]_{158\mu m}$ originates from both ionized and neutral gas, while $[\text{O} \text{I}]_{146\mu m}$ emission arises from only neutral regions. Therefore, more $[\text{O} \text{I}]_{146\mu m}$ emission would indicate
Figure 3.10: Fraction of [C\textit{II}]158\,\mu m emission originating from neutral gas, \(f_{[\text{C\textit{II}},\text{neutral}]}\), calculated from the [C\textit{II}]158\,\mu m/\text{[N\textit{II}]}205\,\mu m ratio. Top: SPT0346-52 (pink star) is compared to galaxies from SPT (brown triangles Gullberg et al., 2015; Cunningham et al., 2020; Reuter et al., 2020), high-z sources (tan dots; Decarli et al., 2014; Lu et al., 2017b; Pensabene et al., 2021), and GOALS (black dots; Díaz-Santos et al., 2017; Lutz et al., 2016; Lu et al., 2017b). Bottom: Fraction of [C\textit{II}]158\,\mu m originating from neutral gas in SPT0346-52, with the galaxy-integrated value listed in the upper left corner (\(f_{[\text{C\textit{II}},\text{neutral}]} \sim 0.85\)).
the presence of more dense, neutral gas. The ratio of these lines has therefore been used in the literature as an indicator of the prevalence of dense gas (De Breuck et al., 2019; Li et al., 2020).

Figure 3.11 plots $L_{[CII]158\mu m}/L_{[OI]146\mu m}$ as a function of $\Sigma_{\text{FIR}}$ for SPT0346-52, both integrated and spatially resolved, and values from the literature. SPT0346-52 has similar $[\text{CII}]158\mu m/[\text{OI}]146\mu m$ ratio compared to galaxies in the SHINING sample (Herrera-Camus et al., 2018a). It is higher than SPT0418-47, a $z = 4.2$ lensed DSFG. De Breuck et al. (2019) determined that SPT0418-47 had an $[\text{CII}]158\mu m/[\text{OI}]146\mu m$ ratio $\sim 5\times$ lower than local galaxies, leading them to conclude that the ISM in SPT0418-47 is dominated by dense gas. Li et al. (2020) also found $[\text{CII}]158\mu m/[\text{OI}]146\mu m$ in their $z \sim 6$ quasar was comparable to the lowest values in ULIRGs, implying that SDSS J2310+1855 has warmer and denser gas compared to local galaxies. The higher $[\text{CII}]158\mu m/[\text{OI}]146\mu m$ ratio in SPT0346-52, implying a smaller dense gas component, is consistent with the lower hydrogen gas densities found using CLOUDY in Section 3.4.2.

### 3.5.5 Non-Detection of $[\text{NII}]122\mu m$

$[\text{NII}]122\mu m$ is expected to be brighter than $[\text{NII}]205\mu m$. However, due to atmospheric $\text{O}_2$ at 368.5 GHz, just $\sim 800\text{km/s}$ from the expected center of the $[\text{NII}]122\mu m$ emission, $[\text{NII}]122\mu m$ is not detected in SPT0346-52. However, we can use the upper limit obtained in Section 3.2 to place constraints on the ISM conditions.

Nitrogen ions are only expected to be found in ionized regions of the ISM. In this regime, the $[\text{NII}]122\mu m$ and $[\text{NII}]205\mu m$ fine structure lines would be excited mostly through collisions with electrons (Goldsmith et al., 2015). Therefore, the relative intensity of $[\text{NII}]122\mu m$ compared to $[\text{NII}]205\mu m$ will depend on the electron density of the ISM and can be used to calculate this density.

We calculate the theoretical relation between the $[\text{NII}]122\mu m/[\text{NII}]205\mu m$ flux
Figure 3.11: [CII]158$\mu$m/[OI]146$\mu$m. Top: $L_{[\text{CII}]}$/L$_{[\text{OI}]}$ vs $\Sigma_{\text{FIR}}$. Pink diamonds are the individual pixels in SPT0346-52, while the pink star represents SPT0346-52. Comparison samples are taken from De Breuck et al. (2019) (SPT0418-47; brown triangle), Lee et al. (2021); Decarli et al. (2014); Novak et al. (2019) (BR1202-0725 and J1342+0928; tan dots), and Herrera-Camus et al. (2018a) (SHINING; grey dots. Bottom: Mapped ratio of [CII]158$\mu$m/[OI]146$\mu$m. Lower $L_{[\text{CII}]}$/L$_{[\text{OI}]}$ values (more [OI]146$\mu$m) indicate more dense, neutral gas.
Figure 3.12: Theoretical and calculated electron densities for SPT0346-52. The grey line is the theoretical relation between the $\frac{[\text{N} \text{II}]_{122 \mu m}}{[\text{N} \text{II}]_{205 \mu m}}$ ratio and electron density. The purple star represents the global $\frac{[\text{N} \text{II}]_{122 \mu m}}{[\text{N} \text{II}]_{205 \mu m}}$ ratio and corresponding $n_e$. The black dashed line represents the median value from the GOALS sample, and the dotted lines are the maximum and minimum values (Díaz-Santos et al., 2017).
ratio and the electron density, $n_e$, following Goldsmith et al. (2015) and using the collision rate coefficients from Tayal (2011). This relation is shown as the grey line in Figure 3.12. The left panel also shows the upper-limit to the ratios and corresponding $n_e$ values for SPT0346-52.

In SPT0346-52, we find $n_e < 36$ cm$^{-3}$. The densities observed in SPT0346-52 are lower than the densities calculated in other, comparable systems using the [N$_i$]122/[N$_i$]205 ratio. For example, Díaz-Santos et al. (2017) found a median $n_e = 41$ cm$^{-3}$ for local LIRGs, with densities ranging from $20$ cm$^{-3} < n_e < 100$ cm$^{-3}$ (black dashed and dotted lines in Figure 3.12), comparable to those found by Zhao et al. (2016), while De Breuck et al. (2019) calculated $n_e \sim 50$ cm$^{-3}$ for the lensed DSFG SPT0418-47. The non-detection of [N$_i$]122 indicates low densities in the ionized phase of the ISM.

### 3.5.6 Non-Detection of [Oi]63$\mu$m

[C$_i$]158$\mu$m and [Oi]63$\mu$m are both major coolants of the ISM. As one transitions to high-density ($n > 10^{3-4}$ cm$^{-3}$), high-temperature ($T > 10^4$ K), high-radiation ($G_0 > 10^3$) regimes, [Oi]63 becomes the dominant coolant over [C$_i$]158 (Tielens and Hollenbach, 1985; Hollenbach et al., 1991). One would expect to find bright [Oi]63$\mu$m emission comparable to or greater than the [C$_i$]158$\mu$m emission in FIR-bright systems like starbursts, where the ISM is heated by strong FUV radiation and warmer, denser gas is expected (Tielens and Hollenbach, 1985). In the first $z > 3$ detection of [Oi]63$\mu$m, Rybak et al. (2020) found [Oi]63$\mu$m was $\sim 4$ times brighter than [C$_i$]158 in the $z \sim 6$ DSFG, G09.83808. Given the intense star formation in SPT0346, we could reasonably expect that [Oi]63$\mu$m might be significantly more luminous than [C$_i$]158$\mu$m. However, we are unable to detect this line in our observations, finding a luminosity ratio of $L_{[C_i]158}/L_{[O_i]63} > 0.7$. Our inability to place a tighter detection limit reflects the impact of atmospheric O$_2$ absorption centered at 715.4 GHz, just
∼ 1000 km/s from the redshifted [O\textsc{i}]63\textmu m line center.

The [O\textsc{i}]63\textmu m emission may be intrinsically weak. Spinoglio and Malkan (1992) also found lower [O\textsc{i}]63\textmu m intensities with their CLOUDY modeling of starburst regions. In addition, Abel et al. (2009) found that low values of the ionization parameter, $U$, were associated with lower [O\textsc{i}]63\textmu m/[C\textsc{ii}]158\textmu m ratio in their CLOUDY models of ULIRGs. For SPT0346-52, [O\textsc{i}]63\textmu m/[C\textsc{ii}]158\textmu m < 1.5, which is lower than [O\textsc{i}]63\textmu m/[C\textsc{ii}]158\textmu m ∼ 4 in the $z = 6$ DSFG G09.83808 (Rybak et al., 2020). Rybak et al. (2020) found $G = 10^4 \, G_0$ (corresponding to log $U \approx -2$), which is higher than the values found in SPT0346-52. Our CLOUDY modeling of SPT0346-52 indicates lower ionization parameters, consistent with the lower [O\textsc{i}]63\textmu m/[C\textsc{ii}]158\textmu m ratio.

Often [O\textsc{i}]63\textmu m is optically thick (Liseau et al., 2006; Kaufman et al., 1999; Tielens and Hollenbach, 1985). It is also easily self-absorbed; small amounts of cold foreground gas can absorb [O\textsc{i}]63\textmu m while leaving [O\textsc{i}]146\textmu m unaffected (Liseau et al., 2006). This effect has been measured to reduce the [O\textsc{i}]63\textmu m emission by factors of $1.3 \pm 1.8$ (Kramer et al., 2020) up to $2.9 \pm 1.6$ (Liseau et al., 2006). If [O\textsc{i}]63\textmu m/[O\textsc{i}]146\textmu m < 10, [O\textsc{i}]63\textmu m is likely self-absorbed (Díaz-Santos et al., 2017; Cormier et al., 2015; Tielens and Hollenbach, 1985). Taking the $3\sigma$ upper limit and correcting for the lensing magnification, [O\textsc{i}]63\textmu m/[O\textsc{i}]146\textmu m < 14 in SPT0346-52. The [O\textsc{i}]63\textmu m/[O\textsc{i}]146\textmu m intensity ratio may be < 10, so [O\textsc{i}]63\textmu m may be self-absorbed.

The [O\textsc{i}]63\textmu m/[C\textsc{ii}]158\textmu m ratio may also be influenced by the presence of an AGN. With its high critical density (Table 3.6), [O\textsc{i}]63\textmu m is produced primarily in dense, neutral gas. In models of PDRs and X-ray dominated regions (XDRs), the [O\textsc{i}]63\textmu m/[C\textsc{ii}]158\textmu m ratio is higher in XDRs (which are expected near AGN) than in PDRs (Maloney et al., 1996; Meijerink et al., 2007). Ma et al. (2016) found no evidence of AGN activity in this source, so we do not expect an AGN-based
enhancement of [O I] 63µm emission.

3.5.7 Gas Mass Estimates

In this section, we estimate the ionized, neutral, and molecular gas masses using the various fine-structure lines observed in SPT0346-52. For ease of comparison, and because of the higher metallicity expected by gas to dust mass ratio in SPT0346-52, the ionic abundances are assumed to be the same as the global abundances in H II regions from Savage and Sembach (1996) (i.e., \( \chi([\text{C II}]) = \text{C/H} \), \( \chi([\text{N II}]) = \text{N/H} \), and \( \chi([\text{O I}]) = \text{O/H} \)). Table 3.7 lists a summary of the different masses calculated using the various methods described below. Figure 3.13 shows the various masses calculated for SPT0346-52 and several other high-redshift sources, normalized by the molecular gas mass calculated using CO.

Molecular Gas Mass from \( \alpha_{[\text{CII}]} \)

In their study of \( z \sim 2 \) main sequence galaxies, Zanella et al. (2018) found that the \([\text{C II}] 158 \mu \text{m} \) luminosity and the molecular gas mass of a galaxy were correlated. \( \alpha_{[\text{CII}]} = 31 M_{\odot}/L_{\odot} \), with a standard deviation of 0.3 dex, is mostly independent of depletion time, metallicity, and redshift.

Using our observed \([\text{C II}] 158 \mu \text{m} \) luminosity, we find a molecular gas mass of \( M_{\text{gas, } \alpha_{[\text{CII}]}} = 1.1 \pm 0.3 \times 10^{11} M_{\odot} \). This is between the molecular gas mass calculated by Aravena et al. (2016) using CO \( (8.2 \pm 0.6 \times 10^{10} M_{\odot}) \) and the molecular gas mass calculated by Apostolovski et al. (2019) using radiative transfer modeling \( (3.9 \pm 2.2 \times 10^{11} M_{\odot}) \).

Zanella et al. (2018) calibrated \( \alpha_{[\text{CII}]} \) using main sequence galaxies at \( z \sim 2 \). However, for DSFGs and quasar host galaxies, this method tends to result in higher molecular gas masses than those obtained using CO, as shown by the green points in Figure 3.13. The molecular masses calculated using \( \alpha_{[\text{CII}]} \) are also higher than the
Table 3.7. Summary of Mass Estimates

<table>
<thead>
<tr>
<th>Mass Type</th>
<th>Line or Reference</th>
<th>SPT0346-52 (×10^9 M⊙)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dust</td>
<td>1</td>
<td>2.1 ± 0.3</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>2.0 ± 0.6</td>
</tr>
<tr>
<td>Molecular</td>
<td>2</td>
<td>82 ± 6</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>390 ± 220</td>
</tr>
<tr>
<td>Stellar</td>
<td>4</td>
<td>&lt; 310</td>
</tr>
<tr>
<td>Molecular</td>
<td>[Cu]158μm</td>
<td>106 ± 15</td>
</tr>
<tr>
<td>PDR</td>
<td>[Cu]158μm</td>
<td>4.1 ± 0.6</td>
</tr>
<tr>
<td>Neutral</td>
<td>[Cu]158μm</td>
<td>24 ± 4</td>
</tr>
<tr>
<td></td>
<td>[O]146μm</td>
<td>18 ± 3</td>
</tr>
<tr>
<td>Ionized</td>
<td>[N]205μm</td>
<td>0.8 ± 0.1</td>
</tr>
</tbody>
</table>

1Spilker et al. (2015)

2Aravena et al. (2016)

3Apostolovski et al. (2019)

4Ma et al. (2015)
Figure 3.13: Mass estimates for SPT0346-52 and other high-redshift sources, normalized by the molecular gas mass from CO measurements, vs $L_{\text{FIR}}$. The stars represent the mass estimates for SPT0346-52. The masses for J1342+0928 ($z \approx 7.5$; Venemans et al., 2017; Novak et al., 2019), PJ308-21 ($z \approx 6.2$; Decarli et al., 2019; Pensabene et al., 2021), SDP.11 ($z \approx 1.8$; Lamarche et al., 2018), MIPS J1428 ($z \approx 1.3$; Iono et al., 2006; Hailey-Dunsheath et al., 2010), Cloverleaf ($z \approx 2.5$; Weiß et al., 2003; Ferkinhoff et al., 2011), J2310+1855 ($z \approx 6.0$; Shao et al., 2019; Li et al., 2020), HFLS3 ($z \approx 6.3$; Riechers, 2013; Cooray et al., 2014), and SPT0311-58 (Marrone et al., 2018; Jarugula et al., 2021, $z \approx 7$) are those reported in the literature. The dust and CO molecular masses for SPT galaxies, including SPT0346-52, are taken from Aravena et al. (2016) and Marrone et al. (2018) and the stellar masses are taken from Ma et al. (2015) and Marrone et al. (2018); the rest of the masses are calculated using the methods described in Section 3.5.7 using data from Gullberg et al. (2015); Cunningham et al. (2020); Reuter et al. (2020). Tan represents dust masses, green is molecular gas estimates using $[\text{C}]\alpha158\mu\text{m}$ (Molecular$_{\alpha[\text{C}]\alpha}$) (see Section 3.5.7), silver is a PDR model-based gas mass estimate (Section 3.5.7), blues are neutral gas mass estimates (Section 3.5.7), pinks/reds are ionized gas mass estimates (Section 3.5.7), and gold are stellar mass estimates. The black dashed line represents $M = M_{\text{CO}}$. 
neutral gas masses calculated using the method in Section 3.5.7 in both this work and previous studies (Decarli et al., 2019; Novak et al., 2019).

**Neutral Gas Mass from [CII]158µm PDR Modeling**

Hailey-Dunsheath et al. (2010) calculate the atomic mass associated with PDRs in the z = 1.3 hyperluminous starburst galaxy MIPS J1428 using the [CII]158µm luminosity and PDR models from Kaufman et al. (1999). Assuming the [CII]158µm emission is optically thin and that a single temperature characterizes the [CII]158µm-emitting region, the PDR mass is given by

$$\frac{M_{\text{PDR}}}{M_\odot} = 0.77 \left( \frac{f_{[\text{CII}],\text{neutral}} L_{[\text{CII}}}}{L_\odot} \right) \left( \frac{1.4 \times 10^{-4}}{\chi(C^+)} \right) \times \frac{1 + 2 \exp\left(\frac{-91K}{T}\right) + \frac{n_{\text{crit}}}{n}}{2 \exp\left(\frac{-91K}{T}\right)}. \quad (3.7)$$

Following Hailey-Dunsheath et al. (2010), we assume the gas temperature is the surface temperature of their modeled PDR, $T \approx 230$ K, $n = 10^{4.2}$ cm$^{-3}$, $n_{\text{crit}} = 2.7 \times 10^3$ cm$^{-3}$ (Launay and Roueff, 1977), and $C^+ / H = 1.4 \times 10^{-4}$ (Savage and Sembach, 1996). We use our calculated value of $f_{[\text{CII}],\text{neutral}} = 0.84$. We calculate a PDR mass of $M_{\text{PDR}} = 4.1 \pm 0.6 \times 10^9 M_\odot$ for SPT0346-52. This is $\sim 5\%$ of the total gas mass from Aravena et al. (2016).

The PDR mass fraction calculated for SPT0346-52 is much lower than that found by Hailey-Dunsheath et al. (2010) for MIPS J1428 ($\sim 55\%$). We also find a similarly lower PDR mass compared to the molecular gas mass in SPT0346-52 than in HFLS3 (20%; Riechers, 2013), and SDP.11 (23%; Lamarche et al., 2018). This method assumes a gas density log $n/cm^{-3} = 4.2$, $\sim 100\times$ higher than the density found using CLOUDY (Section 3.4.2). If we instead use log $n/cm^{-3} = 2$, we calculate an atomic PDR mass fraction of 58%, which is more comparable to other high-z sources. This discrepancy could explain the difference in atomic PDR masses between SPT0346-52 and other high-z sources. Masses calculated with this method are shown as silver points in Figure 3.13.
Neutral Gas Masses from $[\text{C} \, \text{II}]_{158 \mu m}$ and $[\text{O} \, \text{I}]_{146 \mu m}$

We next estimate the neutral gas mass in SPT0346-52 using $[\text{C} \, \text{II}]_{158 \mu m}$ and $[\text{O} \, \text{I}]_{146 \mu m}$. Based on the work by Weiß et al. (2005) and Li et al. (2020), the mass associated with a single transition can be calculated using

$$M_x = m_x \frac{8\pi k \nu_0^2 Q(T_{ex})}{h c A} \frac{e^{T_e/T_{ex}}}{g_u} L', \quad (3.8)$$

where $m_x$ is the mass of atom $x$, $\nu_0$ is the emission frequency, $A$ is the Einstein coefficient, $Q$ is the partition function, $g_u$ is the statistical weight of the upper level, $k$ is the Boltzmann constant, $h$ is the Planck constant, $T_e$ is the excitation temperature needed to populate the transition level from Table 3.6, $T_{ex}$ is the excitation temperature of the gas, and $L'$ is line luminosity in K km/s/pc$^2$. The Einstein A coefficients, upper level statistical weights, and transition temperatures can be found in Table 3.6.

We adopt an excitation temperature of $T_{ex} = 100$ K. Based on PDR modeling by Meijerink et al. (2007), 100 K is the temperature of a PDR cloud near the outer regions where $[\text{C} \, \text{II}]_{158 \mu m}$ is primarily emitted. The cloud will cool off to $\sim 20$ K in the inner parts of the cloud as carbon transitions from $[\text{C} \, \text{II}]$ to neutral C to CO. We also use this temperature for the $[\text{O} \, \text{I}]_{146 \mu m}$-based mass calculation. This method assumes the $[\text{C} \, \text{II}]_{158 \mu m}$ and $[\text{O} \, \text{I}]_{146 \mu m}$ emission is optically thin.

For $[\text{C} \, \text{II}]_{158 \mu m}$, Equation 3.8 becomes

$$\frac{M_{C+}}{M_\odot} = 3.21 \times 10^{-4} \frac{Q(T_{ex})}{4} e^{91/T_{ex}} L'_{[\text{C} \, \text{II}]_{158 \mu m}}, \quad (3.9)$$

where $Q(T_{ex}) = 2 + 4e^{-91/T_{ex}}$ and $L'_{[\text{C} \, \text{II}]_{158 \mu m}}$ is multiplied by $f_{[\text{C} \, \text{II}], \text{neutral}}$ so only the neutral gas contribution to the $[\text{C} \, \text{II}]_{158 \mu m}$ emission is included. Decarli et al. (2019) argue that the mass calculated using $[\text{C} \, \text{II}]_{158 \mu m}$ is a lower limit as it does not include non-ionized carbon or effects from lower metallicity gas, suppressed $[\text{C} \, \text{II}]_{158 \mu m}$ emission from collisional de-excitation, and optical depth effects.
For [O\textsc{i}]146\,\mu m, we can calculate the oxygen mass using

\[
\frac{M_O}{M_\odot} = 6.20 \times 10^{-5} Q(T_{ex})e^{329/T_{ex}}L'_{[O\textsc{i}]146\mu m}.
\]  \hspace{1cm} (3.10)

In this case, \(Q(T_{ex}) = 5 + 3e^{-228/T_{ex}} + e^{-329/T_{ex}}\).

To get the neutral gas mass, we divide by the \(C/H\) or \(O/H\) abundance. Using the abundance from Savage and Sembach (1996) (\(C/H = 3.98 \times 10^{-4}\) and \(O/H = 5.89 \times 10^{-4}\)), we find neutral gas masses of \(M_{\text{neutral},[C\textsc{ii}]158\mu m} = 2.4 \pm 0.4 \times 10^{10} M_\odot\) and \(M_{\text{neutral},[O\textsc{i}]146\mu m} = 1.8 \pm 0.3 \times 10^{10} M_\odot\). The [C\textsc{ii}]158\mu m and [O\textsc{i}]146\mu m neutral gas masses are approximately one-quarter the total gas mass calculated by Aravena et al. (2016). In general, the neutral gas masses calculated using [C\textsc{ii}]158\mu m, [O\textsc{i}]146\mu m, and [C\textsc{i}]369\mu m in both SPT0346-52 and in dusty star-forming galaxies and quasar host galaxies in the literature are within a factor of \(~10\) of the molecular gas mass (blue points in Figure 3.13).

The mass calculated using [C\textsc{ii}]158\mu m is \(~6\times\) higher than the mass calculated using [C\textsc{ii}]158\mu m and PDR modeling in Section 3.5.7. While two different temperatures were used (230 K vs 100 K), this difference only changes the calculated masses by \(~30\%) and does not fully account for the large discrepancy in the mass estimates. The mass estimate in Section 3.5.7 is based on the PDR model of a cloud illuminated on one side from Kaufman et al. (1999). As discussed in Section 3.4, this is a simple model compared to the complexity of a galaxy. On the other hand, the method used in this section assumes optically thin emission and that the lines are in local thermodynamic equilibrium. These assumptions may not be valid for all of the [C\textsc{ii}]158\mu m emission in SPT0346-52 and could also account for the discrepancy between the [C\textsc{ii}]158\mu m neutral gas mass estimates. In addition, as discussed in Section 3.5.7, the discrepancy also arises from the density of the gas in the PDR model. Using \(n = 10^2\, cm^{-3}\) from our CLOUDY modeling instead of \(n = 10^{4.2}\, cm^{-3}\) from Hailey-Dunsheath et al. (2010) results in consistent PDR masses using the different methods.
Ionized Gas Mass

Following the method Ferkinhoff et al. (2010) used for [O\textsc{iii}]88\,\micron and Ferkinhoff et al. (2011) adapted for [N\textsc{ii}]122\,\micron, we can calculate the minimum ionized gas mass required to produce the observed [N\textsc{ii}]205\,\micron emission. This method assumes all the nitrogen in the H\textsc{ii} regions is singly ionized, and that the gas is in the high-temperature limit as would be expected in active star-forming regions. With these assumptions, we can calculate the minimum ionized gas mass using

\[ M([\text{H}\textsc{ii}])_{205} = \frac{L_{[\text{N}\textsc{ii}]205\mu m}}{g_u Q(T_{ex}) A_{205} h \nu_{205} \chi([\text{N}\textsc{ii}]}) m_H. \]  

(3.11)

Here, \( h \) is the Planck constant and \( m_H \) is the mass of the Hydrogen atom. In the high temperature limit, the partition function of [N\textsc{ii}]205 is \( Q(T_{ex}) \rightarrow 9 \). \( g_u \), \( A \), and \( \nu_{205} \) can all be found in Table 3.6. Using the nitrogen abundance from Savage and Sembach (1996), \( N/H = 7.76 \times 10^{-5} \), we find a minimum ionized gas mass of \( M([\text{H}\textsc{ii}])_{205} \leq 7.5 \pm 1.0 \times 10^8 \, M_\odot \).

Ferkinhoff et al. (2011) found that \( M_{[\text{H}\textsc{ii}]}/M_{mol} \) is correlated with \( \Sigma_{\text{SFR}} \), where more intensely star-forming galaxies have higher fractions of ionized gas. The minimum ionized gas mass in SPT0346-52 is \( \sim 1\% \) of the total molecular gas mass from Aravena et al. (2016). These values are lower than the ionized gas mass fractions determined for the Cloverleaf (\( \sim 8\% \) Ferkinhoff et al., 2011) and J1342+0928 (\( \sim 4\% \) Novak et al., 2019). As mentioned above, this method assumes the gas is in the high-temperature limit. This is likely not the case for SPT0346-52. At lower temperatures, more mass will be required to produce the observed [N\textsc{ii}]205\,\micron emission. The ionized gas masses calculated here are therefore lower limits to the total ionized gas mass.

As shown in Figure 3.13, the molecular phase is the most significant mass component in SPT0346-52. There is \( \sim 4\times \) more molecular gas than neutral gas and \( \sim 100\times \) more molecular gas than ionized gas. This is in contrast to galaxies in the nearby
universe; for example, the Milky Way has a molecular gas mass ($\sim 2 \times 10^9 \, M_\odot$) very close to its ionized gas mass ($\gtrsim 1.6 \times 10^9 \, M_\odot$), and more than twice as much atomic gas compared to molecular gas (Ferrière, 2001). The large molecular gas reservoir in SPT0346-52 fuels the large star formation rate observed in this system.

3.6 Summary and Conclusions

In this work we present ALMA Bands 6, 7, and 9 observations of [N\text{II}]122\mu m, [C\text{II}]158\mu m, [O\text{I}]146\mu m, and undetected [N\text{II}]205\mu m and [O\text{I}]63\mu m, as well as the underlying continuum at all five wavelengths, in the $z = 5.7$ lensed dusty star-forming galaxy SPT0346-52. We reconstruct the lensed continuum and line data using the pixelated, interferometric lens modeling code RIPPLES in order to study the source-plane structure of SPT0346-52. We analyze both the galaxy-integrated properties and the spatially resolved properties of SPT0346-52.

We use the photoionization code CLOUDY to model the physical conditions of the ISM in SPT0346-52. It has lower ionization parameter ($\log U \sim -2.75$) and hydrogen density ($\log n_H/cm^{-3} \sim 2$) than other high-$z$ DSFGs. Based on CLOUDY modeling, we find supersolar metallicity ($\log Z/Z_\odot = 0.75$), similar than would be expected from the gas to dust ratio in SPT0346-52.

We calculate the dust temperatures throughout SPT0346 and compare the global dust temperature and the wavelength where the SED peaks to other models. We look at line deficits and find deficits in all five lines and spatially-resolved deficits in all three detected lines, [N\text{II}]205\mu m, [C\text{II}]158\mu m, and [O\text{I}]145\mu m. We use the limit on the [N\text{II}]122\mu m/[N\text{II}]205\mu m ratio to find $n_e < 36 \, cm^{-3}$ in SPT0346-52, which is lower than what is observed in ULIRGs and other DSFGs. Using [C\text{II}]158\mu m/[N\text{II}]205\mu m, we determine $\sim 84\%$ of the [C\text{II}]158\mu m emission originates from neutral gas, comparable to other high-$z$ sources and ULIRGs. Using the [C\text{II}]158\mu m/[O\text{I}]146\mu m ratio, we see that SPT0346-52 has similar dense gas in PDRs to local galaxies.
Finally, we calculate ionized, neutral, and molecular gas masses using a variety of methods. The molecular gas mass is $\sim 100 \times$ the ionized gas mass and $\sim 4 \times$ the neutral atomic gas mass. The molecular ISM dominates the mass budget of SPT0346-52, fueling the intense star-formation in this system.
SPT0311-58, a z = 6.9 system of interacting galaxies in the Epoch of Reionization (EoR), exists in one of the rarest, most massive dark matter haloes possible in that era. In this work, we explore the multi-phase interstellar medium (ISM) in this system, using ALMA observations of fine structure lines of carbon, nitrogen, and oxygen atoms and ions, and the underlying dust continuum. We find wide variations in line ratios between the eastern and western galaxies, and even across the northern and southern regions of the western galaxy. We find SPT0311-58 E has higher ionization parameter ($\log U \approx -2.8$) than SPT0311-58 W ($\log U \approx -3.1$). Though all components show surprising metal enrichment just 800 Myr after the Big Bang, there are variations between SPT0311-58 NW ($Z/Z_\odot \approx 1.4 \pm 1.0$) and SPT0311-58 SW and E ($Z/Z_\odot \approx 0.9 \pm 0.4$). In contrast, all parts of SPT0311-58 have similarly high average neutral gas densities. These observations indicate heterogeneous galaxies in the EoR, even within the same dark matter halo, highlighting the need for spatially resolved studies of the ISM at high redshift.

4.1 Introduction

During the Epoch of Reionization (EoR; $z > 6$), the first galaxies formed and reionized the intergalactic medium (Fan et al., 2006; Bouwens et al., 2011; Finkelstein et al., 2012; Carilli and Walter, 2013). During this time, the cosmic star formation rate density rose (Behroozi et al., 2013; Madau and Dickinson, 2014) and stellar nucleosynthesis enriched the interstellar medium (ISM) with heavier elements. The accumulation of metals (elements heavier than hydrogen and helium) in the ISM
during the EoR is only beginning to be understood using telescopes such as the
Atacama Large Millimeter/submillimeter Array (ALMA; Dayal and Ferrara, 2018;
Miralda-Escudé et al., 2000). The presence of dust in early galaxies is an unambigu-
ous signature of metal enrichment. However, the dust masses observed in some EoR
galaxies can be difficult to explain in the context of known mechanisms for forming
(and destroying) dust (Michałowski, 2015).

Far-infrared fine structure lines are powerful tools for studying the ISM in dusty
galaxies, particularly for EoR galaxies where they redshift into submillimeter atmo-
spheric windows. The fine structure line of singly ionized carbon at 158 µm, [CII]158,
is one of the brightest cooling lines of the neutral ISM, emitting up to 1% of the total
IR luminosity (Hollenbach and Tielens, 1997, 1999). In more highly ionized envi-
ronments, [OIII]88 can be even brighter than [CII]158 (Spinoglio and Malkan, 1992;
Carilli and Walter, 2013). This has led to several detections of [CII]158 and [OIII]88
at z > 6 in recent years (e.g., Marrone et al., 2018; Novak et al., 2019; Hashimoto
et al., 2019b; Carniani et al., 2020; Harikane et al., 2020; Decarli et al., 2022). Details
about the ISM conditions can be found by combining these brightest lines with other
lines. Line ratios such as [OIII]88/[NII]122 have shown promise as indicators of the
metallicity in high-z galaxies (Pereira-Santaella et al., 2017; Rigopoulou et al., 2018;
De Breuck et al., 2019; Novak et al., 2019). Other ratios such as [CII]158/[OI]146
have been used to study the dense neutral gas in PDRs (Meijerink and Spaans, 2005;
De Breuck et al., 2019; Novak et al., 2019; Litke et al., 2022). Observations of mul-
tiple lines and continuum, combined with modeling of the ISM, can provide many
constraints on the ISM in high-z galaxies (e.g., De Breuck et al., 2019; Novak et al.,
2019; Meyer et al., 2022; Litke et al., 2022; Decarli et al., 2022).

At z = 6.9, less than 800 Myr after the Big Bang, SPT0311-58 is the most distant
object discovered in the South Pole Telescope (SPT)-SZ survey (Strandet et al., 2017;
Carlstrom et al., 2011; Vieira et al., 2013). Using spatially resolved ALMA observa-
tions of [C\text{II}]158, [O\text{iii}]88, and the underlying dust continuum, combined with optical and IR observations from HST, Gemini, Spitzer, and Herschel, Marrone et al. (2018) resolved SPT0311-58 into two sources, separated by less than 8 kpc in projected distance and 700 km/s in velocity. Both galaxies are massive, though SPT0311-58 E was found to have an order of magnitude less dust and gas than SPT0311-58 W. Unlike other $z > 6$ dusty galaxies, UV emission is detectable in SPT0311-58 E, though most of the star formation is dust-obscured (Marrone et al., 2018). SPT0311-58 is gravitationally lensed by a nearly edge-on spiral galaxy at $z = 1.4$. Gravitational lens modeling by Marrone et al. (2018) found magnifications of $\mu = 2.2$ and $\mu = 1.3$, in SPT0311-58 W and E, respectively, and $\mu = 2.0$ in the total system. Marrone et al. (2018) also found that SPT0311-58 exists in one of the rarest, most massive dark matter haloes that should exist at this epoch, representing a peak in the cosmic density field at $z = 6.9$.

Jarugula et al. (2021) followed up on the molecular interstellar medium of SPT0311-58 using high resolution ALMA observations of CO, [C\text{i}], and H$_2$O. They used non-local thermodynamical equilibrium radiative transfer models to estimate the gas masses, dust masses, and more in SPT0311-58 E and W. They also found the CO spectral line energy distributions in both components were similar to other high-$z$ DSFGs. Recently, Spilker et al. (2022) observed [C\text{ii}]158 and the underlying dust continuum at 70 mas resolution with ALMA and found at least 12 kpc-size clumps between the two components. They found highly turbulent velocity dispersions inconsistent with dynamically cold disks observed at $z \sim 4$ (Rizzo et al., 2021), and instead observed chaotic and clumpy structures in this massive dark matter halo, similar to what is observed in simulations of high-redshift galaxies (Spilker et al., 2022).

In this paper, we expand on previous observations by Marrone et al. (2018) to explore the multi-phase ISM in SPT0311-58 with ALMA observations of [C\text{ii}]158,
[O\textsc{i}] 146, [N\textsc{ii}] 122, [O\textsc{iii}] 88, and the underlying dust continuum. We begin by describing the ALMA observations and data reduction in Section 4.2. We then explore the distribution of various ISM properties across the two galaxies in Section 4.3 Finally, we discuss the heterogeneous conditions observed in this EoR system in Section 4.4. We adopt the cosmology of Planck Collaboration et al. (2016) ($\Omega_m = 0.309$, $\Omega_\Lambda = 0.691$, and $H_0 = 67.7$ km/s.)

4.2 ALMA Observations

SPT0311-58 was observed in ALMA Bands 6, 7, and 8 (Project IDs 2016.1.01293.S, 2017.1.01423.S, 2018.1.00575.S, 2018.1.01778.S; PI: Marrone). Tables 4.1 and 4.2 list the observing dates, frequencies, number of antennae, flux and phase calibrators, maximum baselines, on-source integration times, mean precipitable water vapor, resolution, continuum noise level, and project IDs for the observations of [C\textsc{ii}] 158, [O\textsc{i}] 146, [N\textsc{ii}] 122, and [O\textsc{iii}] 88. The data were processed using the Common Astronomy Software Applications package (CASA; McMullin et al., 2007; Petry and CASA Development Team, 2012).
Table 4.1. ALMA Observations of SPT0311-58: Calibration

<table>
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<th>Date</th>
<th>Freq.(^a) (GHz)</th>
<th>Calibrator</th>
<th>Phase Calibrator</th>
<th>Baseline(^b)</th>
<th>Project ID</th>
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\(^a\)First local oscillator frequency

\(^b\)Maximum baseline
Table 4.2. ALMA Observations of SPT0311-58: Results

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<th>Resolution</th>
<th>Noise</th>
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<td>Ant.</td>
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<td>(mm)</td>
<td>(arcsec)</td>
<td>($\mu$Jy/bm)</td>
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<tr>
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<td>0.08×0.07</td>
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<td>16-Nov-2016</td>
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<td>34</td>
<td>0.3</td>
<td>0.37×0.20</td>
<td>108</td>
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</tbody>
</table>
Figure 4.1 shows the continuum emission (top row) and moment 0 (velocity-integrated) maps of the line emission (bottom row) from SPT0311-58. Images were created using the CASA task tclean with Briggs weighting (robust=0.5) and the auto-multithresh mask option. The 158 µm observations have the highest resolution, with 0′′07 × 0′′08, while the 122 µm observations have the lowest resolution at 0′′63 × 0′′53. [OIII]88 has native resolution of 0′′2 × 0′′3 but was tapered to 0′′5 to ensure the flux was fully recovered. For the imaging (Figure 4.1) and spectra (Figure 4.2), [CII]158 was divided into 50 km/s channels, [OI]146 and [NII]122 were divided into 100 km/s channels, and [OIII]88 was divided into 200 km/s channels.

All four lines and the dust continuum show different morphologies. The two galaxies of SPT0311-58 show strong [CII]158 and [OI]146 emission. The [OI]146 emission also shows the clumpy structure observed by Spilker et al. (2022) in continuum and [CII]158. SPT0311-58 W is bright in continuum and [NII]122, while SPT0311-58 E is faint in continuum and [NII]122. Meanwhile, [OIII]88 is bright in SPT0311-58 E and
Figure 4.1: Observed emission from SPT0311-58. Top: Continuum images in mJy. Bottom: Moment 0 maps of line images in mJy km/s. From left to right: 158µm, 146µm, 122µm, 88µm. All images show the beam as an ellipse in the lower left corner. The 158µm continuum emission is shown as red 10σ contours on each panel. The white ellipses in the 158µm continuum image show the apertures used to find the flux in each component. The [OIII]88µm observations have intrinsic resolution 0".3 × 0".2, but were tapered to 0".5 resolution to ensure the flux was completely recovered. All four lines show different morphologies across SPT0311-58.

the southern part of SPT0311-58 W, but is faint in the northern part of SPT0311-58 W.

These morphological differences result in varying spectra, shown in Figure 4.2. The spectra are also shown on the same vertical scale in Figure 4.3. The [CII]158, [Oi]146, and [NII]122 spectra were obtained using images tapered to 400kλ, while [OIII]88 was tapered to 200kλ. The flux in each channel was summed within the ellipses shown in Figure 4.1 in tapered images with natural weighting. While [CII]158 and [Oi]146 span approximately -600 km/s to +1200 km/s in velocity, the bright-
Figure 4.2: Observed spectra from SPT0311-58. The colored region is the total line emission, while the pink, purple, and dark blue outline the spectra of SPT0311-58 NW, SW, and E, respectively. Top row: [CII]158, [OI]146. Bottom row: [NII]122, [OIII]88. Spectra are obtained by summing the the natural weighted and tapered images within the ellipses plotted in Figure 4.1.

The [NII]122 emission is within ±600 km/s of the systemic velocity (z=6.900), while the [OIII]88 emission is mostly at velocities >0 km/s. [CII]158 and [OIII]88 are comparably bright in SPT0311-58E. [OI]146 and [NII]122 are comparably bright in the red-shifted (southern) portion of SPT0311-58W, but [OI]146 is brighter than [NII]122 in SPT0311-58E.

Previous analysis (e.g., Jarugula et al., 2021; Marrone et al., 2018) has analyzed SPT0311-58 as two components: SPT0311-58 W and E. Because of the clearly varying line ratios across in SPT0311-58 W, we further divide SPT0311-58 W into two components: SPT0311-58 NW and SPT0311-58 SW. The moment 0 maps in Fig-
Figure 4.1 were created by summing the emission from -600 km/s to +1200 km/s. To separate the components, elliptical apertures were then drawn over the moment 0 maps of SPT0311-58 E and SPT0311-58 SW (shown as white ellipses in Figure 4.1). Emission within these ellipses was assigned to SPT0311-58 E and SPT0311-58 SW. A third ellipse is shown encompassing all of SPT0311-58 W. Emission within the SPT0311-58 W ellipse, but outside the SPT0311-58 SW ellipse, was summed to find the total emission in SPT0311-58 NW. SPT0311-58 is gravitationally lensed by a $z = 1.4$ edge-on spiral galaxy, with magnification $\mu = 1.3$ in SPT0311-58 E and $\mu = 2.2$ in SPT0311-58 W (Marrone et al., 2018). The lensed counterimage (in the center of each panel of Figure 4.1) is primarily associated with negative velocities, as is the emission in the northern part of SPT0311-58 W, so emission from the counterimage is included with SPT0311-58 NW. SPT0311-58 NW is associated with clumps W1-W4, SPT0311-58 SW with clumps W5-W8, and SPT0311-58 E with clumps E1-E4 identified by Spilker et al. (2022). In addition to the total spectra, Figure 4.2 outlines the individual spectra of the three components for each line, while Figure 4.3 shows all four lines overlaid on the same vertical scale for each component.

Table 4.3 lists the observed continuum flux densities and line luminosities for the three components of SPT0311-58. The far-infrared luminosity ($L_{\text{FIR}}$) is also listed for each component. For SPT0311-58 E, $L_{\text{FIR}}$ was determined by Marrone et al. (2018) using SED fitting that included resolved ALMA and unresolved Herschel photometry. Marrone et al. (2018) used the ALMA continuum observations to divide the total flux density from Herschel into SPT0311-58 E and W, and we adopt those values here. For SPT0311-58 E, $L_{\text{FIR}}$ was determined by Marrone et al. (2018). For SPT0311-58 NW and SW, we take the observed $L_{\text{FIR}}$ for SPT0311-58 W from Marrone et al. (2018) and scale it based on the 88$\mu$m continuum emission: $L_{\text{FIR, NW}} = L_{\text{FIR, W}} \times f_{\text{88, NW}} / f_{\text{88, W}}$ and $L_{\text{FIR, SW}} = L_{\text{FIR, W}} \times f_{\text{88, SW}} / f_{\text{88, W}}$. None of these values have been corrected for magnification due to gravitational lensing. Throughout this paper, we work with
Figure 4.3: Observed spectra from SPT0311-58 in each component on the same vertical scale. Top: total emission, SPT0311-58 E, SPT0311-58 W. Bottom: SPT0311-58 NW, and SPT0311-58 SW. [CII]158 is shown in red, [OI]146 in orange, [NII]122 in green, and [OIII]88 in blue.
ratios for each component, so effects from magnification due to gravitational lensing within each component will cancel out and not affect our results. In addition, the effects of gravitational lensing are minimal in this system. The foreground lensing galaxy lies just to the east (left) of SPT031-58 W. Gravitational lens modeling by Marrone et al. (2018) and Spilker et al. (2022) show that the source-plane structure is similar to what is observed in the image-plane, but with the emission in SPT0311-58 W in an almost straight line rather than curved around the foreground galaxy. SPT0311-58 E is not strongly lensed. However, to better compare against other galaxies, we do correct for lensing for $L_{\text{FIR}}$ in the figures, using $\mu = 1.3$ in SPT0311-58 E and $\mu = 2.2$, the total magnification for SPT0311-58 W, in SPT0311-58 NW and SPT0311-58 SW (Marrone et al., 2018).

4.3 ISM Properties

In this section, we explore the properties of the multi-phase ISM throughout SPT0311-58 using line and continuum ratios. In Section 4.3.1, we explore the metallicity and ionization state of the ISM using [O\text{III}]88 line ratios and continuum color. Finally, in Section 4.3.2, we look at the density of neutral gas using the $[\text{C\text{II}}]_{158}/[\text{O\text{I}}]_{145}$ line ratios.

Marrone et al. (2018) discussed the possibility that the high [O\text{III}]88/$[\text{C\text{II}}]_{158}$ luminosity ratio in SPT0311-58 E could result from lower metallicity gas in the ISM. When possible, we therefore compare our results to galaxies from the Dwarf Galaxy Survey (DGS; Madden et al., 2013; Cormier et al., 2015), which includes a sources with a range of metallicities down to $Z = 0.02Z_\odot$. SPT0311-58 W is dusty and luminous in the FIR, so we also compare to (Ultra-)Luminous Infrared Galaxies (ULIRGs) from the Great Observatories All-sky LIRG Survey (GOALS; Díaz-Santos et al., 2017; Lu et al., 2017b; Lutz et al., 2016; Israel et al., 2015). Finally, we compare to a selection of $z > 4$ sources in the literature with detections of the continuum and
<table>
<thead>
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<th>Wavelength/Line</th>
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<th>SW</th>
<th>E</th>
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<td></td>
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<td>158(\mu m)</td>
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<td>12.1 ± 1.2</td>
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<td>122(\mu m)</td>
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<td>2.7 ± 0.3</td>
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<td>88(\mu m)</td>
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<td>FIR Luminosity ((10^{12} , L_\odot))&lt;sup&gt;c&lt;/sup&gt;</td>
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<td>(L_{\text{FIR}})</td>
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<td>17.6 ± 4.5</td>
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<td>([\text{CII}]158\mu m)</td>
<td>317.9 ± 34.1</td>
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<td>126.3 ± 14.0</td>
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<td>([\text{NII}]122\mu m)</td>
<td>37.2 ± 5.7</td>
<td>20.5 ± 3.4</td>
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<tr>
<td>([\text{OIII}]88\mu m)</td>
<td>35.0 ± 7.2</td>
<td>109.5 ± 13.5</td>
<td>103.7 ± 12.6</td>
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</tbody>
</table>

<sup>a</sup>Observed values (not corrected for lensing). E has magnification \(\mu = 1.3\), W has \(\mu = 2.2\), and the total system has \(\mu = 2.0\) (Marrone et al., 2018).

<sup>b</sup>The aperture used to obtain the continuum fluxes in SPT0311-58 E is slightly larger than the aperture used for the line luminosities to fully encompass the 122\(\mu m\) emission.

<sup>c</sup>\(L_{\text{FIR}}\) for the three components of SPT0311-58. \(L_{\text{FIR}}\) for SPT0311-58 E is taken from Marrone et al. (2018). For SPT0311-58 NW and SW, we take \(L_{\text{FIR}}\) for SPT0311-58 W from Marrone et al. (2018) and scale it based on the fraction of 88\(\mu m\) emission from SPT0311-58 NW and SW compared to the total 88\(\mu m\) emission in SPT0311-58 W.
at least two of the lines explored in this work. These sources and the observed lines are listed in Table 4.4.

### 4.3.1 Ionization Parameter and Metallicity

A critical question for understanding galaxy formation in the EoR is how and when the ISM becomes enriched by metals. One method for estimating the metallicity of the gas at high redshift is to use the \([\text{O}^\text{III}]\lambda 88/\text{[N}^\text{II}]\lambda 122 \) ratio. Pereira-Santaella et al. (2017) found using photoionization models from \texttt{CLOUDY} that this ratio can be used to constrain the metallicity, but it is highly dependent on the ionization parameter, \(U\). However, other authors such as Fernández-Ontiveros et al. (2016) have suggested using the same \([\text{O}^\text{III}]\lambda 88/\text{[N}^\text{II}]\lambda 122 \) ratio as a measure of ionization. The strong dependence on \(U\) results from the significant difference in the ionization energies needed to create \([\text{O}^\text{III}]\) and \([\text{N}^\text{II}]\) (35.1 eV and 14.5 eV, respectively); this makes the \([\text{O}^\text{III}]\) abundance much more sensitive to the ionization parameter.

To use the \([\text{O}^\text{III}]\lambda 88/\text{[N}^\text{II}]\lambda 122 \) ratio to constrain the metallicity in a galaxy, we require independent information about the ionization parameter. One method is to use the IR color to constrain the ionization state. Abel et al. (2009) found that \(C(60/100)\) is correlated with the ionization parameter, where warmer IR colors (higher ratios) indicate higher ionizations. Rigopoulou et al. (2018) found similar trends using \(C(88\mu m/122\mu m)\). This is because as \(U\) increases, the total ionizing flux increases, which injects additional energy and heating into the surrounding gas and dust. As the dust temperature increases, the dust radiates more energy at shorter wavelengths, resulting in warmer IR colors (Rigopoulou et al., 2018).

We choose to use the \(88\mu m\) and \(158\mu m\) continuum measurements to calculate the IR color because these are our deepest, highest-resolution measurements. To be able to compare against other literature sources, we convert \(C(88\mu m/158\mu m)\) to \(C(70\mu m/100\mu m)\) by creating a set of modified blackbodies with dust temperatures
### Table 4.4. High-z Reference Sample

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<th>Lines</th>
<th>References</th>
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<td>3, 4</td>
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<td>4.70</td>
<td>[CII]158 [OII]146 [NII]122</td>
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<td>6.00</td>
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<td>[CII]158 [OII]146</td>
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</table>

ranging from 20 to 80 K, the range observed in the SPT survey (Reuter et al., 2020). Following Reuter et al. (2020), we fix the slope of the Rayleigh-Jeans tail to $\beta = 2$ and use the empirical relation between $\lambda_0$ and $T_{\text{dust}}$ from Spilker et al. (2016). We calculate $C(70\mu m/100\mu m)$ and $C(88\mu m/158\mu m)$, then fit a quadratic line to the output. The fit is given by

$$C(70\mu m/100\mu m) = 0.44 \times (C(88\mu m/158\mu m))^2 - 0.70 \times (C(88\mu m/158\mu m)) + 0.67.$$  

(4.1)

Similarly, we convert the $C(88\mu m/122\mu m)$ colors from the models in Figure 4 of Rigopoulou et al. (2018) to $C(70\mu m/100\mu m)$. We then use these converted colors and Figure 4 of Rigopoulou et al. (2018) to calculate the ionization parameter, $U$. We find $C(70\mu m/100\mu m) = 0.81 \pm 0.41$ and $\log U = -2.82 \pm 0.39$ in SPT0311-58 E, $C(70\mu m/100\mu m) = 0.62 \pm 0.27$ and $\log U = -3.07 \pm 0.35$ in SPT0311-58 NW, and $C(70\mu m/100\mu m) = 0.69 \pm 0.32$ and $\log U = -2.98 \pm 0.37$ in SPT0311-58 SW. SPT0311-58 considered as a single system as $C(70\mu m/100\mu m) = 0.66 \pm 0.26$ and $\log U = -3.02 \pm 0.32$.

Figure 4.4 shows the metallicity constraints for the components of SPT0311-58. We use the cloudy models for the $[\text{O} \text{iii}]88/[\text{N} \text{ii}]122$ ratio from Table A.1 of Pereira-Santaella et al. (2017). We interpolate the line ratios in their grid of this line ratio vs metallicity and ionization parameter and present contours of constant line ratio in the $\log U$ vs $Z$ plane. Their model also includes gridding in density, but this amounts to a 20% effect on line ratio across 3 decades of density variation at fixed $Z$, so we average over the densities in the grid. The light shaded regions in the figure represent the line ratios observed for each of our components. The darker regions include the constraint on $U$ obtained from the IR continuum ratio. The line ratios alone allow wide ranges in metallicity, but the inclusion of the $U$ constraints suggest that the metallicities in the subcomponents are similar. We find SPT0311-58 E ($Z/Z_{\odot} = 0.8 \pm 0.4$) and SPT0311-58 SW ($Z/Z_{\odot} = 0.9 \pm 0.4$) have slightly lower
metallicities than SPT0311-58 NW ($Z/Z_\odot = 1.4 \pm 1.0$), though the uncertainties are large due to the uncertainty from the ionization parameter.

Another line ratio found to correlate with metallicity is [O\text{iii}]88/[C\text{ii}]158 (Inoue et al., 2016; Cormier et al., 2015). Based on this ratio and the [C\text{ii}]158/continuum ratio, Marrone et al. (2018) discussed the possibility that SPT0311-58 E has a more primordial ISM than SPT0311-58 W. Based on [O\text{iii}]88/[N\text{ii}]122, SPT0311-58 E has near solar metallicity, however. Harikane et al. (2020) and Hashimoto et al. (2019a) found that [O\text{iii}]88/[C\text{ii}]158 was higher in high-z galaxies compared to local galaxies due to increased ionization parameters (as $U$ increases, [O\text{iii}]88 emission will increase and [C\text{ii}]158 emission will decrease as more carbon is doubly rather than singly ionized) and as well as lower metallicities (from lower C/O abundance ratios). Observations of a higher ionization nitrogen line combined with existing observations would provide additional constraints on both the ionization parameter and the metallicity in SPT0311-58. [N\text{iii}]57/[N\text{ii}]122 would constrain the ionization parameter independent of the relative abundances of different elements (Nagao et al., 2011; Pereira-Santaella et al., 2017; Herrera-Camus et al., 2018a), while [O\text{iii}]88/[N\text{ii}]57 would constrain the metallicity with minimal dependence on the ionization parameter.

4.3.2 Density Constraints in Neutral Gas

While [C\text{ii}]158 can originate from either ionized or neutral gas, $\sim 85\%$ of the emission is produced in neutral gas. Because [O\text{i}]146 has a higher critical density than [C\text{ii}]158 ($\sim 10^4$ cm$^{-3}$ vs $\sim 50$ cm$^{-3}$; Stacey, 2011) and a higher excitation temperature needed to populate the upper level (329 K vs 91 K; Stacey, 2011), [O\text{i}]146 traces warmer, denser gas than [C\text{ii}]158. We can therefore use the [C\text{ii}]158/[O\text{i}]146 ratio to examine the relative contribution of warm, dense, neutral gas to the ISM. Figure 4.5 shows [C\text{ii}]158/[O\text{i}]146 as a function of L$_{\text{FIR}}$. We also plot [C\text{ii}]158/[O\text{i}]146 from the PDR models of Meijerink and Spaans (2005) for log $G_0 = 3$ (log $U \approx -3$; Abel et al., 2009;
Figure 4.4: Ionization parameter and metallicity. The contours represent [O\textsc{iii}]88/[N\textsc{ii}]122 ratios as a function of $U$ and $Z$ as modeled by Pereira-Santaella et al. (2017). For each data point, the IR color is used to calculate $U$ (Rigopoulou et al., 2018), which is combined with the observed [O\textsc{iii}]88/[N\textsc{ii}]122 ratio to determine $Z$ (Pereira-Santaella et al., 2017). Pink stars represent SPT0311-58 NW, purple stars SPT0311-58 SW, dark blue stars SPT0311-58 E, and turquoise stars represent SPT0311-58 as a whole. The dark shaded regions represent the 1\sigma uncertainties in ionization parameter (IR color) and [O\textsc{iii}]88/[N\textsc{ii}]122 ratio. The light shaded regions indicate the metallicities allowed by the observed [O\textsc{iii}]88/[N\textsc{ii}]122 ratios. Grey dots are local dwarf galaxies (Madden et al., 2013; Cormier et al., 2015) and black dots are local (U)LIRGs (Lutz et al., 2016; Lu et al., 2017b; Díaz-Santos et al., 2017). Brown circles are $z > 4$ galaxies from the literature (see Table 4.4 for references).
Litke et al., 2022) at \( \log n_H/cm^{-3} = 3 \) and \( \log n_H/cm^{-3} = 5.5 \). Lower ratios indicate a higher average neutral gas density, which may indicate more gas in dense PDR regions (Meijerink and Spaans, 2005; De Breuck et al., 2019).

While SPT0311-58 E has a slightly lower \([\text{Cu}]158/\text{[O]}146\) ratio than SPT0311-58 NW and SW, all components of SPT0311-58 have \([\text{Cu}]158/\text{[O]}146\) ratios comparable to other high-z sources with continuum detections. The ratios in SPT0311-58 and other high-z sources are closer to the \( \log n_H/cm^{-3} = 5.5 \) than the \( \log n_H/cm^{-3} = 3 \) model ratio, indicating a higher neutral gas density and/or a larger contribution from PDRs. This is in contrast to the local dwarf galaxies, which are consistent with smaller PDR contributions or lower neutral gas densities (Cormier et al., 2019).

Lee et al. (2021) found an inverse relation between \( L_{\text{FIR}} \) and \([\text{Cu}]158/\text{[O]}146\), indicating that higher density gas is associated with the high star formation rates observed in high-z dusty galaxies. Both galaxies in SPT0311-58 have high star formation rates, forming stars at \( 2900\pm1800 \, M_\odot/\text{yr} \) in SPT0311-58 W and \( 540\pm175 \, M_\odot/\text{yr} \) in SPT0311-58 E, similar to other high-z dusty galaxies (Marrone et al., 2018). Dense neutral gas has also been associated with higher densities in the ionized gas phase (De Breuck et al., 2019; Lee et al., 2021). Lee et al. (2021) argue that this may be expected since H\( \text{II} \) regions (ionized gas) are physically connected to PDRs (neutral gas). The low \([\text{Cu}]158/\text{[O]}146\) ratios are consistent with the high star formation rates and indicate high gas densities in regions of active star formation.

### 4.4 Summary and Conclusions

We have explored the ISM in SPT0311-58 using ALMA observations of \([\text{Cu}]158\), \([\text{O]}146\), \([\text{NII}]122\), \([\text{OIII}]88\), and the underlying dust continuum. Across SPT0311-58, we found widely varying line ratios, and therefore divided SPT0311 into three components. These components are all interacting within the same DM halo and represent heterogeneous conditions in the EoR.
Figure 4.5: $L_{\text{[CII]158}}/L_{\text{[OII]146}}$ versus $L_{\text{FIR}}$. Dotted and dashed lines represent theoretical $[\text{CII}]/[\text{OII}]$ from the PDR models of Meijerink and Spaans (2005) for log $G_0 = 3$ (log $U \approx -3$) and log $n_H/cm^{-3} = 3$ and log $n_H/cm^{-3} = 5.5$, respectively. Pink stars represent SPT0311-58 NW, purple stars SPT0311-58 SW, dark blue stars SPT0311-58 E, and turquoise stars represent SPT0311-58 as a whole. Grey dots are local dwarf galaxies (Madden et al., 2013; Cormier et al., 2015) and black dots are local (U)LIRGs (Israel et al., 2015; Lutz et al., 2016; Lu et al., 2017b; Díaz-Santos et al., 2017). Brown circles are $z > 4$ galaxies from the literature (see Table 4.4 for references).
We calculated the ionization parameters in SPT0311-58 using IR colors and the models of Rigopoulou et al. (2018). All components have ionization parameter \( \log U \approx -3 \). We then determined the metallicities using \([\text{O}III]88/\,[\text{N}II]122\) and the models of Pereira-Santaella et al. (2017). We see heterogeneous and near-solar metallicity across the sources, but no strong evidence for a metal-poor component. We then used the \([\text{C}II]158/\,[\text{O}I]146\) ratio and PDR models from Meijerink and Spaans (2005) and found high average neutral gas densities throughout SPT0311-58 as expected from the high star formation rates in this system.

The formation of early galaxies is a chaotic process. Using 70 mas observations of \([\text{C}II]158\), Spilker et al. (2022) found a dozen turbulent clumps within SPT0311-58 with masses similar to other high-z \((6 < z < 8)\) galaxies. Even at lower resolution, spatially resolved observations reveal variations between SPT0311-58 E, NW, and SW. This work illustrates the importance of spatially resolved studies at high redshift, in particular in the EoR, to help us understand the formation of early galaxies such as SPT0311-58.
CHAPTER 5

Summary and Conclusions

In this dissertation, I studied two of the most distant objects identified in the SPT survey (Reuter et al., 2020). SPT0346-52 is the most intensely star-forming galaxy from the SPT survey, with intrinsic $L_{IR} = 3.6 \times 10^{13}$ and star formation rate 4800 $M_\odot/yr$ (Ma et al., 2015). The extremely luminous $L_{IR}$ is due to star formation, with Chandra observations revealing negligible contribution to $L_{IR}$ from an active galactic nucleus (Ma et al., 2016). SPT0311-58 is the most distant system from SPT (Strandet et al., 2017). Comprised of two massive star-forming galaxies, it resides in one of the rarest, most massive dark matter haloes that can exist 780 Myr after the Big Bang (Marrone et al., 2018). The molecular gas phase in SPT0311-58 has previously been studied in detail, revealing CO spectral line distributions and CO-to-H$_2$ conversion factors similar to other high-z DSFGs (Jarugula et al., 2021). These galaxies push the limits of what is physically possible, with SPT0346-52 maximally forming stars and SPT0311-58 in one of the rarest dark matter haloes predicted at that epoch. Here, I have explored in depth the multi-phase ISM of these two massive, dusty star-forming galaxies within one billion years of the Big Bang.

5.1 SPT0346-52

In Chapters 2 and 3, I explored the ISM of the gravitationally lensed galaxy SPT0346-52, the most intensely star-forming galaxy from the SPT survey. Located at $z = 5.7$, this system lies just one billion years after the Big Bang.

I used a pixelated, interferometric lens modeling code, Ripples, to “de-lens” the emission from SPT0346-52 and study its source-plane structure. Unlike a parametric
code, a pixelated code does not assume a specific functional form, e.g. a Gaussian or Sérsic source, for the spatial distribution of the emission. By using an interferometric lens modeling code, I was able to directly model the complex visibilities observed by ALMA instead of making assumptions about the image-plane structure during the imaging process before modeling. This lens modeling was consistent with previous parametric modeling done on SPT0346-52.

In Chapter 2, I utilized high resolution (sub-kpc) ALMA observations of [C\textsc{ii}]158, one of the brightest cooling lines of the ISM, to study the spatial and kinematic structure of SPT0346-52. I investigated the “[C\textsc{ii}]-deficit”, an observed phenomenon where the [C\textsc{ii}]158/L\textsubscript{FIR} luminosity ratio falls as $\Sigma\text{FIR}$ increases beyond a critical threshold. Using the spatially resolved [C\textsc{ii}]158/L\textsubscript{FIR} luminosity ratio, I confirmed that the [C\textsc{ii}]-deficit occurs on local scales, and is not a result of integrating the total emission in a galaxy. I then studied the kinematic structure of SPT0346-52 in detail using moment 1 (flux-weighted velocity) maps and position-velocity diagrams. I determined that SPT0346-52 is composed of two components merging together. This merger activity is likely fueling the intense star-formation rates observed in this system. Finally, I calculated the Toomre Q stability parameter throughout both components and found values $Q \ll 1$ everywhere. These low values indicate that the gas in SPT0346-52 is globally unstable as it collapses to form stars.

In Chapter 3, I used ALMA observations of multiple tracers of the ISM in SPT0346-52. [C\textsc{ii}]158 is emitted in both the neutral phase and the diffuse ionized phase of the ISM. [N\textsc{ii}]205 and [N\textsc{ii}]122 trace diffuse ionized gas, while [O\textsc{i}]146 and [O\textsc{i}]63 trace the warm neutral medium. The underlying continuum emission originates from dust. [N\textsc{ii}]122 and [O\textsc{i}]63 were undetected in SPT0346-52. Using these different ISM tracers, I thus explored different phases of the ISM. I used Ripples to model mass distribution of the foreground galaxy and map the source-plane emission in continuum and the detected lines. The dust continuum emission was more com-
pact than the $[\text{Cu}]158$ emission, and the brightest $[\text{O}i]146$ emission was offset from the brightest $[\text{Cu}]158$ and $[\text{N}i]205$ emission.

I used the photoionization code CLOUDY to model the line and continuum ratios in SPT0346-52. The best-fit models indicated supersolar metallicity in SPT0346-52, consistent with the gas to dust mass ratio. SPT0346-52 has lower ionization parameter and density than comparable high-z sources.

I explored the line/L$_{\text{FIR}}$ ratios for all five lines, on spatially resolved scales for the detected lines, and found deficits (decreasing line/L$_{\text{FIR}}$ ratios with increasing $\Sigma_{\text{FIR}}$) in all five lines. I then used the continuum measurements to fit for the dust temperature throughout SPT0346-52. I found $T_D \sim 50$ K, though the calculated dust temperature depends heavily on the form of the SED. Using the $[\text{Cu}]158/[\text{N}i]205$ ratio, I found $\sim 85\%$ of the $[\text{Cu}]158$ emission originated in the neutral gas of the ISM. The $[\text{Cu}]158/[\text{O}i]146$ ratio does not indicate a large warm, neutral component of the ISM in SPT0346-52. The non-detection of $[\text{N}i]122$, combined with the observed $[\text{N}i]205$, places an upper limit on the electron density, $n_e < 36$ cm$^{-3}$. $[\text{O}i]63$ is also undetected, which may indicate self-absorption of $[\text{O}i]63$. I end by calculating the mass of different phases of the ISM. SPT0346-52 has a large molecular gas reservoir, providing fuel for the intense star formation.

It can be very difficult to determine if a system is merging without high-resolution kinematic information. Several high-z galaxies have been observed to contain clumps (e.g., Hodge et al., 2012; Iono et al., 2016; Dannerbauer et al., 2017; Tadaki et al., 2018; Dessauges-Zavadsky et al., 2019; Rosolowsky et al., 2021; Spilker et al., 2022), and these clumps can be massive ($r \sim 1$ kpc, $M \sim 10^2 - 10^3 M_\odot$; Spilker et al., 2022). Some high-z studies have used wide ($\gtrsim 1000$ km/s), asymmetric $[\text{Cu}]158$ line profiles or multiple $[\text{Cu}]158$ emission peaks to argue for the presence of two components (e.g., Neri et al., 2014; Pavesi et al., 2018; Bañados et al., 2019; Decarli et al., 2019). Outflows, which appear to be widespread at high redshift (Bischetti et al.,
further complicate the picture and can result in large line widths. For example, Jones et al. (2019) argue that the blue-shifted component in SPT0346-52 is actually a molecular outflow. However, Spilker et al. (2020) found no high-velocity wings in [CII]158 in any DSFG with an unambiguous molecular outflow, showing that [CII]158 does not reliably trace molecular outflows. Highly asymmetric kinematics can provide a clear signature of merger activity, but 20 − 60% of merging galaxies with stellar mass ratios between 1:1 and 1:4 in hydrodynamic simulations did not contain are not observable as mergers and do not exhibit highly asymmetric kinematics (Hung et al., 2016). Merging galaxies, massive clumps embedded within a galaxy, massive outflows, and rotating disks can have similar kinematic and morphological signatures, especially at low resolution. Detailed, high-resolution kinematic analysis is needed to distinguish between the different possible scenarios.

5.2 SPT0311-58

In Chapter 4, I used ALMA observations of [CII]158, [OI]146, [NII]122, [OIII]88, and the underlying dust continuum to study the \(z = 6.9\) galaxies of SPT0311-58. The observed lines display varying morphologies across the two galaxies (SPT0311-58 E and W), leading me to divide SPT0311-58 W into two components (SPT0311-58 NW and SW). I used the IR color to calculate the ionization parameter, \(U\), in each component, finding \(\log U \approx -2.8\) in SPT0311-58 E and \(\log U \approx -3.1\) in SPT0311-58 W. I then combined the ionization parameter with the [OIII]88/[NII]122 to find possible variation in metallicity in the different components of SPT0311, with \(Z/Z_\odot \approx 0.8 \pm 0.4\) and \(Z/Z_\odot \approx 0.9 \pm 0.4\) in SPT0311-58 E and SW, respectively, and \(Z/Z_\odot \approx 1.4 \pm 1.0\) in SPT0311-58 NW. I then constrained the density of the ISM in the warm neutral phase using [CII]158/[OI]146. Comparing the observed [CII]158/[OI]146 ratio to PDR models,
all components of SPT0311-58 have similar densities and are consistent with high
density neutral gas in PDRs, or a large component of gas in PDRs compared to local
dwarf galaxies. The high gas densities are expected from the intense star formation
rates throughout SPT0311-58.

Galaxy formation is a chaotic, turbulent process, especially in SPT0311-58
(Spilker et al., 2022). The variations observed across SPT0311-58 highlight the need
for spatially resolved studies at high redshift to understand how galaxies form and
interact in the Epoch of Reionization.

The galaxies in SPT0311-58 are rapidly forming stars as they interact. Using the
gas masses from Jarugula et al. (2021) and the star formation rates from Marrone
et al. (2018), I find gas depletion timescales of $\tau_{gas} = M_{gas}/SFR \approx 57$ Myr and
$\tau_{gas} \approx 190$ Myr in SPT0311-58 E and W, respectively. These gas depletion timescales
are longer than the coalescence timescale, $\tau_{coal} \sim \Delta R/\Delta v \approx 10$ Myr (Marrone et al.,
2018). Therefore, SPT0311-58 E and W are likely to coalesce into a single system
before the gas in these galaxies is depleted through star formation.

5.3 Potential and Future Observations

In SPT0346-52, I have so far explored the neutral and diffuse ionized phases. Higher
ionization lines, such as [OIII]52 and [NIII]57, would be ideal for exploring the highly
ionized ISM near sites of active star formation. Unfortunately, these lines are both
redshifted into ALMA Band 10, where atmospheric transmittance is low and compli-
cated by many atmospheric absorption lines, so high resolution observations of these
transitions would be difficult.

While $[\text{OIII}]88/[\text{NII}]122$ provides an initial constraint on the metallicity in
SPT0311-58, $[\text{OIII}]88/[\text{NIII}]57$ would be an ideal line ratio to better measure the
metallicity with less dependence on the ionization parameter (Pereira-Santaella et al.,
2017; Nagao et al., 2011). $[\text{NIII}]57$ observations combined with the existing $[\text{NII}]122$
detection would also provide an additional measure of the ionization parameter in SPT0311-58 (Pereira-Santaella et al., 2017; Herrera-Camus et al., 2018a; Nagao et al., 2011). The continuum at 57µm with previous continuum observations at 88, 122, 146, and 158µm would also allow for spatially resolved dust temperatures in SPT0311-58, similar to what I calculated in SPT0346-52. Given the variation in ionization parameter and metallicity, different dust temperatures between SPT0311-58 E and W would be expected.

Both of these systems are scheduled to be observed with the James Webb Space Telescope (JWST), which launched on Christmas Day 2021, is currently cooling in preparation for observations. JWST will observe the stars within SPT0346-52 and SPT0311-58, helping to understand the dust-enshrouded star formation and the star formation histories in these galaxies. SPT0346-52 is to be observed in the Cycle 1 General Observer Program 1864 (PI: Phadke), and SPT0311-58 in the Cycle 1 General Observer Program 1791 (PI: Spilker) and the Cycle 1 Guaranteed Time Observations Program 1264 (PI: Colina Robledo). Combined with the information gleaned from ALMA observations of SPT0346-52 and SPT0311-58, these JWST observations will allow a comprehensive look at the gas, dust, and stars within these galaxies.
APPENDIX A

Using Visibility Data to Create the [C\textsc{ii}] Spectrum

SPT0346-52 is an extended source with an irregular structure due to gravitational lensing. Therefore, there is no optimal aperture to contain all of the emission. When imaging these data, one has to make assumptions about the structure of the source. Different weightings of the visibilities emphasize different aspects of the galaxy’s structure (i.e., faint emission or small structures) and suppress some of the information inherently available from the visibilities. In contrast, the observed complex visibilities contain all of the spectral line information.

We therefore obtain a spectrum of the observed [C\textsc{ii}] emission from the observed complex visibilities. The flux density in a given channel, $F_v$, is determined by

$$F_v = \frac{\sum_i \tilde{v}_{v,i} |\tilde{m}_i|^2}{\sum_i |\tilde{m}_i|^2},$$

(A.1)

where $\tilde{v}_{v,i}$ is the complex line data visibility and $\tilde{m}_i$ is the complex model visibility for the integrated [C\textsc{ii}] line. Dividing data by the model in the numerator removes the spatial structure, transforming the observed visibilities to a point source. The data visibilities are then weighted by the amplitude of the model visibilities in the sum, which emphasizes the visibilities where line emission is expected, and minimizes the weight of the visibilities with little-to-no sensitivity to the emission structure. We use a model of the complex visibilities for the integrated [C\textsc{ii}] line created using a pixellated gravitational lensing reconstruction described further in Section ??.

The error on the flux density in each channel, $\sigma$, is the quadrature sum of the weights such that

$$\sigma^2 = \left( \sum_i |\tilde{m}_i|^2 \right)^{-1}.$$  

(A.2)
The resulting spectrum is shown in Figure 2.2.
Figure B.1 shows the observed data and modeled image- and source-plane data, along with the residual image-plane emission and the uncertainty in the source-plane. As described in Section 3.3.1, the uncertainty maps are obtained by creating 500 random sets of visibilities and taking the standard deviation in each pixel of the 500 noise reconstructions.
Figure B.1: Image-plane and source-plane maps. From left to right: dirty image of data visibilities, dirty image of model visibilities, residual map of dirty images, high-resolution (non-visibility sampled) image-plane model, source-plane model, source-plane uncertainty. From top to bottom: 205\(\mu\)m, 158\(\mu\)m, 145\(\mu\)m, 122\(\mu\)m, 63\(\mu\)m, [\text{Ng}]205\(\mu\)m, [\text{Nn}]158\(\mu\)m, [O\text{i}]145\(\mu\)m. Contours indicate the observed continuum emission at each wavelength. The dirty observed image, dirty model image, and residual image are on the same color scale for each set of models.
APPENDIX C

Spatially Resolved Best-Fit CLOUDY Ratios

Table C.1 lists the data values compared to the CLOUDY output to determine for the best-fit models. For global values, the log of the ratios and the associated errors are listed. For pixelated values, the mean value is listed. The recorded error is the mean of the uncertainties on the log of the ratios and represents a typical error in a pixel. In parentheses, the minimum and maximum pixel values are listed. Figure C.1 shows the observed continuum and line ratios, as well as the best-fit model ratios from CLOUDY. The fitting procedures and best-fit parameters are described in Section 3.4.
Table C.1. Data Used to Fit to CLOUDY Models

<table>
<thead>
<tr>
<th>log Ratio</th>
<th>Integrated Value$^d$</th>
<th>Pixel-by-Pixel Values$^e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>63µm/122µm$^a$</td>
<td>0.05 ± 0.06</td>
<td>0.10 ± 0.07 (-0.64-0.88)</td>
</tr>
<tr>
<td>63µm/146µm$^a$</td>
<td>0.33 ± 0.06</td>
<td>0.36 ± 0.07 (-0.14-0.89)</td>
</tr>
<tr>
<td>63µm/158µm$^a$</td>
<td>0.37 ± 0.06</td>
<td>0.55 ± 0.07 (-0.32-1.35)</td>
</tr>
<tr>
<td>63µm/205µm$^a$</td>
<td>0.62 ± 0.06</td>
<td>0.77 ± 0.07 (-0.09-1.62)</td>
</tr>
<tr>
<td>[OII]146µm/146µm$^b$</td>
<td>0.38 ± 0.09</td>
<td>0.42 ± 0.44 (0.04-0.99)</td>
</tr>
<tr>
<td>[Cu]158µm/[NII]205µm$^c$</td>
<td>1.45 ± 0.08</td>
<td>1.46 ± 0.62 (1.08-1.69)</td>
</tr>
<tr>
<td>[Cu]158µm/[OII]146µm$^c$</td>
<td>1.03 ± 0.09</td>
<td>0.71 ± 0.62 (0.48-1.11)</td>
</tr>
</tbody>
</table>

$^a$Continuum flux density ratio.

$^b$Line/continuum ratio in $10^7$ L$_\odot$/mJy (see Section 3.4.1).

$^c$Line luminosity ratio.

$^d$Values and uncertainties used to compare to CLOUDY models for galaxy-integrated fits.

$^e$For each set of pixelated values, we list $\bar{R} \pm \bar{\sigma}$ ($R_{\text{min}} - R_{\text{max}}$), where $\bar{R}$ is the mean value in the pixels for the log of the ratio, $\bar{\sigma}$ is the mean of the uncertainties in the pixels for the log of the ratio, and $R_{\text{min}}$ and $R_{\text{max}}$ are the minimum and maximum values of the log of the ratio.
Figure C.1: Maps of observed and modeled ratios from CLOUDY. From left to right: log 63μm/122μm, log 63μm/146μm, log 63μm/158μm, log 63μm/205μm, log [O\textsc{i}]146μm/146μm, log[C\textsc{ii}]158μm/[N\textsc{ii}]205μm, log[C\textsc{ii}]158μm/[O\textsc{i}]146μm. Top: observed. Bottom: modeled. Each column has the same color scale.


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