Discovery of a Dusty, Chemically Mature Companion to a $z \sim 4$ Starburst Galaxy in JWST ERS Data

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Abstract

We report the discovery of two companion sources to a strongly lensed galaxy SPT0418-47 (“ring”) at redshift 4.225, targeted by the JWST Early Release Science program. We confirm that these sources are at a similar redshift to the ring based on Hα detected in the NIRSpec spectrum and [C II] λ158 μm line from the Atacama Large Millimeter/submillimeter Array (ALMA). Using multiple spectral lines detected in JWST/NIRSpec, the rest-frame optical to infrared images from NIRCam and MIRI and far-infrared dust continuum detected by ALMA, we argue that the newly discovered sources are actually lensed images of the same companion galaxy SPT0418-SE, hereafter referred to “SE,” located within 5 kpc in the source plane of the ring. The star formation rate derived using [C II] and the dust continuum puts a lower limit of 17 $M_\odot$ yr$^{-1}$, while the SFR$_{H\alpha}$ is estimated to be >2 times lower, thereby confirming that SE is a dust-obscured star-forming galaxy. Analysis using optical strong line diagnostics suggests that SE has near-solar elemental abundance, while the ring appears to have supersolar metallicity O/H and N/O. We attempt to reconcile the high metallicity in this system by invoking early onset of star formation with continuous high star-forming efficiency or by suggesting that optical strong line diagnostics need revision at high redshift. We suggest that SPT0418-47 resides in a massive dark-matter halo with yet-to-be-discovered neighbors. This work highlights the importance of joint analysis of JWST and ALMA data for a deep and complete picture of the early universe.

Unified Astronomy Thesaurus concepts: James Webb Space Telescope (2291); High-redshift galaxies (734); Companion galaxies (290); Gravitational lensing (670); Metallicity (1031)

1. Introduction

Gravitationally lensed galaxies provide us with unique opportunities to discover and study distant galaxies in detail. Hundreds of ultraluminous infrared galaxies (ULIRGs; $L_{IR} \sim 10^{12}L_\odot$) have been discovered in (sub)millimeter wavelengths (see Ivison et al. 1998; Scott et al. 2008; Weiß et al. 2013; Canameras et al. 2015; Harrington et al. 2016; Berman et al. 2022). Later studies reveal most of the them as strongly lensed galaxies at high redshift (Vieira et al. 2013; Spilker et al. 2016). These dusty star-forming galaxies (DSFGs) are characterized by a very high star formation rate (SFR) and dust mass, and they are thought to be the progenitors of massive early-type galaxies seen in the local universe (Casey et al. 2014). The highest SFR systems likely trace the most massive halos in the universe, and some of these galaxies are later identified as galaxy pairs or protoclusters (Capak et al. 2011; Aguirre et al. 2013; Marrone et al. 2018; Miller et al. 2018). Studying the stellar population and physical conditions in these galaxies can help us understand how such extremely dusty and massive systems have formed and evolved when the universe was less than two billion years old.

SPT-S J041839-4751.8 (hereafter SPT0418-47) is a DSFG discovered in the SPT-SZ survey at redshift 4.2248 (Weiß et al. 2013). Studies using dust continuum and various molecular and fine-structure lines found that SPT0418-47 has very high lensing magnification $μ = 32.3 \pm 2.5$ at 836 μm (rest frame 160 μm) and high intrinsic SFR $\sim 300 M_\odot$ yr$^{-1}$ with a moderate stellar mass $\sim 1.2 \times 10^{10} M_\odot$ (Aravena et al. 2016; Bothwell et al. 2017; Breuck et al. 2019; Rizzo et al. 2020). It is also included in the JWST Early Release Science program, which, for the first time, enables us to study its physical properties in hot ionized gas through optical emission lines, as well as stellar population and distribution. In this paper, we report a serendipitous discovery of a dusty star-forming companion galaxy of SPT0418-47 in JWST/NIRSpec data.

2. Observational Data

2.1. JWST Data

We made use of the JWST data set targeting SPT0418-47 by the Early Release Science Program TEMPLATES (Targeting Extremely Magnified Panchromatic Lensed Arcs and Their Extended Star formation; ID: 1355; PI: Jane Rigby). We downloaded the uncalibrated data from the MAST archive4 and reduced the data with the JWST pipeline version 1.8.5 and the calibration reference file context jwst_1027.pmap.

The data set consists of an NIRSpec integral field unit (IFU) spectral cube, as well as NIRCam and MIRI images. The NIRSpec IFU observations were carried out using the F290LP filter, with wavelength coverage 2.87–5.27 μm. The target was observed with the NIRCam instrument in six filters (F115W, F150W, F200W, F277W, F356W, and F444W) and with the

4 The data and association files are accessible via doi:10.17909/vr1e-rm03.
2. ALMA

We use the deep Atacama Large Millimeter/submillimeter Array (ALMA) observations in the data archive to study the presence of dark-matter substructure through strong lensing measurements. We use the execution block that covers the [C II] fine-structure line \((^3P_{3/2} \rightarrow ^3P_{1/2})\), as well as the underlying dust continuum.

The source was observed with ALMA on 2016 October 25, using 43 12 m antennas with baselines ranging from 18.6 m to 1.4 km and precipitable water vapor (PWV) between 0.65–0.75 mm. Two spectral windows in the upper sideband of the receiver cover the center frequency of the [C II] line \((\nu_{\text{obs}} = 363.794 \text{ GHz})\). The spectral windows in the lower sideband cover a bandwidth of 3.75 GHz around the continuum at rest frame 160 \(\mu\text{m}\) \((\mu_{\text{obs}} \sim 835 \mu\text{m})\). J0455-4615 and J0439-4522 were observed for amplitude and phase calibration. J0538-4405 was used as the band-pass calibrator, and J0519-4546 was used as the flux calibrator. The integration time for our science target is 32.5 minutes.

The data are retrieved from the ALMA data archive and reduced by manually running the pipeline in the Common Astronomy and Software Application (CASA) version 4.7.2 (CASA Team et al. 2022). In particular, we take care to avoid automatic flagging of line channels that are at the edge of the spectral windows. We created a continuum map by collapsing the line-free channels covering a bandwidth of 5.47 GHz and using natural weighting. The image is also corrected for the primary beam as the field center specified for the ALMA observations was offset by 4\(^\circ\)9 from the location of the target. The resulting image has a beam size of 0\(^\circ\)18 \(\times\) 0\(^\circ\)17 with a position angle of \(-87.6^\circ\) and achieved a 1\(\sigma\) sensitivity of 56 \(\mu\text{Jy beam}^{-1}\). We also imaged the line channels to create a spectral cube with a 50 km \(\text{s}^{-1}\) resolution, reaching 1\(\sigma\) noise \(\sim 0.6 \mu\text{Jy beam}^{-1} \text{ch}^{-1}\).

3. Results

3.1. Discovery

We create an image (Figure 1, left panel) by collapsing all emission in spectral channels covering the H\(\alpha\) line in the original NIRSpec spectral cube. This pseudo-narrowband image reveals the presence of two sources in addition to the strongly lensed ring and the lensing elliptical galaxy. The
brighter source at the southeast corner ("B" in Figure 1) is referred to as SPT0418-SE-1 (hereafter "SE-1"), and the source between the lensing galaxy and ring ("C") is denoted as SPT0418-SE-2 (hereafter "SE-2").

The spectra of the newly discovered sources as well as the strongly lensed ring (Figure 1, right panel) show strong detection of the Hα line, [N II]λ6548, 6584 doublet, [S II]λλ6716, 6731 doublet, [S III]λλ9069, 9531 lines, and a tentative detection of the [O I]λ6300 line. These strong emission lines enable us to identify the association of the discovered sources in redshift space.

Both SE-1 and SE-2 also appear in NIRCam and MIRI images from 1 to 10 μm. Based on this knowledge, we also performed forced photometry on the ALMA data and found that SE-1 appears in the 835 μm continuum map with a ~4σ peak, while SE-2 is associated with a tentative 2σ peak (Figure 1, contours enclosed in ellipses “B” and “C”). Both of them are also detected in the [C II] 158 μm line adding to the spectroscopic confirmation of the redshift of the newly discovered sources.

3.2. Observational Properties

We show the moment 0 maps and spectra for the strong lines in Figure 2. Different from the pseudo-narrowband image, the moment 0 maps are created using the lens-subtracted data, and the continuum is removed using a linear fit to the local spectrum. The spectra are extracted from the lens-subtracted cube, and the emission line is modeled and fitted as a Gaussian profile along with a first-order polynomial fit on the local continuum in order to measure the line flux and width. In the fitting procedure, the redshift is fixed relative to that of Hα, and the doublets are fitted as a whole using known emissivity ratio (for [N II]) and the same line width (for the [N II] and [S II] doublets).

The SE-1 and SE-2 sources show up strongly in all the moment 0 maps. Remarkably, in the Hα + [N II] map, SE-1 has an even higher surface brightness than the ring.

In all the spectra (Figure 2, especially Hα), the line peaks of both SE-1 and SE-2 lie consistently at ~175 km s⁻¹ relative to the ring, and the fitted line widths are slightly narrower (NIRSpec spectral resolution ~110 km s⁻¹). The line center wavelengths and the widths are consistent between SE-1 and SE-2 with an SE-1-to-SE-2 flux ratio about 3:1. One caveat is that the fitted line widths for detections with SNR<10 are not well constrained and should not be compared quantitatively. We also caution the absolute wavelength calibration of NIRSpec data is not optimal as the ALMA [C II] line is systematically offset at a lower redshift for both the ring and the newly discovered sources (see Table 1).

The 1–10 μm lens-subtracted images are shown in Figure 3. We note that at wavelengths shorter than λ < 2 μm, SE-1 appears to have a bright nucleus accompanied by two faint patches on both the north and south sides. The NIRCam 2.8 and 3.6 μm images are strongly affected by the [O III]λ5007 and Hα emission lines, respectively; SE-1 appears more extended, and the surface brightness contrast to the ring is higher compared to other wavelengths. The primarily lensed galaxy (ring) also shows extended morphology that agrees with the line maps in Figure 2. Only the images up to 10 μm are plotted as the companion sources are barely detected at longer wavelengths.

The hexagon-like feature present at the center of the short wavelength images is the result of the compact continuum emission from the lensing galaxy (Section 2.1). This PSF residual makes the identification and photometry challenging for SE-2. Further analysis involving subtraction of the lensing galaxy would require a core model convolved with JWST PSF and is a subject of future publication.
Table 1
Properties of the Newly Discovered Source

| Filter         | Sν (μ Jy) | Sν (μ Jy) | Sν (μ Jy) |
|----------------|-----------|-----------|-----------|
| NIRCam/F115w   | 0.272 ± 0.019 | 0.114 ± 0.040 | 0.386 ± 0.044 |
| NIRCam/F150w   | 0.429 ± 0.026 | <0.286 | 0.558 ± 0.099 |
| NIRCam/F200w   | 0.547 ± 0.020 | 0.163 ± 0.050 | 0.710 ± 0.054 |
| NIRCam/F277w   | 0.608 ± 0.020 | 0.134 ± 0.052 | 0.742 ± 0.056 |
| NIRCam/F356w   | 0.845 ± 0.022 | <0.348 | 1.01 ± 0.118 |
| NIRCam/F444w   | 0.808 ± 0.021 | <0.508 | 1.05 ± 0.171 |
| MIRI/F560w     | 0.830 ± 0.068 | 0.358 ± 0.141 | 1.19 ± 0.156 |
| MIRI/F770w     | 0.740 ± 0.106 | 0.227 ± 0.286 | 0.967 ± 0.305 |
| MIRI/F1000w    | 1.02 ± 0.211 | <1.48 | 1.33 ± 0.536 |
| MIRI/F1280w    | 0.776 ± 0.291 | <1.28 | 1.01 ± 0.516 |
| MIRI/F1500w    | <0.963 | <0.393 | <1.34 |
| MIRI/F1800w    | <1.08 | <1.28 | <1.67 |
| MIRI/F2100w    | <0.918 | <1.11 | <1.44 |
| ALMA/835 μm    | 733 ± 227 | 364 ± 150 | 1100 ± 272 |

Derived Properties

μLν [10⁸ L☉] | 13.9 ± 0.31 | 4.24 ± 0.11 | 18.2 ± 0.33 |
μLν [10⁹ L☉] | 26 ± 4.0 | 8.61 ± 1.72 | 34.4 ± 4.4 |
μLν [10¹¹ L☉] | 9.1±6.7 | 2.9±27.0 | 12.0±47.3 |
μSFR,dw [M☉ yr⁻¹] | 29 ± 0.6 | 8.8 ± 0.2 | 38 ± 0.7 |
μSFR,dw [M☉ yr⁻¹] | 65 ± 1.0 | 20 ± 4.2 | 87 ± 11 |
μSFR,dw [M☉ yr⁻¹] | 118±37 | 38±13 | 156±53 |
log(O/H)₁₂    | −3.42 ± 0.10 | −3.42 ± 0.11 | −3.42 ± 0.08 |
log(O/H)₂₃    | −3.52 ± 0.34 | −3.18 ± 0.29 | −3.42 ± 0.26 |
log(N/O)₁₂₁₂  | −0.71 ± 0.21 | −0.80 ± 0.18 | −0.73 ± 0.16 |

Note. The “SE” (SPT0418-SE) column is the combined properties of both SE-1 and SE-2, as we speculate that they are the primary and counter lensed images of the same galaxy. For nondetection in SE-2 we report the 3σ upper limit and scale the SE-1 value up by a factor of 1.3 to estimate the value for SE.

The basic source properties like location, line flux and width, and photometry from NIRCam and MIRI images are summarized in Table 1. Line fluxes and FWHM are derived using a Gaussian fit.

4. Discussion
4.1. Nature and Morphology

Based on the redshift, line profile, and spatial separation between the newly identified source and the ring, it is evident that both SE-1 and SE-2 are physically different sources than the primarily lensed galaxy of the Einstein ring. We further argue that SE-1 and SE-2 are in fact two lensed images of the same galaxy: both sources have the same redshift and line width in the strong (>10σ) line detections within the allowance of measurement error; the line fluxes and continuum consistently show an SE-1-to-SE-2 ratio roughly 3:1; and the location of SE-1 and SE-2 measured with respect to the ring is consistent with them being lensed images of a source separated from the primarily lensed galaxy (ring) by about 0.7, in the southeast direction.
Figure 3. Atlas of lens-subtracted NIRCam and MIRI images in the wavelength range $\lambda_{\text{obs}} = 1.15$–$10 \mu m$, corresponding to $\lambda_{\text{rest}} = 0.22$–$1.9 \mu m$. The filter is shown as the title of each stamp. The images are oriented and cropped to fit the image stamps in the previous images, as are the highlighted regions and color scheme. The color map is adjusted manually to increase the contrasts of the weak sources.

Therefore, we suggest that SE-1 and SE-2 are the primary image and counterimage of a companion galaxy (hereafter referred to as companion or SE) lensed by the same foreground galaxy as the ring (hereafter as the host galaxy). As gravitational lensing nonlinearly distorts the actual physical geometry, based on the separation of SE-1 and SE-2 in the image plane ($\theta^*$), we estimate that the companion must also be within a projected distance of 5 kpc from the host in the source plane. From the lensing models for the ring presented in Spilker et al. (2016) and Rizzo et al. (2020), we know that this galaxy–galaxy lensing system has a relatively simple gravitational potential and line-of-sight alignment (small-impact parameter). We can apply basic gravitational lensing physics (Blandford & Narayan 1992) to posit that the secondary image (SE-2) has a magnification factor $\mu \sim 1$. Furthermore, based on the linear scale of the elongated shape, we estimate that the magnification of SE-1 is at least 8 times smaller than the ring, and we estimate that an upper limit for the total magnification of SE is $\mu_{\text{max}} < 6$. Detailed gravitational-lens modeling involving reconstruction of the sources and their intrinsic arrangement in the source plane is beyond the scope of this Letter.

The morphology of the companion is intriguing. At short wavelengths, the galaxy displays a nuclear feature, which we will argue in Section 4.3 to be a starburst nucleus. The morphology of gas and the old stellar population by $\lambda_{\text{rest}} = 0.8$–$2 \mu m$ images are more extended than the dust traced by the ALMA continuum and young stellar population by $\lambda_{\text{rest}} \lesssim 0.4 \mu m$ images. This dichotomy appears in both the SE-1 and SE-2 and the ring and is consistent with the recent findings that [C II] is often more extended than both the UV and dust continua (Carniani et al. 2018; Fujimoto et al. 2019; Ginolfi et al. 2020; Fudamoto et al. 2022). In addition, there is a dust lane-like gap at the southeast and northwest of the ring in the $H \alpha$ map, 2.8 to $4.4 \mu m$ images (the broken connection of the ring at the lower left and upper right part), suggesting its association with gas emission. We suspect the gaps are regions of very high dust extinction or the line emission is suppressed.

In addition to the newly discovered companion, there are even more arc-like weak features in NIRCam images (see Figure 3 for example) beyond the NIRSpec field of view. Future deeper and wider spectroscopic observations may decipher this seemingly crowded field.

4.2. Dust-obscured Star Formation Rate

We estimate the SFR of the companion galaxy in three ways: SFR$_{H\alpha}$ using the formula in Murphy et al. (2011), SFR$_{CII}$ using [C II]–SFR relation in Herrera-Camus et al. (2015), and SFR$_{FIR}$ using the scaling relation given by Kennicutt (1998). As we have a single point on the dust spectral energy distribution (SED) for the companion, we estimate the far-infrared (FIR) luminosity assuming a $\beta = 1.8$ and the commonly used 850 $\mu m$ relation (Genzel et al. 2010; Carilli & Walter 2013). The estimates of SFR are not corrected for lensing and are thus labeled as $\mu$SFR. The results are summarized in Table 1.

We found that, while the SFR$_{CII}$ agrees with SFR$_{FIR}$ within errors due to the limited fidelity afforded by using a single photometric point, it is a factor of $>2$ times higher than SFR$_{H\alpha}$. By attributing all the difference between SFR$_{CII}$ and SFR$_{H\alpha}$ to dust extinction, we can obtain an obscuration fraction of star formation $>55\%$ for SE, which is at the higher end for the galaxies with similar stellar mass at $z = 4$–5 (Faisst et al. 2022). This high obscuration fraction suggests that the companion galaxy is also dusty in nature. Although the in-flight calibration of JWST instruments is still ongoing and the absolute flux calibration of NIRSpec may be updated in the future, we do not anticipate any order of magnitude correction in calibration. And as a consistency check, we compared the continuum flux density measured in the NIRSpec spectrum and find it matches well with the photometric measurements on the better calibrated NIRCam and MIRI images.

Using the upper limit of the magnification for the companion galaxy SE and a reconciled $\mu$SFR = $100 M_\odot$ yr$^{-1}$, we can obtain a lower limit of the intrinsic SFR of $17 M_\odot$ yr$^{-1}$. This intrinsic SFR is about 20 times less than the host galaxy...
The dust continuum. The stellar mass in this galaxy. Although, we still caution the
possible obscuration by dust content accounting for up to 2% of the mass end for star-forming galaxies at this redshift
using other methods and clearly highlight the poor constraints provided by the single data point in the rest-frame FIR band. For estimating infrared luminosity using a single photometric
fitting also yields a depth \( \Delta \approx 1.49 \pm 0.5 \) and the companion SE has a
surface brightness in SE-1 than the ring. The SED fitting carried out with high-\( z \) extension to MAGPHYS
(da Cunha et al. 2008; Cunha et al. 2015) shows SE has a stellar mass \( \mu M_\odot = 7.0^{+3.0}_{-2.3} \times 10^8 M_\odot \), placing it at the lower-mass end for star-forming galaxies at this redshift (Rizzo et al. 2020) but above the star-forming main sequence (Sparre et al. 2015). The SED-based \( \mu \text{sFR} = 5.8^{+15}_{-13} M_\odot \text{yr}^{-1} \) and \( \mu L_\text{IR} = 7.4^{+7.0}_{-7.0} \times 10^{11} L_\odot \) agree with our estimates for SE using other methods and clearly highlight the \(-2\times \) uncertainty for estimating infrared luminosity using a single photometric data point. The SED fitting also yields a depth \( \tau_s = 1.49^{+1.5}_{-0.5} \), and dust mass \( \mu M_d = 1.5^{+1.5}_{-0.8} \times 10^8 M_\odot \), suggesting a significant obscuration by dust content accounting for up to 2% of the stellar mass in this galaxy. Although, we still caution the poor constraints provided by the single data point in the rest-frame FIR band.

Most (U)LIRGs in the local universe are in the process of merging, which likely triggers the starburst activity in these systems (Sanders & Mirabel 1996; Armus et al. 2009). It is thus natural to speculate SPT0418-47 as an analog of a ULIRG triggered by a merger at \( z \sim 4.2 \). The small size of the companion and the distortion by gravitational lensing lead to some uncertainty about studying the relation between the host and the companion galaxies in 3D and determining whether it can be classified as a major or a minor merger. The physical proximity, both in projected distance and redshift space, supports the merger scenario and also raises questions with respect to the dynamical interaction timescale. These could potentially be in contradiction to the observed low-velocity dispersion or the “dynamically cold” disk scenario suggested by Rizzo et al. (2020), which will be disrupted by either tidal interactions that are commonly seen in the local (U)LIRGs or the cold accretion expected for high-redshift minor mergers.

Figure 4. SED of SPT0418-47 system (red square) and the companion SE (blue square), along with the Arp-220 (red dashed line and red dotted line) and M82 (cyan dashed line) SED templates (Polletta et al. 2007) normalized by the dust continuum. The figure is adapted from Vishwas (2019).

4.3. Radiation field

We characterized the radiation field using the nitrogen and sulfur lines detected in the NIRSpec spectrum. The \([\text{N}\,\text{II}]\) \( \lambda 6584/\text{H}\alpha \) ratio \( \sim 0.25 \) places SE in the star-forming locus in the BPT diagram with relatively soft radiation (Baldwin et al. 1981; Kewley et al. 2019). This leads to the argument that the compact nuclear feature present in the \( \lambda_{\text{rest}} \leq 5000 \) Å images is more likely a starburst nucleus instead of an active galactic nucleus (AGN). While we cannot rule out a low-luminosity AGN being present, the star formation scenario is further supported by the lack of strong rest-frame UV radiation, dimming in mid-infrared bands, and the high SFR inferred in this galaxy.

The S32 index of \( \log [\text{S}\,\text{III}]/[\text{N}\,\text{II}] \) is primarily a measure of the ionization parameter \( U \). The shorter wavelength [S II] line is more extincted, so we can only put an upper limit on the S32 ratio to be \( \approx 0.25 \). We then estimated an upper limit of \( \log U \leq -3 \) using the diagnostics given in Sanders et al. (2020). This is within the range measured in the local universe, suggesting similar conditions in the ionized gas of the star-forming region Kewley et al. (2019). The small value of \( U \) also predicts relatively weak [O III]λ4959,5007 lines (Strom et al. 2018), as is also suggested by its allowed position on the BPT diagram.

4.4. Metallicity

We estimated the chemical abundance in SE using three methods. The absolute abundance O/H is calculated using two strong line methods: the N2 index with the third-order polynomial fit in PP04 (Pettini & Pagel 2004); and the S23 index in Díaz & Pérez-Montero (2000). We also used the N2/S2 index (Viiroen et al. 2007; Perez-Montero & Contini 2009) to measure the nitrogen-to-oxygen abundance ratio N/O. The results are recorded in Table 1.

We found SE to be chemically mature with O/H \( \sim 0.6 \) times the solar abundance and N/O \( \sim 1.2 \) times solar, which are surprisingly high for a galaxy only 1.46 billion years after the big bang. We argue that the metallicity estimates are robust because (1) only line ratios are used, and they are not affected by the uncertainties in the absolute calibration of JWST; (2) the emission lines are close in wavelength, so the line ratio is not subject to differential extinction, with the only exception being the [S III] lines; and (3) the three methods use a suite of lines, and all reach a consistent result of near-solar metallicity; it would require at least two of the line-flux values to change in order to attain some other consistent results. Systematic uncertainty in these empirical optical diagnostics are typically 0.3 dex (Perez-Montero & Contini 2009), but it is not included in the error values reported in Table 1 for clarity. However, the systematic error is reduced when combining and comparing different methods. Besides, the SED fitting of SE using MAGPHYS also yields a reasonably consistent metallicity \( \sim 0.78 Z_\odot \).

The near-solar abundance and the elevated N/O ratio suggest this galaxy hosts highly enriched interstellar medium. It is consistent with the large dust content and relatively soft
radiation field in this galaxy. But drawing a comparison with the metallicity of star-forming galaxies at redshift 1 to 3 from ground-based observations (see Steidel et al. 2014; Kashino et al. 2017; Strom et al. 2022), both O/H and N/O of SE are at the very high end of the distribution, yet they are at a much earlier epoch in the universe. This suggests a rare and unusual chemical evolution history for SE.

It is even more striking that an identical analysis on the host galaxy found the metallicity Z ∼ 1.6Z☉, and (N/O) ∼ 3×(N/O)☉. This metallicity is even higher than Z ∼ Z☉ derived in De Breuck et al. (2019). Because the gas-phase elemental abundance builds up through nuclear synthesis and stellar feedback and the growth of N/O is slower through the prolonged secondary production of nitrogen, O/H and N/O abundances strongly constrain the age and star-forming efficiency (SFE) of a galaxy. Compared with the chemical evolution model in Figure 5 of Vincenzo et al. (2016), the stellar population in SE is inferred to have an age of at least 800 Myr with a preferentially short depletion timescale τ ≲ 0.67 Gyr, while the supersolar metallicity of the host, especially the high N/O, requires the galaxy formation to start shortly after the big bang and being sustained at a high SFE with τ ≲ 0.3 Gyr.

The high SFE inferred from the metallicity supports a decreasing depletion time toward higher redshift found by other studies (Saintonge et al. 2013; Tacconi et al. 2020). The younger age of the companion suggested by the lower metallicity is also consistent with the lack of λrest ∼ 2 μm peak in the SED corresponding to the old stellar population, which shows up strongly for the more-evolved host galaxy. On the other hand, the inferred early onset of galaxy formation, clustering of galaxies, and the potentially crowded field indicate the system might trace a massive dark-matter halo that enables structure formation at a very early time in the universe.

Although the FIR fine-structure line observations are not resolved for SE, we can still compare the FIR diagnostic of the whole system. In addition to [C II], the system is also detected in [O III]88 μm, [N II]122 μm, and [N II]205 μm lines (De Breuck et al. 2019; Cunningham et al. 2020). The [N II]122/[O III]λ88 flux ratio, which can be a rough proxy for N/O, is only 0.05. In the local universe, such a small line ratio is more commonly seen in dwarf galaxies as a consequence of both hard stellar radiation fields and low N/O (Cormier et al. 2015), rather than the [C II]LIRGs (Díaz-Santos et al. 2017) that the dusty and metal-rich SPT0418-47 system resembles. The weak [N II] 122 and 205 μm lines are also in contrast to the relatively bright [N II]λ6584 line.

One possible solution is the applicability of the optical strong line diagnostics in the early universe. Strom et al. (2018) found a slightly modified relation for estimating the elemental abundances using optical spectral lines at redshift 2–3 compared to those from local galaxies. Using the revised N2 and N2S2 calibration in Strom et al. (2018), the N/O of both the host and the companion decrease by about 0.25 dex, corresponding to 1.6 and 1 times the solar abundance, respectively. However, we do not find a significant change in the estimate for O/H. Though still high, the new values of N/O need a much less evolved stellar population, and they are closer to the log(N/O) ∼ −1.1 estimated from the empirical [O III] 88/[N II]122-to-N/O relation in the local universe (B. Peng 2023, in preparation). We leave more detailed analysis on chemical abundance of the ring to future publications.

5. Summary and Future Work

In this study, we report the discovery of a dusty star-forming companion galaxy SPT0418-47 SE in the SPT0418-47 system. The companion galaxy is also gravitationally lensed, which results in the two images SE-1 and SE-2. By combining JWST and ALMA observations, we find a high SFR of the companion galaxy with near-unity dust obscuration fraction. Using strong line indices, we find near-solar and supersolar metallicity for the companion and the host galaxy.

This work highlights the capability of JWST for discovering fainter and lower SFR galaxies in the early universe. It also shows the value of joint study of both optical and submillimeter observations as 55% SFR of the companion galaxy is obscured by dust. JWST for the first time enables us to study the physical conditions of the hot gas through strong optical lines at z > 4. This work illustrates some exciting discoveries and results that are attained with these lines. This spectroscopic study of a z > 4 galaxy opens up many questions, including the spatial arrangement and stellar/gas/metallicity distribution of the companion; the merging hypothesis of SPT0418-47; the dark-matter halo of the system; the overdensity of this potentially crowded field; reconciling the relatively high chemical abundances with the short formation time and the moderate stellar mass for the whole system; and interpreting the small [N II] 122 and 205 μm luminosities in the context of either a soft radiation field and/or a high N/O.

Our work suggests SPT0418-47 is a good example of the very early mass buildup and structure formation based on the solar-like metallicity at a cosmic age of 1.4 Gyr and hints of clustering. The high magnification, rich observational data, and the many intriguing questions on its formation history make it an ideal target for future observations and in-depth study. We therefore call for NIRSpec observations covering the [O III] λλ4959,5007 doublets and [O II]λ3727 lines and an Hα narrowband search in the SPT0418-47 field, as well as deep resolved ALMA [N II] and [O III] observations.

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