Extremely Low Molecular Gas Content in the Vicinity of a Red Nugget Galaxy at $z = 1.91$

T. Morishita$^1$, Q. D’Ama$^{2,3}$, L. E. Abramson$^4$, Abdurro’uf$^5$, M. Stiavelli$^1$, and R. A. Lucas$^1$

$^1$ Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA; tmorishita@stsci.edu
$^2$ INAF/IRA, Istituto di Radioastronomia, Via Piero Gobetti 101, I-40129, Bologna, Italy
$^3$ Dipartimento di Fisica e Astronomia dell’Università degli Studi di Bologna, via P. Gobetti 93/2, I-40129 Bologna, Italy
$^4$ The Carnegie Observatories, 813 Santa Barbara Street, Pasadena, CA 91101, USA
$^5$ Institute of Astronomy and Astrophysics, Academia Sinica, Taipei 10617, Taiwan

Received 2020 October 18; revised 2020 December 20; accepted 2020 December 30; published 2021 February 22

Abstract

We present Atacama Large Millimeter/submillimeter Array Band 5 observations of a galaxy at $z = 1.91$, GDS24569, in search of molecular gas in its vicinity via the $\text{[C}\text{I}]\,\text{P}_1-\text{P}_0$ line. GDS24569 is a massive ($\log M_\ast/M_\odot = 11$), passively evolving galaxy, characterized by compact morphology with an effective radius of $\sim 0.5$ kpc. We apply two blind detection algorithms to the spectral data cubes and find no promising detection in or around GDS24569 out to a projected distance of $\sim 320$ kpc, while a narrow tentative line (4.1$\sigma$) is identified at $+1200$ km $\text{s}^{-1}$ by one of the algorithms. From the nondetection of $\text{[C}\text{I}]$, we place a 3$\sigma$ upper limit on molecular hydrogen mass, $\sim 7.1 \times 10^5 M_\odot$, which converts to an extremely low gas-to-stellar mass fraction of $\lesssim 5\%$. We conduct a spectral energy distribution modeling by including optical to far-infrared data and find a considerably high ($\sim 0.1\%)$ dust-to-stellar mass ratio, i.e., $\sim 10-100\times$ higher than those of local early-type galaxies. In combination with a previous result of an insufficient number of surrounding satellite galaxies, it is suggested that GDS24569 is unlikely to experience significant size evolution via satellite mergers. We discuss possible physical mechanisms that quenched GDS24569.

Unified Astronomy Thesaurus concepts: Galaxies (573); Galaxy quenching (2040); Circumgalactic medium (1879)

1. Introduction

The origin of the most massive galaxies in the local universe has been a long-standing subject of galaxy evolution. From analysis of stellar populations and chemical abundances of local galaxies, it has been inferred that the most massive galaxies in the local universe completed their formation at redshift $z \geq 2$ (Kauffmann et al. 2003; Thomas et al. 2003; Gallazzi et al. 2005; Treu et al. 2005; McDermid et al. 2015). Recent near-infrared (NIR) observations indeed found many distant galaxies to be already quenched, showing consistency with the quenching timeline inferred from the local and low-z universe (Brammer et al. 2009; Marchesini et al. 2009; Muzzin et al. 2013; Tomczak et al. 2014).

Interestingly, a large fraction of high-z massive quenched galaxies are characterized by compact morphology (Cimatti et al. 2004; Daddi et al. 2005; Trujillo et al. 2007; Buitrago et al. 2008; Ichikawa et al. 2010; Cassata et al. 2011). While the average size of galaxies is smaller at that high redshift (Trujillo et al. 2006; Morishita et al. 2014; van der Wel et al. 2014), high-resolution imaging by the Hubble Space Telescope (HST) and the adaptive optics of ground-based facilities revealed that some of them have even smaller radius compared to the local counterpart at a similar mass, by a factor of $\sim 5$ (van Dokkum et al. 2008; Damjanov et al. 2009; Szomoru et al. 2010). Given the absence of such a compact galaxy population in normal fields in the local universe (Shen et al. 2003; Taylor et al. 2010; but see Valentinuzzi et al. 2010 for their presence in dense fields), the transition of galaxies in the size–mass plane implies that many high-z compact galaxies would have to experience significant size evolution.

Various scenarios of significant size evolution for compact galaxies have been proposed in the past decade, including dry/wet, major/minor mergers (Khochfar & Silk 2006; Naab et al. 2007, 2009; Hopkins et al. 2009; Nicholls et al. 2009) and active galactic nucleus (AGN) feedback (Fan et al. 2008; Damjanov et al. 2009; see Conselice 2014, for a thorough review). Among these scenarios, the dry minor merger scenario has been popularly discussed and taken as the most successful scenario in terms of its efficiency of size increase; surrounding satellite galaxies accrete to the central compact galaxy, without disturbing the central core, and in this way it can efficiently evolve effective radii with a small increase of stellar mass (Hopkins et al. 2009; Naab et al. 2009; Oser et al. 2010; Trujillo et al. 2011), while not all of them may have to follow the same path (Newman et al. 2012; Nipoti et al. 2012). The resulting stellar populations and mass profiles from this inside-out evolution are in good agreement with findings at intermediate redshifts (van Dokkum et al. 2010; Patel et al. 2013; Morishita et al. 2015; Papovich et al. 2015) and for local massive galaxies (Belfiore et al. 2017; Ellison et al. 2018).

However, such an interpretation remains indirect, and the data still admit other scenarios. For example, such compact galaxies may not have to be the typical massive galaxy population at low redshift. In fact, there are a significant number of compact galaxies but more preferably in cluster environments (Valentinuzzi et al. 2010; Poggianti et al. 2013). It has also been proposed that the observed trend of average galaxy sizes reflects progenitor bias (e.g., Carollo et al. 2013; Fagioli et al. 2016), where large-radius galaxies may appear at later time and drive apparent size evolution while high-z compact galaxies remain as they are.

Toward more direct understanding of their following evolutionary path, Márquez-Queralto et al. (2012) studied satellite galaxies around massive galaxies to calculate possible size increase that would likely happen through accreting these satellite galaxies. Interestingly, their results indicated that the extant satellite galaxies are not enough to account for significant size evolution to the local relation. Furthermore,
Morishita & Ichikawa (2016) studied a compact galaxy at z = 1.91, GDS24569, in deep HST images from the extreme deep field (XDF) project (Illingworth et al. 2016), to search for satellite galaxies around it down to log $M_*/M_\odot \sim 7.2$. Their conclusion is that the number of satellites is not enough either, and extra mass increase by, e.g., additional star formation is required for GDS24569 to be on the local size–mass relation.

This poses the question whether additional in situ star formation is possible in such compact quenched galaxies. One missing key component in these studies is gas, in particular in the form of molecular hydrogen. While the stellar component is not enough for the mass increase required to be on the local relation, additional star formation caused by remaining or newly accreted gas could change their sizes significantly (i.e., scenario C in Morishita & Ichikawa 2016).

To answer the question, we here present new observations with the Atacama Large Millimeter/submillimeter Array (ALMA) on GDS24569. Our configuration allows wide field-of-view (FOV) coverage to the extent of its virial radius, $r \sim 300$ kpc. Due to the spectral window available for the source redshift, we target atomic carbon, $[\text{C} \text{I}] \; ^3P_1-^3P_0$ (rest-frame frequency 492 GHz, hereafter $[\text{C} \text{I}]$), which is known as a good alternative tracer of molecular hydrogen in extragalactic systems, originated from photodissociation regions (e.g., Papadopoulos et al. 2004; Bell et al. 2007; Öffner et al. 2014; Salak et al. 2019). The line has an excitation temperature of 23.6 K and a critical density for collisions with hydrogen atoms of $\sim 1.2 \times 10^3$ cm$^{-3}$. While CO(4–3) is also available in the same spectral window, it is not optimal to search for cool gas owing to its slightly higher excitation temperature (55.3 K). Atomic carbon is found to well trace CO, at least in low-density environments, i.e., at the boundaries of molecular clouds (Glover et al. 2015), at an almost constant ratio of $N([\text{C} \text{I}])$/N(CO) $\sim 0.1$–0.2 in the local universe (Keene et al. 1997; Ojha et al. 2001; Ikeda et al. 2002). Early studies presented $[\text{C} \text{I}]$ as an excellent gas tracer at high redshifts too (e.g., Weiß et al. 2005; Walter et al. 2011; Valentino et al. 2018).

In this study, we exploit the exquisite sensitivity of ALMA and the ubiquity of $[\text{C} \text{I}]$ to search for previously unseen gas content in and around GDS24569, aiming to infer the primary quenching mechanism and possible future evolutionary path. The paper is structured as follows: In Section 2, we describe our observations and data reduction. In Section 3, we present our analysis method of a blind search for gas in the ALMA data, as well as results. While the primary goal in this study is to search for surrounding gas, the data set also provides us an opportunity to investigate the cause of quenching in the central galaxy from a panchromatic analysis over optical to far-infrared (FIR) wavelengths (Section 3.4). In Section 4, we discuss our results and present our interpretation. Throughout, magnitudes are quoted in the AB system assuming $\Omega_m = 0.3$, $\Omega_{\Lambda} = 0.7$, $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, and we assume the Salpeter (1955) initial mass function.

2. Data and Analysis

2.1. Target Galaxy

Our primary target, GDS24569, is a massive ($\log M_*/M_\odot \sim 11$) galaxy at $z = 1.91$, originally reported in Daddi et al. (2005), identified in a spectroscopic campaign with HST, GRAPES (Pírzkal et al. 2004). The galaxy is passively evolving, characterized by its spectral features, and has compact morphology with effective light radius $\sim 0.5$ kpc (Szomoru et al. 2010), which converts to a stellar mass density of $\log \Sigma_*/M_\odot$ kpc$^{-2} \sim 11$ (Figure 1). Morishita et al. (2019) analyzed its spectral energy distribution (SED) by fitting photometric and spectroscopic data points and revealed that the galaxy experienced a very short period of star formation $\sim 0.5$ Gyr prior to its observed redshift, characterizing it as a quenched galaxy (see also Section 4).

On the size–mass plane, GDS24569 is located $\sim 2\sigma$ below the median size of passive galaxies at that redshift and stellar mass (van der Wel et al. 2014). To speculate its future evolutionary path, Morishita & Ichikawa (2016) investigated

![Figure 1. Left: pseudo-RGB image (F160W+F814W+F435W of HST) of the observed field. The two ALMA pointings are overlaid (Data1 and Data2; white circles). The target, GDS24569, is centered in the image (red square). The position of the tentative detection found in Data2 (Section 3.2.2) is also shown (green circle), while no optical/IR counterpart is found at the position. Right: dust continuum map, created by collapsing the entire frequency range of the combined data cube. The coordinates of the objects in the left panel are indicated with the same symbols. No continuum emission is detected near the position of GDS24569. The beam size is shown at the bottom right (orange ellipse).](image-url)
surrounding sources photometrically selected in extremely deep images from the XDF project (Illingworth et al. 2013), down to $10^8 M_\odot$. There are insufficient satellite galaxies to move GDS24569 onto the local size–mass relation when following a simple formula for a minor merger scenario, $\Delta r \propto \Delta M^2$ (Naab et al. 2009). While GDS24569 may end up as one of the compact populations found in the local universe, it is worth investigating any contribution from optically dark components, which may trigger star formation and size evolution, before we conclude its fate.

2.2. ALMA Cycle 7 Observation

Interferometric observations with Band 5 were executed in ALMA cycle 7 (PID. 2019.1.01127.S, PI T. Morishita). We designed the observations so they would reveal gas components down to $10^8 M_\odot$ within the virial radius of GDS24569, $\sim 300$ kpc, via the [CII] emission line with an excitation temperature of $\sim 30$ K. Since our purpose here is not to resolve each gas clump, we optimize the antennas’ configuration for a large FOV, resulting in the final beam size of $1.0 \times 0.8$ arcsec$^2$. We set three $1.875$ GHz width spectral windows, one of which was tuned to cover the [CII] frequency of the target ($\sim 169$ GHz), while the other two spectral windows were centered on 168.5 and 170.4 GHz for a continuum estimate.

Our observations, originally executed in 2019 November with on-source exposure of 107 minutes, were accidently off the central pointing for $\sim 12''$, while GDS24569 was still within the FOV (dubbed as Data2). The observations were compensated in 2020 January, with the target in the center as it was originally planned (Data1). We therefore acquired two data sets with the same setup for frequency and exposure time as described above (Figure 1), which allow us an independent check on possible detection (Section 3). We ran the tclean task of CASA on each of the data sets, with parameters of pixel scale 0$''$.16 and velocity resolution element $\sim 28$ km s$^{-1}$ ($\sim 15.6$ MHz).

3. Method and Results

3.1. Dust Continuum Emission

In Figure 1, we show a continuum map created by collapsing the spectral data cube over the entire velocity range, $-4000$ to $3000$ km s$^{-1}$. No continuum source is detected near the position of GDS24569. The rms values are calculated by imstat of CASA: 27 and $34 \mu$Jy beam$^{-1}$ for Data1 and Data2, respectively, and $21 \mu$Jy beam$^{-1}$ for the combined data cube at the target source position. This nondetection of dust emission is consistent with the optical to NIR SED analysis of GDS24569, $A_V = 0.4$ mag (Morishita et al. 2019). We will use the upper limit derived here for a panchromatic analysis in Section 4.

3.2. Clump Finding Algorithms

Our primary goal in this study is to search for gas clumps in the data cubes via the [CII] emission line, both in the position of GDS24569 and in its neighboring regions out to $r \sim 300$ kpc, which is its approximate virial radius. Despite a complicated aspect of blind detection in interferometric data cubes, our advantage is that we have two independent data cubes, so that any detection found in one data cube can be checked in the other. We start with a fiducial detection algorithm, clumpind (Williams et al. 1994), but we also apply a method introduced in D’Amato et al. (2020) to check the consistency.

3.2.1. Starlink Clumpfind Algorithm

To search for line detection across the data cubes, we apply an automated detection algorithm. We first run the clumpfind algorithm, implemented in the starlink package (Currie et al. 2014). One of the parameters for clumpfind is the noise level of the data represented by the rms values. While imstat of CASA provides an rms value at each frequency value, the noise is correlated significantly for our case with a relatively large beam size. Furthermore, the data show differential noise structure along the radial direction from the center, where larger noise structures frequently appear at a larger radius. To estimate a more realistic noise level, we extract apertures of beam size in 1000 randomly selected positions in each cube, to measure rms values in annuli at every 10 pixels from the center. As an example, the distribution of extracted fluxes is shown in the top panel of Figure 2, where the distribution is well fitted with a Gaussian. A radial distribution of derived rms values ($=\text{FWHM}/2.355$ of Gaussian fit) is shown in the bottom panel of Figure 2. The rms varies from $95 \mu$Jy beam$^{-1}$ per spectral element at the innermost region to $130 \mu$Jy beam$^{-1}$ per spectral element at the outermost region. We run the clumpfind algorithm on each of two data cubes with various rms values taken from the estimated range above. Other configuration parameters are also determined through our initial tests (VELORES = $5$, MINPIX = $50$, and FWHMBEAM = $3$). With the setup, the algorithm initially detects $\sim 100$ sources from the entire FOV of each data set for different rms values. However, most of the identified clumps are located at outer regions, $r \gtrsim 15''$. Our visual inspection does not confirm any of these clumps as real sources. Furthermore, none of these sources are commonly identified in both of the data cubes. We thus conclude that all of the detected clumps are...
Figure 3. Spectrum extracted in the position of GDS24569 in the combined data cube, with an aperture of the beam size. No significant flux excess is seen.

artifacts. To confirm this, we also apply the same method to the data cubes but with signs of fluxes inverted. We find a similar number of detections with a similar spatial distribution to that for the real cubes.

The spectrum extracted from the position of GDS24569 in the combined cubes is shown in Figure 3. No obvious line is detected beyond the noise limit associated with each spectral element.

3.2.2. D’Amato et al. (2020)’s Method

To double-check the nondetection in Section 3.2.1, we also apply a blind detection method introduced in D’Amato et al. (2020), which relies on spectral, spatial, and reliability criteria.

We perform the detection on the signal-to-noise ratio (S/N) cube. In order to produce it, we first generate a noise cube, where the pixels have the value of the rms in a box centered in them. We choose a box with an area equal to that of 10 beams, since we find that this size allows us to trace the local variation of the noise in each channel, still having enough statistics per box. The rms is recursively calculated to convergence masking all pixels above 3×rms at each iteration. The S/N cube is then obtained as the ratio between the original data cube and the noise cube.

In order to perform the detection, we first scan each spaxel searching for a given amount of contiguous channels (Nch) above a given S/N threshold. We search for Nch = 2, 3, 4, 5 (corresponding to ~60, 90, 120, 150 km s⁻¹, respectively) above an S/N threshold of 1.5, 2.5, and 3. Then, among the candidate detections, we reject all those with a number of contiguous pixels lower than a given amount Npx. For each combination of Nch and S/N threshold, we try Npx = 2, 3, 4.

Finally, in order to estimate the incidence of spurious detections, we perform the same algorithm on the “negative” S/N cube, where the pixels have the same value and inverted sign of the original (“positive”) S/N cube. Then, for any combination of Nch, S/N threshold, and Npx we reject all the candidate detections obtained from the positive S/N cube that have a peak S/N lower than the maximum peak S/N of the detections obtained from the negative S/N cube using the same parameter combination. Finally, we crop the detection area to the half-primary beamwidth.

From this analysis, we find one tentative detection (4.1σ) at +1200 km s⁻¹ at projected distance ~14 kpc away from GDS24569 in Data2 (top panel of Figure 4), while no optical counterpart is identified in the XDF data set (Figure 1). The rms at the position is 87 μJy beam⁻¹. The line is narrow and fitted with a Gaussian of FWHM = 84 km s⁻¹ (~3 spectral elements). The total flux from the integral of the Gaussian fit is S[C I]Δν ~ 7.5 mJy km s⁻¹. The line is not identified at the same spectral position in Data1, with only 1 positive pixel of S/N ~ 1 (bottom panel of Figure 4). This may be attributed to lower sensitivity at the position in Data1, which is ~10⁵ S/N away from the center, while the rms value is ~120 μJy beam⁻¹ and the line should still be detectable at S/N ~ 3. We thus leave this detection as tentative, while including this emission would not change our analysis and main conclusion in Section 4.

3.3. Upper Limits in Molecular Gas Mass

In this subsection, we attempt to place an upper limit on molecular hydrogen mass from the estimated rms values in Section 3.2.1. Following a recipe by Papadopoulos et al. (2004; see also Wagg et al. 2006; Man et al. 2019), molecular hydrogen gas mass is inferred by

\[
M_\text{H}_2 = 1375.8 \frac{D_1^2}{(1 + z)} \left( \frac{X_{\text{[C I]}}}{10^{-5}} \right)^{-1} \times \left( \frac{A_{10}}{10^{-7} \text{s}^{-1}} \right)^{-1} S_{\text{[C I]}} \Delta \nu \frac{Q_{10}}{\text{Jy km s}^{-1} \text{M}_\odot}. \tag{1}
\]

The equation consists of two steps: conversion from observed [C I] intensity to atomic carbon mass, and then to molecular hydrogen mass. The conversion involves a couple of parameters. We adopt the excitation factor Q₁₀ = 0.5 as a fiducial value, assuming local thermodynamic equilibrium (i.e., optically thin). Q₁₀ ranges from 0 to 1, depending on the temperature, density, and radiation field, though none of these values can be constrained without line ratios to other excitation levels. We adopt a molecular [C I]-to-H₂ conversion factor X[C I] = 1.5×10⁻⁶ taken from (Jiao et al. 2019). The value is the lower limit measured in nearby galaxies and gives us a conservative upper limit in molecular hydrogen mass, whereas the conversion factor can be as high as X[C I] = 5×10⁻⁵ (e.g., Frerking et al. 1989; Weiß et al. 2003, 2005). The conversion to molecular hydrogen mass includes the mass in helium by a correction factor of 1.36 (Solomon & Vanden Bout 2005). A₁₀ = 7.93×10⁻⁸ cm s⁻¹ is the Einstein A-coefficient, and D₁₀ is the luminosity distance to the source redshift, z = 1.91.

Since our input for the equation above is the upper limit for flux density, we need to assume the line width to obtain a velocity-integrated line intensity, S[C I]Δν. We set Δν = 300 km s⁻¹ based on stellar velocity dispersion measurements in massive compact quiescent galaxies (e.g., van de Sande et al. 2013; Belli et al. 2017), while narrower line width has been seen in massive rotating disks (~200 km s⁻¹; Weiß et al. 2005; Man et al. 2019). With this we obtain S[C I]Δν ~ 42 mJy km s⁻¹ beam⁻¹ as a 3σ upper limit in the position of GDS24569.

By substituting these numbers in the equation above, we obtain a conservative 3σ upper limit on molecular hydrogen mass of ~7.1×10⁶ M_☉, characterizing a significantly low gas mass fraction fgas < 5%.

3.4. Panchromatic Analysis of GDS24569

Morishita et al. (2019) investigated the star formation history of GDS24569 from a combined data set of NIR spectrum and
optical to NIR broadband photometry. We refit the data set with an SED fitting code, gsf (ver.1.46). From Morishita et al. (2019), we retrieve broadband photometry of HST and Spitzer up to IRAC CH4, originally published by the 3D-HST team (Skelton et al. 2014). Deep spectra of WFC3-IR G102 and G141 originally taken in 3D-HST, FIGS (Pirzkal et al. 2017), and CLEAR (Estrada-Carpenter et al. 2019), which were reduced and presented in Morishita et al. (2019), are also included, to constrain its stellar populations and star formation history.

Specifically, in this redshift range, the deep grism spectra capture the Balmer break and absorption features at rest frame $\sim 4000$ Å, while the broadband coverage extending to rest-frame $K$ band is sensitive to variation in metallicity and dust attenuation. This comprehensive coverage enables us to break the well-known age–dust–metallicity degeneracy and enables robust characterization of star formation histories too. Interested readers are referred to Morishita et al. (2018, 2019), which presented intensive tests with simulated data sets, for more details.

We include the upper limit on the continuum obtained from our ALMA observations (Section 3.1). We also include Spitzer MIPS 24 $\mu$m flux from Whitaker et al. (2014) and upper limits on MIPS 70 $\mu$m and Herschel PACS 100 and 160 $\mu$m from the GOODS Herschel program (Elbaz et al. 2011). The broadband photometric data points used here are summarized in Table 1.

In Figure 5, we show the best-fit SED and star formation history of GDS24569. The result indicates that GDS24569 had the last primary star formation activity $\sim$0.5 Gyr ago and then rapidly declined its star formation rate $\sim$100 Myr before the observed redshift. Such a star formation history is in fact speculated from the absence of significant flux at rest-frame UV wavelength, as well as a deep 4000 Å break and Balmer absorption lines seen in the deep grism spectra, characterizing GDS24569 as a post-starburst galaxy (Dressler & Gunn 1983). Such rapid decrease in star formation activity is also seen in other massive galaxies (Belli et al. 2019; Morishita et al. 2019), while their primary quenching process remains unclear. The low gas fraction and the inferred dust mass of the system found

\[ S\Delta v = 7.5 \text{ mJy km s}^{-1} \]
\[ \sigma = 35.6 \text{ km s}^{-1} \]

Figure 4. Top: tentative line detection at $V \sim 1200$ km s$^{-1}$ in Data2 is shown (left panel; red circle) in the velocity-integrated map (centered on its pointing). The position of GDS24569 is also shown (black cross). The beam size is shown in the lower right corner (white ellipse). The Gaussian fit to the tentative line is overlaid in the extracted spectrum (right panel; red dashed line). Bottom: same as above, but for Data1. No significant flux excess is seen at the velocity (red dashed line).

The Astrophysical Journal, 908:163 (9pp), 2021 February 20 Morishita et al.

\[ 7 \text{ https://github.com/mtakahiro/gsf/tree/version1.4] } \]
| $F_{125W}$ | $F_{140W}$ | $F_{160W}$ | $F_{225W}$ | $F_{275W}$ | $F_{336W}$ | $F_{435W}$ | $F_{606W}$ | $F_{775W}$ | $F_{814W}$ | $F_{850LP}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| $K_s$ | IRAC CH1 | IRAC CH2 | IRAC CH3 | IRAC CH4 | MIPS 24μm | MIPS 70μm | PACS 100μm | PACS 160μm | ALMA Band 5 |
| 3.26 ± 0.02 | 4.49 ± 0.03 | 5.30 ± 0.03 | <0.14 | <0.05 | <0.03 | <0.01 | 0.11 ± 0.01 | 0.26 ± 0.01 | 0.35 ± 0.01 | 0.62 ± 0.02 |
| 7.99 ± 0.09 | 11.18 ± 0.07 | 11.98 ± 0.06 | 10.65 ± 0.42 | 6.09 ± 0.44 | 9.84 ± 2.72 | <8538.11 | <2203.38 | <6610.15 | <21.40 | |

**Note.** 1σ errors are quoted for those with S/N > 1, and 1σ upper limits for the rest of the data points.
in this study potentially add further constraints on the primary quenching mechanism (Section 4).

It is worth noting that the derived metallicity of GDS24569, \( \log Z_\star / Z_\odot \sim -0.2 \) dex, is \( \sim 0.4 \) dex below the mean relation of massive, noncompact quenched galaxies at \( z \sim 2 \) (Morishita et al. 2019). While the statistical significance is still small owing to the scatter around the mean relation (\( \Delta \sim 0.2 \) dex), this may further provide us a hint to its following evolution; if GDS24569 is representative of the compact galaxy population at this redshift, then a similarly low metallicity trend may be seen in local compact galaxies. Such a low metallicity implies that GDS24569 presumably experienced star formation of a short timescale in a relatively pristine gas environment (e.g., Kriek et al. 2016; see also below).

The best-fit result returns dust mass \( \log M_{\text{dust}} / M_\odot = 8.3 \pm 0.6 \). Despite the nondetection in ALMA Band 5, its strong upper limit constrains the FIR component sufficiently well within our providing templates, in combination with the MIPS 24 \( \mu \)m data point that constrains the polycyclic aromatic hydrocarbon (PAH) feature. The best-fit dust mass derives dust-to-stellar mass fraction \( M_{\text{dust}} / M_\star \sim 1.4 \times 10^{-3} \) and 3\( \sigma \) upper limit on gas-to-dust ratio of \( \lesssim 30 \). The inferred dust-to-stellar mass fraction is much higher than those of local early-type galaxies, ranging from \( M_{\text{dust}} / M_\star \sim 10^{-6} \) to \( 10^{-5} \) (Smith et al. 2012; Lianou et al. 2016), while a similar value was found from the stacking analysis of massive galaxies at \( z \sim 1.8 \) in Gobat et al. (2018). Such a significant amount of dust may play a critical role in suppressing star formation activity, by preventing formation of hydrogen molecules (e.g., Conroy et al. 2015; Kajisawa et al. 2015). Our finding of the low molecular gas mass fraction derived above is consistent with this scenario.

Our estimate of dust mass is robust to different assumptions in the SED modeling. We also fit our photometric data points with another SED fitting code, \texttt{piXedfit} (Abdurrouf et al. 2021), which adopts broader parameter ranges for the dust component. The code returns \( \log M_{\text{dust}} / M_\odot = 8.2^{+0.4}_{-0.6} \) in good agreement with the dust mass estimated by \texttt{gsf}.

No X-ray counterpart is found in the Chandra 7 Ms catalog (Luo et al. 2017) at the positions of GDS24569 or the tentative line in Section 3.2.2. The nondetection is reasonable given its passively evolving nature inferred from the SED and undisturbed morphology.

### 4. Discussion and Summary

In this study, we investigated the vicinity of a massive compact galaxy, GDS24569, for molecular gas that can induce star formation and lead to strong size evolution to the local...
size–mass relation. Our two independent algorithms on the unique data cubes did not confidently detect any gas clumps or continuum emission, placing a conservative upper limit on molecular hydrogen mass. We use this upper limit to further advance the argument presented in Morishita & Ichikawa (2016), where they consider possible size evolution of GDS24569 through accretion of photometrically identified 34 satellite galaxies. We here assume that each of the satellites (1) has the smaller of \( f_{\text{gas}}^* \sim 7\% \) and \( 7 \times 10^8 M_\odot \), (2) converts gas to stars at 100% efficiency, and (3) accretes to the central galaxy. The total mass contribution under this extreme assumption would be \( \log M_\star/M_\odot \sim 9.5 \), which still remains negligible compared to the observed mass of GDS24569 and the total stellar mass of the satellites (\( \log M_\star/M_\odot \sim 10.8 \)). The result secures the conclusion of Morishita & Ichikawa (2016) that GDS24569 is unlikely to be on the size relation of the early-type galaxies, at least via minor mergers, ending up \( \sim 2\sigma \) below the local size–mass relation of early-type galaxies at \( z \sim 0 \) (e.g., Shen et al. 2003; Taylor et al. 2010; Poggianti et al. 2013) at most. Since most of their satellite galaxies are not spectroscopically confirmed, this extrapolation is rather optimistic, and the actual size evolution can be even less significant.

In the local universe, on the other hand, there are a portion of compact, passively evolving galaxies in high-density regions, i.e., in galaxy clusters (e.g., Valentijnuzzi et al. 2010). These local compact galaxies, characterized by a similar light profile to that for high-\( z \) compact galaxies, dominate a significant fraction of cluster member galaxies at \( > 3 \times 10^{10} M_\odot \), \( \sim 22\% \) (Valentijnuzzi et al. 2010), whereas only \( \sim 4.4\% \) in general fields (Poggianti et al. 2013). These findings imply insignificant size evolution of (at least) some of the compact galaxies at high redshift, as is found in simulations (e.g., Wellons et al. 2016, Poggianti et al. 2013) also found that compact galaxies in dense environments consist of older stellar populations than those in general fields.

From these findings above, systematically earlier evolution of compact galaxies in dense fields is implied, which is suggested by Morishita et al. (2017) and Abramson & Morishita (2018) from their structural analysis on cluster and field galaxies, as well as by direct comparison of stellar age of massive galaxies at \( z \sim 2 \) (Wu et al. 2018, Estrada-Carpenter et al. 2020). In fact, the stellar metallicity of GDS24569 implied from our SED fitting analysis is \( \sim 0.4 \) dex below the average trend of noncompact galaxies at the same redshift. Assuming that GDS24569 is representative of the progenitor population of local compact galaxies, then we may see systematical differences in their metallicity and chemical composition from those of other noncompact galaxies. While Taylor et al. (2010) found no significant metallicity offset of compact galaxies in general fields, currently such systematic comparison of local compact galaxies in dense environments has not been established.

Lastly, we revisit possible quenching mechanisms that could occur in GDS24569. Our observations found an extremely low gas mass fraction in the system, \( f_{\text{gas}} \lesssim 5\% \), whereas the fraction ranges from \( \sim 50\% \) to \( \sim 100\% \) for the main-sequence star-forming galaxies at similar redshifts (Daddi et al. 2010; Hayashi et al. 2018; Tacconi et al. 2018). Such a low gas mass fraction of passive galaxies is not a surprise. For example, Sargent et al. (2015) reported a \( 3\sigma \) upper limit of \( f_{\text{gas}} \lesssim 5.8\% \) in a passively evolving galaxy at \( z = 1.43 \). Bezanson et al. (2019) reported a \( 3\sigma \) upper limit \( f_{\text{gas}} \lesssim 7\% \) in a galaxy at \( z = 1.522 \). Furthermore, the extremely low gas fraction of GDS24569 is worth comparing with those of compact galaxies at an earlier phase, or blue nuggets (Barro et al. 2013; Williams et al. 2014; van Dokkum et al. 2015). Barro et al. (2017) reported a short deactivation time (\( \sim 27 \) Myr) of a star-forming compact galaxy at \( z = 2.3 \) from their CO observations with ALMA. The galaxy is intensively forming stars at \( \sim 500 M_\odot \text{yr}^{-1} \), which is somewhat comparable to the peak star formation rate of GDS24569 (Figure 5). From this perspective, gas depletion by the past intense star formation activity can reasonably be considered as the primary cause of quenching for GDS24569.

We did not find gas clumps, disturbed gas structure, or dust emission in and around GDS24569. Given that the last primary star-forming activity occurred relatively recently (\( \sim 0.5 \) Gyr), this suggests that the past star formation activity was at least not caused by a galaxy–galaxy scale merger, and that gas was consumed inside the system rather than being ejected. This is consistent with a scenario derived from the local galaxies using stellar metallicity as an indicator (Peng et al. 2015). It is yet unclear what caused such intense star formation from our study. For example, Talia et al. (2018) observed an AGN-hosting compact star-forming galaxy and concluded that the star formation is likely caused by positive feedback from the AGN activity. This positive feedback scenario seems possible given that a higher fraction of compact star-forming galaxies host AGNs than the overall star-forming population (e.g., Kocevski et al. 2017; Wisnioski et al. 2018). On the other hand, such high efficiency in star formation can also be induced without AGN activity (Dekel & Burkert 2014; Semenov et al. 2018), leaving the conclusion still pending.

Given that the scenarios above are derived from one galaxy, we are still far from getting a general consensus on primary quenching mechanisms in compact massive galaxies. Nonetheless, in this study we showed that even nondetection of molecular gas and dust emission, in combination with a wide wavelength data coverage, sheds light on the nature of high-\( z \) passive galaxies. Application of this new approach to archival data will immediately improve statistical arguments.

We thank the anonymous referee for providing constructive comments. This paper makes use of the following ALMA data: ADS//JAO.ALMA#2019.1.01127.S. ALMA is a partnership of ESO (representing its member states), NSF (USA), and NINS (Japan), together with NRC (Canada), MOST and ASIAA (Taiwan), and KASI (Republic of Korea), in cooperation with the Republic of Chile. The Joint ALMA Observatory is operated by ESO, AUI/NRAO, and NAOJ. T.M. is grateful to Kate Rowlands and Takuya Hashimoto for helpful discussion and advice on ALMA data reduction. Support for this work was provided by NASA through grant Nos. HST-GO-15702.002, HST-GO-15702.002, and HST-AR-15804.002-A from the Space Telescope Science Institute, which is operated by AURA, Inc., under NASA contract NAS 5-26555.

Software: Astropy (Astropy Collaboration et al. 2013, 2018), numpy (Oliphant 2006; Van Der Walt et al. 2011), python-fsps (Foreman-Mackey et al. 2014), EMCEE (Foreman-Mackey et al. 2013).

---

8 Our star formation rate estimates are time-averaged at each pixel, and actual values could be higher if star formation activity is more instantaneous.
