Star Formation Traced by Optical and Millimeter Hydrogen Recombination Lines and Free–Free Emissions in the Dusty Merging Galaxy NGC 3256—MUSE/VLT and ALMA Synergy

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Abstract

A galaxy–galaxy merger and the subsequent triggering of starburst activity are fundamental processes linked to the morphological transformation of galaxies and the evolution of star formation across the history of the universe. Both nuclear and disk-wide starbursts are assumed to occur during the merger process. However, quantifying both nuclear and disk-wide star-forming activity is nontrivial because the nuclear starburst is dusty in the most active merging starburst galaxies. This paper presents a new approach to this problem: combining hydrogen recombination lines in optical, millimeter, and free–free emission. Using NGC 3256 as a case study, Hβ, H40α, and free–free emissions are investigated using the Multi Unit Spectroscopic Explorer at the Very Large Telescope of the European Southern Observatory (MUSE) and the Atacama Large Millimeter/submillimeter Array (ALMA). The Hβ image obtained by MUSE identifies star-forming regions outside the nuclear regions, suggesting a disk-wide starburst. In contrast, the H40α image obtained by ALMA identifies a nuclear starburst where optical lines are undetected due to dust extinction (AV ∼ 25). Combining both MUSE and ALMA observations, we conclude that the total star formation rate (SFR) is 49 ± 2 M⊙ yr−1 and the contributions from nuclear and disk-wide starbursts are ∼34% and ∼66%, respectively. This suggests the dominance of disk-wide star formation in NGC 3256. In addition, pixel-by-pixel analyses for disk-wide star-forming regions suggest that shock gas tracers (e.g., CH3OH) are enhanced where gas depletion time (τgas = Mgas/SFR) is long. This possibly means that merger-induced shocks regulate disk-wide star formation activities.

Unified Astronomy Thesaurus concepts: Starburst galaxies (1570); Interacting galaxies (802); Luminous infrared galaxies (946); Submillimeter astronomy (1647); Very Large Telescope (1767)

1. Introduction

It has been known for decades that mergers of two disk galaxies can induce “nuclear starbursts” in the central ∼1 kpc region during the coalescence stage (e.g., Keel et al. 1985), triggered by massive gas inflows. In an earlier stage of a merger, “disk-wide starbursts” (∼1 kpc) are seen both in theoretical models (Barnes 2004) and in observations: e.g., the Antennae galaxy (Wang et al. 2004), Arp 140 (Cullen et al. 2007), and NGC 2207+IC 2163 (Elmegreen & Elmegreen 2005). In particular, Cortijo-Ferrero et al. (2017) investigated the star formation history of merging galaxies using optical integral field unit (IFU) observations, showing that disk-wide starbursts arise in the early stages, whereas nuclear starbursts occur in the more advanced stages of a merger process. Theoretical models predict that such disk-wide starbursts can be explained by interstellar medium turbulence and fragmentation into dense clouds in the disk region (Teyssier et al. 2010; Bournaud 2011). In addition, Saitoh et al. (2009) suggest that shock-induced star formation may be efficient during a merger process. Observationally, it is difficult to quantify both nuclear and disk-wide starbursts in a consistent manner. For example, the mapping of hydrogen recombination lines (i.e., Hα and Hβ) by optical IFUs enables us to investigate the spatial distributions of star formation activities in regions where dust extinction is insignificant (e.g., Pan et al. 2019; Thorp et al. 2019), such as the disk component of galaxies. However, optical observation is hampered by extinction from thick layers of interstellar dust clouds, and correct quantification of the star formation activity in dusty regions such as the central nucleus of a merging galaxy is highly nontrivial. One of the best methods of investigating the properties of star formation activities in such extremely dusty regions is hydrogen recombination lines in the millimeter range (Scoville & Murchikova 2013). Recently, the Atacama Large Millimeter/submillimeter Array (ALMA) has detected recombination lines from nearby galaxies, e.g., NGC 253 (Bendo et al. 2015), NGC 4945 (Bendo et al. 2016), and NGC 5253 (Bendo et al. 2017). By cross-checking star formation rate (SFR) measurements from the other wavelengths, Bendo et al. (2015, 2016, 2017) demonstrated that ALMA is effective at studying the starburst activity in dusty regions.
2. The FWHM of the effective spatial resolution is \( \sim 0.6 \) arcsec. The plus, X, and Y signs indicate the positions where H40\( \alpha \) is detected (Section 2.2). The mapping area is 20\(' \) x 20\(' \) with the center at the northern nucleus (plus sign). The 2D maps are downloaded from the MAD project website (Erroz-Ferrer et al. 2019).

\((A_V \gtrsim 10)\). In this paper, we apply this method to investigate dusty starbursts in a merging galaxy.

The SFR estimated from the hydrogen recombination line luminosity (hereafter, SFR\(_{RL}\)) allows us to estimate the calibration constant between the SFR and total infrared (TIR) luminosity. The calibration constant changes depending on the duration of the currently observed starbursts (Calzetti 2013), because both high-mass short-lived stars and low-mass long-lived stars heat the dust and contribute to the TIR emission. If a young stellar population is the predominant energy source within a system, the TIR emission is mainly produced by dust heated by these young stars. However, the recombination line mainly traces the current starbursts, because only stars more massive than \( \sim 20 M_\odot \) produce a measurable ionizing photon flux. As such, the ratio between SFR\(_{RL}\) and recombination line luminosity is constant (when the age of the starburst is longer than \( \sim 6 \) Myr), allowing us to estimate the age of the starburst by comparing SFR\(_{RL}\) with the TIR luminosity. Hence, if the age of the starburst is shorter than the age of the galaxy merger, it is likely that the starburst was triggered by the galaxy interaction.

Little has been reported on the observations of millimeter recombination lines in merging galaxies. For example, in the case of Arp 220, Anantharamaiah et al. (2000) detected H42\( \alpha \), H40\( \alpha \), and H31\( \alpha \) using IRAM 30 m telescopes, and the results suggest multiple starbursts. Scoville et al. (2015) searched for H26\( \alpha \) emission from Arp 220, but detection was unclear due to the contamination of a nearby HCN(4–3) line. In order to investigate optical and millimeter hydrogen recombination lines, we focus on one specific merging galaxy, NGC 3256. In this galaxy, H40\( \alpha \) and H42\( \alpha \) were detected by ALMA (Harada et al. 2018) and Erroz-Ferrer et al. (2019) mapped the H\( \alpha \) and H\( \beta \) emissions with the Multi Unit Spectroscopic Explorer at the Very Large Telescope of the European Southern Observatory (MUSE/VLT) (Bacon et al. 2010).

NGC 3256 (redshift \( z = 0.00935 \)) is a merging galaxy with a TIR luminosity (5–1100 \( \mu m \); \( L_{TIR} \)) of 4.8 \( \times \) 10\(^{11} \) \( L_\odot \) (see Section 3.2.1 for details).\(^8\) This system is at a distance of \( D \sim 41.7 \) Mpc, which translates to 1" \( \sim 198 \) pc. There are two nuclei (northern and southern) separated by \( \sim 970 \) pc in NGC 3256. The systematic velocity of the merger is assumed to be \( cz \sim 2800 \) km s\(^{-1} \) (c is light speed). Lira et al. (2002, 2008) derive normalization of the extinction curve (\( A_V = 5.5 \) and 16 for the northern and southern nuclei, respectively) from the NICMOS \( 10 \) – \( K \) color. The large \( A_V \) makes it impossible to investigate the southern nuclear starburst activity using optical hydrogen recombination lines. The southern nucleus is an ideal laboratory to quantify how much the H\( \alpha \) and H\( \beta \) emission miss the SFR using H40\( \alpha \) emission. In Section 2, the VLT and ALMA observations are explained. In Section 3, the formula to calculate the SFR is introduced. In Section 4, we investigate the nuclear starbursts, disk-wide starbursts, starburst timescale, and electron temperature. Finally, we summarize this project in Section 5.

2. Data

2.1. MUSE

NGC 3256 was observed by MUSE as one of the targets for the MUSE Atlas of Disks (MAD) project (Erroz-Ferrer et al. 2019). The processed MUSE 3D data cube of NGC 3256 can be downloaded from the ESO science archive portal,\(^11\) and has a field of view (FOV) of 1 arcmin\(^2\), with spatial sampling of 0.0625 arcsec. The FWHM of the effective spatial resolution is \( \sim 0.6 \) arcsec, with spectral sampling of 1.25 \( \AA \), and an observation date of 2016 April 6.\(^12\) Figures 1(a) and (b) show the extinction map and an extinction-corrected H\( \beta \) map processed by Erroz-Ferrer et al. (2019). The 2D maps in Figure 1 are downloaded from the MAD project webpage.\(^13\) We use these 2D maps for the main analysis (i.e., measurements of SFR). We use the 3D data cube only for measuring line profiles (see Section 2.3). The errors for the emission line flux are about 10% for the low signal-to-noise-ratio (S/N < 3) regions, and 2% for the higher S/N regions (Erroz-Ferrer et al. 2019). A conservative overall

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\(^8\) The redshift is from the NASA/IPAC Extragalactic Database (https://ned.ipac.caltech.edu).

\(^9\) We have adopted \( H_0 = 67.7 \) km s\(^{-1}\) Mpc\(^{-1} \) and \( \Omega_m = 0.307 \) (Planck Collaboration et al. 2016) as cosmological parameters throughout this article.

\(^10\) The Near Infrared Camera and Multi-Object Spectrometer (NICMOS) mounted on the Hubble Space Telescope (HST).

\(^11\) http://archive.eso.org/scienceportal/home

\(^12\) ESO Programme ID 097.B-0165.

\(^13\) https://www.mad.astro.ethz.ch/data-products
Note. Maximum recovery scale for each configuration at 100 GHz according to the ALMA configuration schedule (https://almascience.nrao.edu/observing/observing-configuration-schedule).

photometric error of 5% is adopted for the analysis using the H\beta map. In order to compare the MUSE/VLT and ALMA images, the H\beta peak position at the nondusty northern nucleus is assumed to be same as the H40\alpha peak position.

### 2.2. ALMA

The H40\alpha, H42\alpha, ^13\text{CO} (1–0), and CH3OH (2_{0–1}_{1}) data cubes were obtained as part of the 85–110 GHz range line search ALMA project for NGC 3256 (ID: 2015.1.00993.S). In addition, the data from two other ALMA projects (ID: 2015.1.00412.S and 2016.1.00965.S) (Harada et al. 2018) were combined during data processing in order to produce higher quality H40\alpha and H42\alpha images (Table 1). The calibrated visibility data were obtained by the calibration scripts that were provided by the ALMA East Asian Regional Center and processed using Common Astronomy Software Applications (CASA) (McMullin et al. 2007). We manually applied band-edge flagging and flux scaling for the data obtained in one specific execution block (uid__A002_Xb00ce7_X47b4). Eight channels were flagged at the band edge, whereas the original script flags 15 channels which included channels near the H40\alpha emission. In addition, the absolute flux was corrected by a factor of 1.115 since the continuum flux for this execution block was systematically lower than the others. The continuum emissions were subtracted using the \texttt{uvcontsub} task in \texttt{CASA}. The data cubes were produced by using the \texttt{tclean} task in \texttt{CASA} with the Briggs weighting (robust = 2.0; natural waiting), a velocity resolution of 50 km s\(^{-1}\), and a pixel size of 0\''125. The clean masks were selected by the automatic masking loop (sidelobethreshold = 2.0, noisethreshold = 2.5, lownoisethreshold = 1.5, minbeamfrac = 0.3, growiterations = 75, and negativethreshold = 0.0). The FOV of the ALMA map is 59\''4 at the sky frequency of H40\alpha emission. For ^13\text{CO} (1–0) imaging, we applied robust = 0.5 since the S/N is high enough. The continuum map was produced using the line-free channels beside the H40\alpha emission line. Table 2 is a summary of the achieved angular resolution and sensitivity for each line.

Figure 2 shows the HST optical color image\(^{14}\) and the integrated intensity map of H40\alpha and H42\alpha. Channel maps are shown in Figure 3 and the spectra are shown in Figure 4 for each region. We use H40\alpha line flux to derive physical parameters, because the image quality (i.e., angular resolution and sensitivity) is better than that of H42\alpha. In order to identify the H\textsc{ii} regions probed by the H40\alpha line, we use the \textit{imfit} task in \texttt{CASA} to fit elliptical Gaussian components on the integrated intensity map. H40\alpha is detected at the northern nucleus, southern nucleus, and northeastern peak with S/N of >10, >8, and >4, respectively. Table 3 is a summary of the coordinates, line flux, and source

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\(^{14}\) Based on observations made with the NASA/ESA HST, and obtained from the Hubble Legacy Archive, which is a collaboration between the Space Telescope Science Institute, the Space Telescope European Coordinating Facility, and the Canadian Astronomy Data Centre. The coordinates are manually corrected based on the positions of stars to compare ALMA images.
size (FWHM of major and minor axes) of the detected regions. Figure 5 shows the spatial distribution of \(^{13}\)CO (1–0) and 99 GHz continuum emission. Disk-wide distributions are seen in both \(^{13}\)CO (1–0) and the rest-frame 99 GHz continuum.

2.3. Line Profiles

Figure 6 shows the line profiles for each line, and the results of Gaussian fittings are shown in Table 4. We use 3D data cube (without extinction correction) obtained by ESO archive that is not processed by MAD project. The velocity range is consistent among each line. The peak velocity of H40\(\alpha\) emission at the southern nucleus is blueshifted compared with the \(\text{H}\alpha\) and \(\text{H}\beta\) lines, while the three lines have similar velocities at the northern nucleus and northeastern peak. This may mean that dusty star formation activities that H40\(\alpha\) can trace (but optical lines cannot) have different velocity components, yielding variation of the derived SFR between H40\(\alpha\) and \(\text{H}\beta\) lines. The velocity width is larger in the optical lines than in the mm ones. This is likely due to the lower S/N of the H40\(\alpha\) detection than optical line detections.

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Figure 2: (Top left) Optical color image of the entirety of NGC 3256 obtained by HST. Black contours show H40\(\alpha\) with 11 × (3, 4, 5, 6, 7, 8, 9) mJy beam\(^{-1}\) km s\(^{-1}\). A magenta square shows a central 20\" × 20\" region. (Top right) Integrated intensity map of H40\(\alpha\) image that achieves an angular resolution of 1\"48 × 1\"31. Contours are the same as in the left panel. The plus, X, and Y signs indicate the positions where H40\(\alpha\) is detected. (Bottom) Figures as in the top panels for H42\(\alpha\) results. Black contours indicate H42\(\alpha\) with 22 × (3, 4, 5, 6) mJy beam\(^{-1}\) km s\(^{-1}\). The achieved angular resolution is 2\"57 × 2\"05. We detect H42\(\alpha\) at the northern and southern nuclei with S/N of 5.
Figure 3. (Top) H40α channel map. The contour is 0.08 × (3, 4, 5, 6, 7) mJy beam$^{-1}$. The symbols are the same as those in Figure 1. The velocity offset from the systematic velocity is labeled. (Bottom) H42α channel map. The contour is 0.18 × (3, 4, 5) mJy beam$^{-1}$.
3. Analysis

3.1. SFR Diagnostic for Hydrogen Recombination Lines

The relation between ionizing photon rate \( Q \) (s\(^{-1}\)) and SFR \( (M_\odot \text{ yr}^{-1}) \) depends on the initial mass function (IMF), mass range of stellar IMF, and timescale \( (\tau) \) over which star formation needs to remain constant, and on stellar rotation effects. According to Bendo et al. (2016), SFR can be calculated using the relation of

\[
\frac{\text{SFR}}{M_\odot \text{ yr}^{-1}} = 5.41 \times 10^{-54} \left[ \frac{Q}{\text{s}^{-1}} \right].
\]
The calibration constant between SFRRL and recombination luminosity (Calzetti 2013). Finally, the relation between SFR and total line flux (Bendo et al. 2016) is

\[
\frac{\text{SFR}_{\text{RL}}}{\text{M}_\odot \text{ yr}^{-1}} = 2.16 \times 10^{-23} \left[ \frac{\alpha_B \text{ cm}^6}{\epsilon \text{ erg}} \right]^{0.79} \left[ \frac{\nu}{\text{GHz}} \right]^{1.22} \left[ \frac{D_L}{\text{Mpc}} \right] \left[ \frac{f_{\text{RL}} \text{ d}v}{\text{Jy km s}^{-1}} \right].
\]

The \( \alpha_B \) terms depend on electron temperature \( (T_e) \) and electron density \( (n_e) \), assuming case-B recombination. The \( \alpha_B \) values are listed in Storey & Hummer (1995). We fixed the \( n_e \) to \( 10^3 \text{ cm}^{-3} \), as the dependence is negligible in the range of \( 10^2-10^5 \text{ cm}^{-3} \) (Storey & Hummer 1995; Bendo et al. 2015).

We use an interpolated relation between \( \alpha_B \) and \( T_e \) (500 K–30,000 K) for hydrogen recombination:

\[
\frac{\alpha_B}{\text{cm}^3 \text{s}^{-1}} = (3.63 \times 10^{-10}) \left[ \frac{T_e}{500 \text{ K}} \right]^{-0.79}.
\]

The \( \epsilon \) values are also listed by Storey & Hummer (1995), and we fixed the \( n_e \) of \( 10^3 \text{ cm}^{-3} \) to use the interpolated relation between \( \epsilon \) and \( T_e \) (500 K–30,000 K). For example, in the case of optical, infrared, and millimeter recombination lines,

\[
\left[ \frac{\epsilon}{\text{erg s}^{-1} \text{cm}^{-3}/n_e n_p} \right] \\
\sim \begin{cases} 
(3.00 \times 10^{-22}) \left[ \frac{T_e}{\text{K}} \right]^{-1.30} & \text{(for H40a)} \\
(1.22 \times 10^{-21}) \left[ \frac{T_e}{\text{K}} \right]^{-0.89} & \text{(for H\alpha)} \\
(1.83 \times 10^{-22}) \left[ \frac{T_e}{\text{K}} \right]^{-0.80} & \text{(for H\beta)} \\
(3.36 \times 10^{-23}) \left[ \frac{T_e}{\text{K}} \right]^{-1.00} & \text{(for Br\gamma)}.
\end{cases}
\]

In order to estimate the electron temperature, 99 GHz flux density can be used. The free–free (bremsstrahlung) continuum emission can also be used to probe the ionized gas EM.
The spectra are taken at the H40α detected area (Table 3) at the (top) northern nucleus, (middle) southern nucleus, and (bottom) northeastern peak. Therefore, it is possible to calculate SFR from the 99 GHz flux density (Draine 2011; Scoville & Murchikova 2013; Bendo et al. 2016):

$$\frac{\text{SFR}}{M_\odot \text{ yr}^{-1}} = 9.49 \times 10^{10} g_{\text{ff}}^{-1} \left[ \frac{a_B}{\text{cm}^3 \text{s}^{-1}} \right]$$

$$\times \left[ \frac{T_e}{\text{K}} \right]^{0.5} \left[ \frac{D_L}{\text{Mpc}} \right]^{-1} \left[ \frac{f_{\text{cont}}}{\text{Jy}} \right].$$

(9)

$$g_{\text{ff}} = 0.5535 \ln \left[ \frac{T_e}{\text{K}} \right]^{0.5} \left[ \frac{\nu}{\text{GHz}} \right]^{-1} Z^{-1} - 1.682.$$  

(10)

Here, we assume an ionic charge of $Z = 1$. From Equations (6) and (9), the ratio of the line flux density integrated over velocity $v$ to the free–free flux density can be written as

$$R = \left[ \frac{f_{\text{cont}}}{\text{Jy} \text{ km s}^{-1}} \right] / \left[ f_{\text{cont}} \right]$$

$$= 4.38 \times 10^{33} g_{\text{ff}}^{-1} \left[ \frac{\nu}{\text{GHz}} \right] \left[ \frac{T_e}{\text{K}} \right]^{0.5}.$$  

(11)

The 99 GHz continuum emission is dominated by free–free emission in most cases (Saito et al. 2016). However, there is a possible contribution from nonthermal radio emissions and dust emissions. In order to check this contribution, we use the 5.0, 8.3, and 15 GHz continuum flux density measured by the Very Large Array (VLA) from the literature (Neff et al. 2003) and 200 GHz Band 6 data from archival ALMA data (Harada et al. 2018). Figure 7 shows the spectral energy density (SED) of the northern and southern nuclei. Three components can explain 1–300 GHz SED. The first component is the power law from nonthermal emission using the slope as a free parameter. The second is the free–free emission, which is scaled by the Gaunt factor (Equation (10)). The third component is dust emission with a slope of 4.0. Assuming $T_e = 5000$ K, the SED fittings show that the contribution of free–free emission at 99 GHz continuum flux density (frac-FF) is $\sim 76\%$ and $\sim 90\%$ at the northern and southern nuclei, respectively. We note that the values of frac-FF obtained by SED fitting are not significantly sensitive to the assumption of electron temperature. Therefore, the variation in electron temperature can be investigated by Equation (11). Subsequently, $a_B$, $\epsilon$, and SFR can be derived.

### 3.2. Molecular Gas Mass

Assuming optically thin emission and local thermodynamic equilibrium conditions, the molecular gas mass associated with H40α detected regions can be estimated from $^{13}$CO (1–0). It is better to use $^{13}$CO (1–0) than $^{12}$CO (1–0) when investigating very dusty regions in LIRGs, because the $^{13}$CO (1–0) line is most likely optically thick. It is assumed that the excitation

| Position          | Line       | Velocity Offset (km s$^{-1}$) | FWHM (km s$^{-1}$) |
|-------------------|------------|------------------------------|--------------------|
| Northern nucleus  | Hα         | -10                          | 280                |
| Northern nucleus  | Hβ         | -10                          | 310                |
| Northern nucleus  | H40α       | 0                            | 180                |
| Northern nucleus  | $^{13}$CO (1–0) | -20                       | 140                |
| Southern nucleus  | Hα         | 30                            | 260                |
| Southern nucleus  | Hβ         | 30                            | 280                |
| Southern nucleus  | H40α       | -60                          | 250                |
| Southern nucleus  | $^{13}$CO (1–0) | 20                        | 170                |
| Northeastern peak | Hα         | 80                            | 170                |
| Northeastern peak | Hβ         | 80                            | 220                |
| Northeastern peak | H40α       | 70                            | 120                |
| Northeastern peak | $^{13}$CO (1–0) | 70                        | 90                 |

Note. The MUSE spectral resolution of 1.25 Å corresponds to the velocity resolutions of $\sim 57$ km s$^{-1}$ for Hα and $\sim 77$ km s$^{-1}$ for Hβ. In the case of ALMA observations, the velocity resolution is 50 km s$^{-1}$.
temperature of 10 K (Harada et al. 2018) and the \(^{12}\)CO/\(^{13}\)CO ratios \((R_{12/13})\) of \(~100\) (Henkel et al. 2014) are constant. Finally, we use the equation
\[
\frac{M_{\text{H}}}{M_\odot} = 0.41 R_{12/13} \frac{L^{13\text{CO}}_{\text{K km s}^{-1} pc^{-2}}}{10^{11} L_\odot}
\]
when we derive molecular gas mass from \(^{13}\)CO luminosity (Battisti & Heyer 2014). Table 5 shows the information of gas mass in each region.

### 3.2.1. Total Infrared Luminosity

The total far-infrared luminosity \((L_{\text{IR}})\) of \((4.8 \pm 0.2) \times 10^{11} L_\odot\) (5–1100 µm) for NGC 3256 is calculated using Spitzer and Hershel observations of 24, 70, 100, 160, and 250 µm flux density. \(S_{24} = 12.6 \pm 0.25\) Jy (Engelbracht et al. 2008), \(S_{70} = 120.3 \pm 6.0\) Jy, \(S_{100} = 145.4 \pm 6.8\) Jy, \(S_{160} = 93.48 \pm 4.68\) Jy, and \(S_{250} = 93.48 \pm 4.68\) Jy (Chu et al. 2017). The calibration coefficients derived by Galametz et al. (2013) are used to calculate \(L_{\text{IR}}\). The TIR luminosity (8–1000 µm) calculated using the IRAS flux and coefficients (Sanders & Mirabel 1996; Sanders et al. 2003) is \(~4.97 \times 10^{11} L_\odot\). We use the former value in the following sections since the two values are consistent within the error.

#### 3.3. Results

The dust-extinction-corrected H\(^{\beta}\) map (Figure 1(b)) shows disk-wide starbursts. The total SFR based on the H\(^{\beta}\) map is \(SFR_{\text{H}^{\beta}} \sim 40 \pm 2 M_\odot\) yr\(^{-1}\), assuming \(T_e = 5000\) K. The SFR measured by H\(^{\beta}\) is insensitive to \(T_e\), as the relations of \(\alpha_{\text{H}^{\beta}}-T_e\) and \(\epsilon-T_e\) have similar indexes of \(~0.8\) (Equations (6)-(8)). However, this value likely underestimates the total SFR due to dust extinction. Table 6 shows the SFR at star-forming regions where H40\(\alpha\) is detected. A conservative overall photometric error of 5\% is adopted.\(^\text{15}\) The SFRs of the three detected regions measured by H40\(\alpha\) emissions are \(SFR_{\text{H}40\alpha} = 9.8 \pm 0.5\), \(SFR_{\text{H}40\alpha}^\text{NE} = 6.8 \pm 0.3\), and \(SFR_{\text{H}40\alpha}^\text{S} = 9.8 \pm 0.05\) M\(_\odot\) yr\(^{-1}\). In contrast, the SFRs of these regions measured by extinction-corrected H\(^{\beta}\) data are \(SFR_{\text{H}^{\beta}}^\text{NE} \sim 6.8 \pm 0.1\), \(SFR_{\text{H}^{\beta}}^\text{S} \sim 1.7 \pm 0.1\), and \(SFR_{\text{H}^{\beta}}^\text{NE} \sim 0.47 \pm 0.02\) M\(_\odot\) yr\(^{-1}\). The systematically lower SFR derived from the H\(^{\beta}\) line suggests the presence of intervening dust, especially in the southern nucleus.

Finally, the total SFR \((SFR_{\text{total}})\) is calculated as \(SFR_{\text{total}} = (SFR_{\text{H}^{\beta}} + SFR_{\text{H}^{\beta}}^\text{NE} + SFR_{\text{H}^{\beta}}^\text{S} + SFR_{\text{H}^{\beta}}^\text{SFR})\). The total SFR from pure H\(_\beta\) regions is calculated as \(~40 M_\odot\) yr\(^{-1}\), which is consistent with \(SFR_{\text{total}}\) derived by this project. The total SFR from TIR luminosity \((L_{\text{TIR}} = (4.8 \pm 0.2) \times 10^{11} L_\odot)\) is \(51.5 \pm 2.6 M_\odot\) yr\(^{-1}\), assuming a young starburst (100 Myr), Kroupa IMF, and a mass range of 0.1–100 M\(_\odot\) (Calzetti 2013). The comparison between hydrogen recombination lines and TIR luminosity is investigated in Section 4.4 in terms of the starburst age.

Figure 8 shows the relation between SFR derived by H\(^{\beta}\) and free–free emission. The SFR traced by free–free emission is systematically higher than SFR from H\(^{\beta}\), which suggests the contamination from synchrotron and/or dust in the 99 GHz continuum flux density. The typical frac-FF can be roughly estimated from the ratio of the SFRs derived by the H\(^{\beta}\) and free–free emission. The mean value of the ratio is \(~0.7\),

| Position          | \(\frac{\int L_{\text{CO}} d\nu}{(\text{Jy km s}^{-1})}\) | \(M_\odot\) | \(\Sigma_{\text{H2}}\) |
|-------------------|------------------------------------|-------------|---------------|
| Northern nucleus  | 6.06 ± 0.3                         | 14.2 ± 0.7  | 1756 ± 88  |
| Southern nucleus  | 4.79 ± 0.24                        | 11.2 ± 0.6  | 2091 ± 105 |
| Northeastern peak | 0.66 ± 0.03                        | 1.5 ± 0.1   | 1666 ± 83  |

Note. The flux is measured by the same aperture as in Table 6. If we use the source size in Table 3, the surface density \(\Sigma_{\text{H2}}\) is \(2772 ± 139, 2936 ± 147, 1769 ± 88 M_\odot\) pc\(^{-2}\) for the northern nucleus, southern nucleus, and northeastern peak, respectively.
indicating the typical frac-FF of ~70%. This fraction is consistent with the frac-FF of typical starburst galaxies such as NGC 253 (Bendo et al. 2015). While uncertainties in the dust extinction correction exist, we adopt the SFR derived using the Hβ line in the following sections because the S/N is higher than the 99 GHz continuum map. In Section 4.3, we investigate the possible regions where Hβ may underestimate the SFR outside the southern nucleus.

4. Discussion

The key questions we endeavor to answer are: (i) “What is the fraction of star formation missed by optical and infrared observations (e.g., Hα, Hβ, and Brγ)”; (ii) “What is the fraction of the nuclear starburst that contributes to the total SFR?”; (iii) “Can the variation of gas depletion time be seen within NGC 3256?”; and (iv) “How long is the starburst timescale in NGC 3256?” Finally, we investigate the properties of HII regions (i.e., electron temperature) in H40α detected regions.

4.1. Northern Nucleus

The northern nucleus contains the largest (area = 0.38 ± 0.01 kpc²) H40α nebula of the three identified (Table 3). The derived SFR is SFRH40α = 9.8 ± 0.5 Msol yr⁻¹, which is ~20% of the total SFR. The SFR derived from Hβ is SFRHβ = 6.8 ± 0.3 Msol yr⁻¹, and this is ~70% of the SFR derived from H40α (Table 6). This difference may be explained by insufficient dust extinction correction which was performed using optical lines alone (i.e., the conversion from Hα/Hβ ratio to Aν). The star formation rate surface density (Σinner SFRH40α) is 32.9 ± 1.6 Msol yr⁻¹ kpc⁻², and the molecular gas mass surface density (Σinner H2) around the northern nucleus is 2772 ± 139 Msol pc⁻², which is a typical disk-averaged surface density for starburst galaxies (Kennicutt 1998). This suggests that the characteristics of the HII regions near the northern nucleus are consistent with regions in typical starburst galaxies.

4.2. Southern Nucleus

Despite the significant H40α emission, there is no strong emission in the extinction-corrected Hβ map at the southern nucleus (Figure 1(c)). Consequently, the SFR derived from H40α (SFRH40α = 6.8 ± 0.3 Msol yr⁻¹) is larger than that derived from the Hβ map (SFRHβ = 1.75 ± 0.09 Msol yr⁻¹). This suggests that the optical emission around the southern nucleus does not originate from extremely dust-obscured nebulae emission; rather, it may be contributed from the different components (e.g., the surface of the dusty star-forming region). In addition, the offset in the H40α line profile relative to the Hα and Hβ lines in the southern nucleus (Table 4 and Figure 6) may be evidence showing that millimeter and optical lines trace different components. This demonstrates the benefits of examining both the spectral line parameters as well as the integrated fluxes when investigating dusty starbursts at the nucleus of ultra/luminous infrared galaxies (ULIRGs).

Emission lines in IR can also be used as an independent proxy of SFR in galaxies. The southern nucleus can be detectable at a wavelength > 1 μm (López et al. 2012, 2013) detected Brγ emission from the southern nucleus of NGC 3256 (the northern nucleus is not in the FOV) using the Spectrograph for Integral Field Observations in the Near Infrared integral field spectroscopy observation with VLT. We use the Brγ data obtained from an online catalog (Piqueras-López et al. 2016) and measured the Brγ to be ~6.3 × 10⁻¹⁵ erg s⁻¹ cm⁻² at the southern nucleus. Assuming ABrγ ∼ 1.2 estimated from the Brγ/Brβ ratio (Piqueras-López et al. 2013), we find that the SFR estimated from Brγ (SFRBrγ) is 1.4 Msol yr⁻¹. The significantly lower SFR derived from Brγ suggests that it may not be an ideal tracer of SFR in dusty regions, such as the southern nucleus of NGC 3256. The comparison between Brγ and H40α flux indicates ABrγ ∼ 2.4 (Aν ~ 25 assuming ABrγ = 0.096 Aν).

4.3. Disk-wide Starburst

The sum of the nuclear starbursts in the northern and southern nuclei derived from the H40α data is 16.6 ± 0.6 Msol yr⁻¹. Using the total SFR of ~48 ± 2 Msol yr⁻¹ (Section 3.3), the contributions of the nuclear and disk-wide starbursts are ~34% and ~66%, respectively. In addition, H40α is detected at northeastern peak (Figure 2) on the dust lane of the arm that has offset from the two nuclei.

Figure 9(a) shows that star-forming regions in NGC 3256 have large scatter in the ΣHν–ΣSFR Plane, particularly in the regions with τgas of <0.1 Gyr as well as regions with τgas of >0.4 Gyr outside the nuclear region (the gas depletion time τgas = Mgas/SFR). This large scatter suggests a nonuniform gas depletion time. In addition, from a direct comparison with the results from a broadband spectral survey of NGC 3256 (Harada et al. 2018), we find that shock gas tracers (e.g., CH3OH, SiO, HNCO) are coincident with the regions where τgas is long. Figure 9(b) shows the spatial distribution of τgas and the contours show the CH3OH (2ν–1ν) emission. Figure 9(c) shows the relation between CH3OH (2ν–1ν) CO (1–0) and τgas. The Spearman’s rank correlation coefficient (c-value) is 0.315, possibly suggesting a weak correlation. The probability (p-value) is 0.002, which means that the possibility for rejecting
Using Hβ and $^{13}$CO(1-0)

![Image](https://example.com/image)

Using free-free and $^{13}$CO(1-0)

![Image](https://example.com/image)

Figure 9. (a) Pixel-by-pixel analysis for an empirical star formation relation ($\Sigma_{eff} - \Sigma_{map}$). A pixel corresponds to 1\" $\times$ 1\". The red, green, and blue stars indicate the SFR measured by H40a at the northern nucleus, southern nucleus, and northeastern peak, respectively, in Tables 5 and 6 (the +, X, and Y signs in Figures 1 and 2). The red, green, and blue diamonds indicate the SFR based on the Hβ map for the northern nucleus, southern nucleus, and northeastern peak, respectively. The cyan, orange, and yellow circles indicate the pixels with $\tau_{gas} [\mathrm{Gyr}] < 0.1$, $0.1 \leq \tau_{gas} [\mathrm{Gyr}] \leq 0.4$, $\tau_{gas} [\mathrm{Gyr}] > 0.4$, respectively. The SFR for each point is calculated using Hβ emission. (b) Spatial information of $\tau_{gas}$ and CH$_3$OH (2–1) emission. The cyan, orange, and yellow squares indicate the positions for the pixels with $\tau_{gas} [\mathrm{Gyr}] < 0.1$, $0.1 \leq \tau_{gas} [\mathrm{Gyr}] \leq 0.4$, $\tau_{gas} [\mathrm{Gyr}] > 0.4$, respectively. The red, green, and blue stars indicate the respective stars in (a). The cyan contours show the distribution of CH$_3$OH (2–1) at 0.013 $\times$ (3, 6, 12, 24) $\mathrm{km \ s^{-1}}$. (c) Relation between CH$_3$OH (2–1) and CO (1–0) and $\tau_{gas}$. The Spearman’s rank correlation coefficient and $p$-values are shown. (d–f) Same figures as (a–c) but with the SFR measured by free-free emission. The SFR from free-free emission is measured by assuming frac-FF = 70%.

Table 6

| Position          | $\int f_{H40a} \, dv^a$ (mJy km s$^{-1}$) | $f_{cont}^b$ (mJy) | $R$ (km s$^{-1}$) | $T_e$ (K) | SFR$^{H40a}$ (M$_{\odot}$ yr$^{-1}$) | $\Sigma_{SFR_{H40a}}^c$ (M$_{\odot}$ yr$^{-1}$ kpc$^{-2}$) | $\int f_{cont} \, dv$ (10$^{-13}$ erg s$^{-1}$ cm$^{-2}$) | SFR$^{cont}$ (M$_{\odot}$ yr$^{-1}$) |
|-------------------|---------------------------------------|-------------------|-----------------|---------|-----------------------------------|------------------------------------------------|-------------------------------|---------------------|
| Northern nucleus  | 273 ± 14                              | 6.36 ± 0.32       | 43 ± 3          | 5900$^{+400}_{-400}$ | 9.8 ± 0.5                         | 12.1 ± 0.6                                            | 28.6 ± 1.4                                               | 6.82 ± 0.34          |
| Southern nucleus  | 143 ± 7                               | 5.96 ± 0.30       | 24 ± 2          | 10200$^{+700}_{-600}$ | 6.8 ± 0.3                         | 12.7 ± 0.6                                            | 7.3 ± 0.4                                                | 1.75 ± 0.09          |
| Northeastern peak | 26 ± 1                                | 0.66 ± 0.03       | 40 ± 3          | 6300$^{+400}_{-400}$ | 0.98 ± 0.05                        | 10.7 ± 0.5                                            | 2.0 ± 0.1                                                | 0.47 ± 0.02          |

Notes.

a The flux in this table is measured by an aperture 2.5 times larger than the source size shown in Table 3 to cover all the flux from the northern and southern nuclei. However, the H40a emission at the northeastern peak is not spatially resolved, and an aperture 1.2 times larger than the source size is applied.

b The 99 GHz continuum flux is corrected using frac-FF of 76%, 90%, and 80% at the northern nucleus, southern nucleus, and northeastern peak, respectively.

c The surface density is measured by the aperture shown in Table note a. If we measure the surface density inside the source size shown in Table 3, $\Sigma_{SFR_{cont}} = 32.9 \pm 1.6, 36.2 \pm 1.8,$ and $12.0 \pm 0.3$ M$_{\odot}$ yr$^{-1}$ kpc$^{-2}$ for the northern nucleus, southern nucleus, and northeastern peak, respectively.
the null hypothesis is 2%. These suggest that merger-induced large-scale shock can possibly suppress the star formation activity in the disk region, although the statistical significance is not very strong. Figures 9(d)–(f) are similar to (a)–(c) but plotted using the SFR measured by the 99 GHz continuum after correcting for the contamination from dust and nonthermal emission (assuming 70%) (see also Wilson et al. 2019). Even after correcting frac-FF, a few regions have \( \tau_{\text{gas}} > 0.4 \text{ Gyr} \), suggesting that an extinction-corrected H\( \beta \) map underestimates SFR due to incomplete extinction correction. Alternatively, frac-FF for the 99 GHz continuum is much lower than 70%. It is, however, noteworthy that a possible correlation between CH\(_3\)OH and metallicity suggests regions with lower metallicity are higher in electron temperature (Shaver et al. 1983), which is a direct consequence of inefficient cooling in low-metallicity regions (Pagel et al. 1979). Our analysis of NGC 3256 suggest that the metallicity of the extremely dusty (\( \text{A}_V \sim 25 \)) southern nucleus is lower than that of the non-dusty regions where UV and optical emission lines can be detected. Low-metal environments are seen in other galaxies. For example, Kewley et al. (2006), Ellison et al. (2013) show that the metallicity in interacting galaxies tends to be lower than in noninteracting systems of equivalent mass, and later Rupke et al. (2008) and Herrera-Camus et al. (2018) find the same trend for U/LIRGs. The low metallicity at the southern nucleus may suggest the past occurrence of a large-scale inflow of metal-poor gas. Other possibilities for the low metallicity include massive outflows (Sakamoto et al. 2014; Michiyama et al. 2018) which can remove gas and metals (e.g., Chisholm et al. 2018).

The free–free emission flux is comparable between the northern and southern nucleus, while the recombination line flux at the southern nucleus is about half of the northern nucleus. An empirical relation between electron temperature and metallicity suggests regions with lower metallicity are higher in electron temperature (Shaver et al. 1983), which is a direct consequence of inefficient cooling in low-metallicity regions (Pagel et al. 1979).

4.4. Starburst Timescale

The calibration constant between SFR and \( L_{\text{TIR}} \) changes depending on how long the currently observed starbursts have remained constant, because not only the young stellar population but also old, long-lived, low-mass stars contribute to \( L_{\text{TIR}} \). If the calibration constant is correct, the SFR estimated from \( L_{\text{TIR}} \) should be the same as \( \text{SFR}_{\text{RL}} \). Assuming constant star formation and a Kroupa IMF in the stellar mass range of 0.1–100 \( M_\odot \), the ratio of \( \text{SFR}_{\text{RL}} \) to \( L_{\text{TIR}} \) is calculated as below (Calzetti 2013):

\[
\frac{\text{SFR}_{\text{RL}} [M_\odot \text{ yr}^{-1}]}{L_{\text{TIR}} [\text{erg s}^{-1}]} = \begin{cases} 
1.6 \times 10^{-44} & (\tau = 10 \text{ Gyr}) \\
2.8 \times 10^{-44} & (\tau = 100 \text{ Myr}) \\
3.7 \times 10^{-44} & (\tau = 10 \text{ Myr}).
\end{cases}
\]

The \( \text{SFR}_{\text{RL}} \) of NGC 3256 is 48 \( \pm 2 \) \( M_\odot \) yr\(^{-1}\), estimated using the H\( \beta \) and H\( 40\alpha \) maps. Using this \( \text{SFR}_{\text{RL}} \) and \( L_{\text{TIR}} \) of \((4.8 \pm 0.2) \times 10^{11} L_\odot \) (Sanders et al. 2003), the ratio between \( \text{SFR}_{\text{RL}} \) and \( L_{\text{TIR}} \) is estimated to be \((2.63 \pm 0.17) \times 10^{-44}\). This is similar to the theoretical value for \( \tau = 100 \) Myr, suggesting that the current starburst has continued for \( \sim 100 \) Myr. This period is shorter than the age of the merger of NGC 3256 (\( \sim 500 \) Myr; Lípari et al. 2000). Thus, it is likely that the current starburst in NGC 3256 was triggered by the galaxy interaction.

4.5. Electron Temperature Variations

The electron temperatures are calculated using Equation (11). The electron temperature around the northern nucleus is 5900 \( \pm 400 \) K. This value is consistent with H\( \text{H}_\text{II} \) regions at the central part (<4 kpc) of the Milky Way (Shaver et al. 1983) and other starburst galaxies (e.g., NGC 253 and NGC 4945) (Bendo et al. 2015, 2016). In contrast, the electron temperature around the southern nucleus is 11500 \( \pm 800 \) K, which is consistent with the H\( \text{H}_\text{II} \) regions in the outer part of the Milky Way (>10 kpc). The different electron temperatures between the northern and southern nucleus is originally from the different line ratios of \( R = \int f_{\text{line}} dv / f_{\text{cont}} \).

The origin of recombination line flux may be related to the presence of an active galactic nucleus (AGN), especially at the southern nucleus. The presence of an AGN is suggested from the IRAC\(^{17} \) color and silicate absorption feature (Ohyama et al. 2015). The possible AGN is categorized as a low-luminosity AGN with the \( 2–10 \text{ keV} \) luminosity of \( L_{2–10\text{keV}} \sim 2 \times 10^{40} \) erg s\(^{-1} \) (Lémer et al. 2015; Ohyama et al. 2015). In order to explain the molecular outflows from the southern nucleus, a previously active AGN is needed (Sakamoto et al. 2014; Michiyama et al. 2018). If the AGN ionizes the surrounding gas, the velocity dispersion of hydrogen recombination lines is nominally \( >1000 \) km s\(^{-1} \). However, the line profile at the southern nucleus has the same line width as that of the northern nucleus (\( \sim 300 \) km s\(^{-1} \)) (Table 4 and Figure 6). In addition, Izumi et al. (2016) show that the expected line flux of millimeter hydrogen recombination lines is too low to be detected even by ALMA. Therefore, the H\( 40\alpha \) emission is likely originated from star formation activity at the southern nucleus.

The AGN may enhance the TIR luminosity independent of star formation activities. In such a case, the expected starburst timescale is shorter than those derived in Section 4.4. Finally, a higher electron temperature in the southern nucleus could be due to previous AGN activities. For example, Popović (2003) estimated an electron temperature of \( >10,000 \) K in broad line regions based on the Boltzmann plot method to Balmer lines, which is higher than the typical electron temperature at the typical H\( \text{II} \) regions (e.g., Shaver et al. 1983).

5. Summary

In order to show evidence of the large contribution of disk-wide starbursts to the total SFR in a merging galaxy, NGC 3256, we investigated spatially resolved SFR using optical and millimeter hydrogen recombination lines. At first, we used optical IFUs (MUSE mounted on VLT) to obtain maps of recombination lines (i.e., H\( \alpha \) and H\( \beta \)). We found many

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\(^{17}\) Infrared Array Camera on the Spitzer Space Telescope.
star-forming regions outside the nuclear regions. However, it is difficult to investigate star formation activities in dusty nuclear regions using optical observations. ALMA observation of the millimeter recombination lines H40α and H42α allowed us to quantify the true star formation activity in these regions. The total SFR obtained by H3 and H40α line emission is ∼48 ± 2 M⊙ yr⁻¹. The main findings are as follows:

1. H40α emission is detected at the northern nucleus, southern nucleus, and northeastern peak. However, there are no bright H3 emissions at the southern nucleus. The SFR from the southern dusty region is 6.8 ± 0.3 M⊙ yr⁻¹, which is ∼14% of the total SFR.

2. The sum of the nuclear starbursts in the northern and southern nuclei is 16.6 ± 0.6 M⊙ yr⁻¹, which means that the contributions of the nuclear and disk-wide starbursts are ∼34% and ∼66%, respectively. The disk-wide starbursts are predominant compared to the nuclear starbursts, even considering the very dusty starburst seen in the southern nucleus.

3. We find that τgas is not uniform in NGC 3256. There are regions with τgas < 0.1 Gyr as well as regions with τgas ≈ 0.4 Gyr outside the nuclear region. One possible explanation is merger-induced large-scale shocks that suppress star formation activities in the disk region.

4. Recombination lines and total FIR luminosity suggest the current starburst started ∼100 Myr ago. This is shorter than the timescale of a merger process (∼500 Myr), and this supports the idea that the current starbursts are triggered by a merger process.

5. The electron temperature is higher in the dusty southern nucleus (10200±600 K) than in the nondusty northern nucleus (5900±500 K). One possible explanation is the lower metallicity in the southern nucleus than in the northern nucleus, suggesting metal-poor gas inflows or metal-rich gas outflows at the southern nucleus.

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