The Nuclear Region of NGC 1365: Star Formation, Negative Feedback, and Outflow Structure

Yulong Gao1,2,3,4,5, Fumi Egusa3, Guilin Liu1,2, Kotaro Kohno3, Min Bao3,4,6, Kana Morokuma-Matsu4,6, Xiu Kong1,2,7, and Xiaoyang Chen8

1 CAS Key Laboratory for Research in Galaxies and Cosmology, Department of Astronomy, University of Science and Technology of China, Hefei 230026, People’s Republic of China; ylgao@mail.ustc.edu.cn, glliu@ustc.edu.cn
2 School of Astronomy and Space Science, University of Science and Technology of China, Hefei 230026, People’s Republic of China
3 Institute of Astronomy, The University of Tokyo, Otsawa 2-21-1, Mitaka, Tokyo 181-0015, Japan; egusa@ia.s.u-tokyo.ac.jp
4 Department of Astronomy, Nanjing University, Nanjing 210009, People’s Republic of China
5 Key Laboratory of Modern Astronomy and Astrophysics (Nanjing University), Ministry of Education, Nanjing 210093, People’s Republic of China
6 School of Physics and Technology, Nanjing Normal University, Nanjing 210023, People’s Republic of China
7 Frontiers Science Center for Planetary Exploration and Emerging Technologies, University of Science and Technology of China, Hefei, Anhui, 230026, People’s Republic of China
8 National Astronomical Observatory of Japan, National Institutes of Natural Sciences, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan

Received 2020 September 1; revised 2021 March 30; accepted 2021 April 10; published 2021 June 4

Abstract

High-resolution observations of ionized and molecular gas in the nuclear regions of galaxies are indispensable for delineating the interplay of star formation, gaseous inflows, stellar radiation, and feedback processes. Combining our new Atacama Large Millimeter/submillimeter Array band 3 mapping and archival Very Large Telescope/MUSE data, we present a spatially resolved analysis of molecular and ionized gas in the central 5.4 kpc region of NGC 1365. We find the star formation rate/efficiency (SFR/SFE) in the inner circumnuclear ring is about 0.4%/1.1 dex higher than in the outer regions. At a linear resolution of 180 pc, we obtain a superlinear Kennicutt–Schmidt law, demonstrating a steeper slope (1.96 ± 0.14) than previous results presumably based on lower-resolution observations. Compared to the northeastern counterpart, the southwestern dust lane shows lower SFE, but denser molecular gas and larger virial parameters. This is consistent with an interpretation of negative feedback from an active galactic nucleus (AGN) and/or starburst, in the sense that the radiation/winds can heat and interact with the molecular gas even in relatively dense regions. After subtracting the circular motion component of the molecular gas and the stellar rotation, we detect two prominent noncircular motion components of molecular and ionized hydrogen gas, reaching a line-of-sight velocity of up to 100 km s⁻¹. We conclude that the winds or shocked gas from the central AGN may expel the low-density molecular gas and diffuse ionized gas on the surface of the rotating disk.

Unified Astronomy Thesaurus concepts: Starburst galaxies (1570); Seyfert galaxies (1447); Galaxy kinematics (602)

1. Introduction

The star formation mechanism in galactic environments is of fundamental importance to understand the formation and evolution of galaxies, such as gas depletion, metal enrichment, and the accumulation of stellar mass. Meanwhile, star formation results from the interplay of a series of perplexing processes and interactions, including the geometrical, dynamical, and chemical aspects of the interstellar medium (ISM), as well as feedback from young stellar objects, supernovae, and active galactic nuclei (AGNs).

In barred spiral galaxies, star formation activity often behaves differently in the spiral arms, interarm, and bar regions (e.g., Foyle et al. 2010; Momose et al. 2010; Eden et al. 2013). Optical and sub/millimeter observations show that young stars and molecular gas clouds are concentrated in the spiral arms, harboring higher star formation rate (SFR) densities and molecular gas densities. The cloud–cloud collisions in spiral arms and the gravitational collapse in giant molecular clouds (GMCs) are suggested to trigger star formation (Elmegreen & Elmegreen 1983, 2019; Dobbs 2008; Jefferson & Kruisjen 2018). However, some observations (e.g., Foyle et al. 2010; Eden et al. 2012, 2015; Kreckel et al. 2016) show that the difference in star formation efficiency (SFE) between arm and interarm regions is insignificant. In nuclear regions, star formation can also be affected by outflows and radio jets from the central AGN, for which two opposite scenarios have been proposed. On one hand, the energy from an AGN may prevent the gas from cooling (Fabian 1994), and massive and powerful outflows will sweep out gas from their host galaxies (Fabian 2012; Cheung et al. 2016; Harrison et al. 2018), therefore star formation will be suppressed (i.e., negative feedback). On the other hand, star formation in some high-density regions of the host galaxy will be triggered or enhanced by the outflows, because cold gas is compressed both in the galactic disk and in outflow regions (i.e., positive feedback, Silk 2013; Cresci et al. 2015; Maiolino et al. 2017; Gallagher et al. 2019). Delineating the impact of AGN feedback on star formation is a long-standing challenge. Recently, using the Very Large Telescope (VLT)/MUSE and the Atacama Large Millimeter/submillimeter Array (ALMA) data, Shin et al. (2019) have presented a spatially resolved analysis of ionized and molecular gas, reporting both negative and positive feedback in the nearby Seyfert 2 galaxy NGC 5728.

An empirical scaling relation known as the Kennicutt–Schmidt law (or the K-S law) that links the surface densities of SFR ($\Sigma_{\text{SFR}}$) and molecular gas ($\Sigma_{\text{H}_2}$), formulated as a single power law, $\Sigma_{\text{SFR}} \propto \Sigma_{\text{H}_2}^\alpha$, has been well established (Schmidt 1959; Kennicutt 1998). Thanks to the development of relevant instrumentation, extensive works (Kennicutt et al. 2007; Bigiel et al. 2008;
Momose et al. 2010, 2013; Liu et al. 2011; Xu et al. 2015; Azeez et al. 2016; Wilson et al. 2019) have been undertaken, with a focus on the spatially resolved K-S law by measuring the SFR and gas properties at subkiloparsec scales. Bigiel et al. (2008) find that the slope (N) of the K-S law is nearly 1.0 at 750 pc resolution, while Kennicutt et al. (2007) obtained $N \sim 1.56$ for spiral galaxy M51 at 520 pc scales, where the linear versus superlinear discrepancy is quantitatively explained by Liu et al. (2011). For spiral galaxies, Momose et al. (2010) find the SFEs in arm regions to be twice those in the bar regions, and the K-S law appears to break down at 250 pc resolution. Liu et al. (2011) and Momose et al. (2013) remove the local diffuse emission in the H$\alpha$ and mid-infrared images, achieving a superlinear K-S law. In M51a and NGC 3521, Liu et al. (2011) also derive the variation of the slope as a function of linear resolution (250 pc–1 kpc) and find that the slope increases monotonically with increasing resolution.

The wide variety of K-S laws found in different populations of galaxies using different tracers and spatial resolutions may be interpreted in terms of two theoretical frameworks of star formation in molecular gas. One is the density threshold model (e.g., Gao & Solomon 2004; Wu et al. 2005; Lada et al. 2010, 2012; Evans et al. 2014), which suggests that the fraction of dense gas in molecular clouds is a key factor, and thus a linear correlation between SFRs and dense gas surface densities is found ($\Sigma_{\text{gas}} \gtrsim 116 M_\odot \text{pc}^{-2}$, Lada et al. 2010). The other is a turbulent model (e.g., Krumholz & McKee 2005; Krumholz & Thompson 2007; Federrath & Klessen 2012), which is based on integrals over the log-normal distribution of turbulent gas. Krumholz & Thompson (2007) find that the slope of the K-S law is dependent on the choice of molecular line tracers, such as CO(1–0), HCO$^+$ (1–0), and HCN(1–0), because different transition lines trace regions of different densities. Federrath & Klessen (2012) conclude that SFR in molecular clouds is controlled by interstellar turbulence and magnetic fields. Recently, some studies (e.g., García-Burillo et al. 2012; Usero et al. 2015; Querejeta et al. 2019; Genzel et al. 2020) have found that the density threshold model is partly incompatible with the observed SFEs for dense gas, and suggest that the dynamical effects in local and global environments should be taken into account as well.

In the nuclear kiloparsec region, Xu et al. (2015) reported the breaking down of the K-S law at 100 pc scale in NGC 1614, in which the higher SFEs are probably triggered by feedback from the central starburst. However, when focusing on the peaks of molecular and ionized gas at smaller scales, Krujssen et al. (2019) reported that SFE has two different branches, implying that the star formation in galactic GMCs is fast and inefficient because of the rapid feedback from radiation and stellar winds. The complication of the relation between star formation and molecular/ionized ISM is evident in spiral galaxies, especially in the circumnuclear kiloparsec region where a central AGN is present. High-resolution mapping of ionized and molecular gas in the nuclear regions is indispensable for unraveling the entanglements between star formation, gas inflows in the spiral arm, radiation, and outflows from AGNs.

NGC 1365 is a nearby ($z = 0.0054$, at a distance of 21.2 Mpc, where $1'' \sim 90$ pc) archetypical barred spiral (SBb(s)) Seyfert 1.8 galaxy with a stellar mass of $\sim 3.6 \times 10^{11} M_\odot$, and is a member of the Fornax cluster (Lindblad 1999). It harbors a low-luminosity AGN with $L_{\text{bol}} \sim 2 \times 10^{44}$ erg s$^{-1}$, exhibiting a biconical outflow and intense star formation in its central regions (e.g., Galliano et al. 2005, 2008, 2012; Sakamoto et al. 2007; Elmegreen et al. 2009; Wang et al. 2009;Venturi et al. 2018; Fazeli et al. 2019).

The position of the central AGN that we adopt is $\alpha = 03^h33^m36^s.35, \delta = -36^\circ08'25''.8$, the systemic velocity, position angle (PA), and inclination angle are taken to be $1618 \text{ km s}^{-1}$, $220^\circ$, and $40^\circ$, respectively, following the parameter-setting in Sakamoto et al. (2007). A pair of dark dust lanes are located in front of the nuclear region and partially obscure the nucleus. Star formation and young massive star clusters are predominantly distributed in an elongated circumnuclear ring. Recently, Fazeli et al. (2019) presented a detailed study about the properties and kinematics of star and warm/hot gas in the central 800 pc of NGC 1365 by near-infrared integral-field observations from VLT/SINFONI. However, the impacts of strong outflows from AGNs or stellar winds from starbursts on the gas consumption and star formation in NGC 1365 remain unexplored. In this work, with the facilitation of our new high-resolution sub/millimeter ALMA mapping and archival optical VLT/MUSE data, we investigate the connection between star formation, radiation, and inflows/outflows at subkiloparsec scales in the central $\sim 1' \times 1'$ (5.4 kpc $\times 5.4$ kpc) region of this galaxy.

This paper is organized as follows. In Section 2, we describe the observations and data reduction. The properties of the molecular and ionized gas are analyzed in Section 3. The main results and discussion are presented in Sections 4 and 5, respectively, along with a summary in Section 6. We adopt a flat $\Lambda$CDM cosmological model throughout this work, $\Omega_\Lambda = 0.7$, $\Omega_m = 0.3$, and $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

2. Observations and Data Reduction

2.1. ALMA Data

NGC 1365 has been observed multiple times with ALMA in previous cycles. In this work, we map it in the CO ($J = 1$–0) line, a cold molecular gas tracer, which falls in band 3 (Table 1). CO data of higher rotational transitions are also available in the ALMA archive, but we prefer to avoid complications in determination of gas mass caused by heterogeneous excitation conditions. In band 3, the 12 m array observing campaign was undertaken on 2016 March 20 (ID: 2015.1.01135.S, PI: Egusa). The integration time is about 1 minute per mosaic point (135 points in total). The correlator with a bandwidth of 468.7 MHz in spectral mode is adjusted to a central frequency of $\sim 115.27$ GHz, so that the CO($J = 1$–0) line is covered. The 7 m array campaign was executed on 2017 November 30 (ID: 2017.1.00129.S, PI: Morokuma), with an integration time of 30 minutes, and the CO($J = 1$–0) emission line was also covered. The total power (TP) observation took place on 2019 October 26, with an integration time of 66,508 s. Standard calibrations were performed using the Common Astronomy Software Applications (CASA) package (version 5.5, McMullin et al. 2007). The 12 m and 7 m data were imaged together with the CASA task tclean using the Briggs weighting with a robustness of 0.5 and with a threshold of 8.3 mJy for a channel width of 5 km s$^{-1}$. The cleaned data were then primary-beam-corrected and combined with the TP data using the CASA task image. The synthesized beam size and rms are listed in Table 1. CO moment maps were created by applying a 4$\sigma$ threshold. The moment 0 and 1 maps of CO(1–0) are presented in the top row of Figure 1.

2.2. Archival VLT/MUSE Data

NGC 1365 was observed with the VLT/MUSE (Bacon et al. 2010) on 2014 October 12, as a part of the Measuring Active Galactic Nuclei Under MUSE Microscope (MAGNUM) survey.
| Telescope        | Project ID                  | PI              | Wavelength/Frequency | Resolution/Beam Size | FoV       | rms                  |
|------------------|-----------------------------|------------------|----------------------|----------------------|-----------|----------------------|
| VLT/MUSE         | 094.B-0321(A)               | Marconi          | 4750–9352 Å          | 0"76                | 63"8 × 63"4 |                      |
| ALMA 12 m + 7 m + TP | 2015.1.01135.S, 2017.1.00129.S | Egusa, Morokuma | 99–115 GHz           | 1"92 × 1"51         | 8' × 10'  | 8.3 mJy/beam (5 km s⁻¹) |
A fully reduced data cube is available on the ESO archive website,\(^9\) which we use for our analysis in this work. The field of view (FoV) is \(63.8^\circ \times 63.4^\circ\), consisting of \(319 \times 317\) spaxels (0.2 each), and is compared to the entire galaxy in Venturi et al. (2018, Figure 1). The average seeing during the observations was about 0.76. Using the Python package MPDAF\(^{10}\) (Bacon et al. 2016), the median FWHM of the point-spread function at 4500 Å < \(\lambda\) < 7000 Å is about 0.8. The spectral window is 4750–9352 Å and the channel width is 1.25 Å.

\(^9\) https://archive.eso.org/scienceportal/home

\(^{10}\) https://mpdaf.readthedocs.io/en/latest/start.html
3. Data Analysis

3.1. Molecular Gas Mass from CO(1–0)

In order to compare the molecular gas to the ionized gas, we construct the CO(1–0) map within the FoV of the MUSE data, which are shown in Figure 1. Following Sakamoto et al. (2007), we assume a 12CO to H2 conversion factor of $X_{\text{CO}} = 0.5 \times 10^{20} \text{ cm}^{-2} (\text{K km s}^{-1})^{-1}$, a value commonly adopted for galactic centers and starburst nuclei. Note that adopting alternative $X_{\text{CO}}$ values (e.g., Bolatto et al. 2013) will not change the slope and scatter in the K-S law. Hence, the molecular gas mass can be estimated as

$$M_{\text{H}_2} = 1.0 \times 10^9 \left( \frac{S_{\text{CO}}}{\text{Jy km s}^{-1}} \right) \left( \frac{D}{\text{Mpc}} \right)^2 \times \left[ \frac{X_{\text{CO}}}{2.0 \times 10^{20} \text{ cm}^{-2} (\text{K km s}^{-1})^{-1}} \right] M_\odot,$$

(1)

where $D = 21.2 \text{ Mpc}$ is the distance of NGC 1365 (Sakamoto et al. 2007). We divide the molecular gas mass in each spaxel by its corresponding physical area (corrected by the inclination angle), to determine the molecular gas mass surface density $\Sigma_{\text{H}_2}$. The lowest $\Sigma_{\text{H}_2}$ value that we detect is about $2.7 \times 10^6 M_\odot \text{ kpc}^{-2}$, which is adopted as the 4σ threshold.

3.2. SFR and Stellar Mass from MUSE Data

We perform a series of spectral fitting analysis on the spectra in the MUSE data cube, whose spectral coverage is 4750–8500 Å with the primary optical emission lines covered (e.g., Hβ, [O III] λλ4959, 5007, Hα, [N II] λλ6548, 6583, and [S II] λλ6716, 6731). With the optical emission lines masked, we employ the STARLIGHT routine (Cid Fernandes et al. 2005) to recover the underlying stellar continuum. Assuming the initial mass function (IMF) from Chabrier (2003), we fit each spectrum to a combination of 45 single stellar populations (SSPs) from the model of Bruzual & Charlot (2003), which are distributed over three different metallicities ($Z = 0.01, 0.02, \text{ and } 0.05$) and 15 stellar ages (1 Myr to 13 Gyr). We obtain the stellar mass within each spatial pixel from the SSP fitting results. When the signal-to-noise ratio (S/N) of the continuum is above 5, the uncertainty of the stellar mass is smaller than 0.11 dex (Bruzual & Charlot 2003; Cid Fernandes et al. 2005).

To optimally recover the fluxes of the strong emission lines (Hβ, [O III] λλ4959, 5007, Hα), we fit them to multiple Gaussians using the IDL package MPFIT (Markwardt 2009). The estimation of S/N for these emission lines is done following the method used in Ly et al. (2014) and Gao et al. (2018). The velocities of stellar and ionized gas can be derived from the absorption lines embedded in the continuum and from the strong emission lines, respectively. In Figure 1, we show the integrated flux and velocity maps for strong emission lines Hα and [O III] λλ5007. To obtain extinction-corrected SFRs, we locate the regions in the Hα and Hβ images with S/N larger than 5, and derive $A_v$ with Hα/Hβ ratios, employing a “Case B” recombination model and the reddening formalism of Calzetti et al. (2000). Assuming the solar metallicity and Chabrier IMF, SFR can be derived from the Hα luminosity by using $\text{SFR}(M_\odot \text{ yr}^{-1}) = 4.4 \times 10^{-45} \times L_{\text{H}\alpha} (\text{erg s}^{-1})$ (Kennicutt 1998). For stellar mass and SFR, we compute their surface densities, $\Sigma_{\ast}$ and $\Sigma_{\text{SFR}}$, respectively, as we do for $\Sigma_{\text{H}_2}$.

3.3. The Spatially Resolved BPT Diagram and AGN Fraction

We construct a pixel-based BPT diagram (Baldwin et al. 1981; Kewley et al. 2001; Kauffmann et al. 2003) using the [N II] diagnosis to scrutinize the ionization state of the nuclear region of NGC 1365 in Figure 2 (left panel), similar to Venturi et al. (2018, Figure 5). We derive the AGN contribution fraction ($f_{\text{AGN}}$) for each spaxel following the method used in Davies et al. (2016) and Shin et al. (2019). The AGN fraction spans a wide range (from 0% to 100%, Figure 2). As seen in the right panel of Figure 2, $f_{\text{AGN}} < 20\%$ in the circumnuclear ring, consistent with previous studies (e.g., Davies et al. 2016; Agostino & Salim 2019; Shin et al. 2019). In the biconical outflow, in contrast, $f_{\text{AGN}} > 60\%$. We then correct SFR and $\Sigma_{\text{SFR}}$ by quantifying the star formation fraction in the Hα luminosities. For comparison, Durré & Mould (2018) report that the AGN fraction of the star-forming ring in NGC 5728 is about 40%, which is caused by the determination of fractions in logarithmic space. Nevertheless, even if we assume...
the AGN fraction in the circumnuclear ring to be 40%, the SFR distribution remains comparable to our results given in Section 4.

4. Results

4.1. Star Formation Relations in the Nuclear Region

In this section, we analyze the spatially resolved K-S relation, and the stellar mass–SFR (main sequence) relation in the nuclear region of NGC 1365. Considering the fact that the beam size in our CO (1–0) data is \( 1.9'' \times 1.5'' \), a spatial resolution significantly lower than that of the maps of SFR and stellar mass surface density, we regird the latter maps to a resolution of \( 2'' \times 2'' = 180 \) pc to prevent oversampling. To minimize the AGN contamination to the determination of SFR and stellar mass, we also mask the central nine pixels. In Figure 3, we show the surface density maps of (a) molecular gas mass, (b) SFR, and (c) stellar mass at a resolution of \( \sim 180 \) pc.

In the left panel of Figure 4, we plot the spatially resolved molecular gas surface density versus SFR density, where data points are color-coded by their galactocentric distances \( r \). We also compare our analysis with the K-S laws derived in five previous investigations in Figure 4: (1) Kennicutt et al. (2007) at 500 pc scale in the M51a disk, (2, 3) Liu et al. (2011) in M51a and NGC 3521 at spatial resolutions ranging from 250 pc to \( \sim 1 \) kpc, (4) Azeez et al. (2016) in the central region of M100 (NGC 4321) at 330 pc resolution, (5) Nguyen-Luong et al. (2016) using the young stellar objects (YSOs) at 30 pc resolution in the GMCs of the Galaxy. The gray dashed lines represent different SFE levels. The two vertical gray lines separate regimes of low, intermediate, and high density (Table 3 of Kennicutt & Evans 2012). Right: the SFR surface densities vs. the stellar mass surface densities, known as the resolved main-sequence relation. The blue, red, and brown solid lines represent the resolved relations in the MaNGA survey (Liu et al. 2018), M51a, and NGC 4254 (Enia et al. 2020), with resolutions of 1–2 kpc, 330 pc, and 500 pc, respectively. The gray dashed lines represent different sSFR levels. The error bars show the median values of uncertainties in the determination.

Figure 3. Surface density maps of (a) molecular gas mass, (b) SFR, and (c) stellar mass at the same resolution of \( 2'' \sim 180 \) pc. We mask the central nine pixels around the AGN position.

Figure 4. Left: the SFR surface densities as a function of molecular gas surface densities, i.e., the resolved K-S law, colored by the distance \( r \) between each pixel and the central AGN. The cyan, blue, brown, red, and orange solid lines show the K-S laws in M51a (500 pc, 250 pc, Kennicutt et al. 2007; Liu et al. 2011), NGC 3521 (250 pc; Liu et al. 2011, NGC3521), M100 (330 pc, Azeez et al. 2016), and GMCs/YSOs (Nguyen-Luong et al. 2016), respectively. The black solid and dashed lines represent the best fitted relations for the data with \( \Sigma_{\text{H}_2} > 10 \) M\(_{\odot}\) pc\(^{-2}\) and \( \Sigma_{\text{H}_2} > 1 \) M\(_{\odot}\) pc\(^{-2}\), respectively. The two vertical gray lines separate regimes of low, intermediate, and high density (Table 3 of Kennicutt & Evans 2012). Right: the SFR surface densities vs. the stellar mass surface densities, known as the resolved main-sequence relation. The blue, red, and brown solid lines represent the resolved relations in the MaNGA survey (Liu et al. 2018), M51a, and NGC 4254 (Enia et al. 2020), with resolutions of 1–2 kpc, 330 pc, and 500 pc, respectively. The gray dashed lines represent different sSFR levels. The error bars show the median values of uncertainties in the determination.
Following Kennicutt et al. (2007), the K-S relation can be expressed as

\[
\log \left( \frac{\Sigma_{\text{SFR}}}{M_\odot \, \text{yr}^{-1} \, \text{kpc}^{-2}} \right) = N \log \left( \frac{\Sigma_{\text{H}_2}}{M_\odot \, \text{pc}^{-2}} \right) + A, \tag{2}
\]

where \(N\) denotes the index of the power law. We fit the \(\Sigma_{\text{H}_2}\) versus \(\Sigma_{\text{SFR}}\) relation at \(\Sigma_{\text{H}_2} > 10 M_\odot \, \text{pc}^{-2}\) and \(\Sigma_{\text{H}_2} > 1 M_\odot \, \text{pc}^{-2}\) in sequence, based on an orthogonal distance regression algorithm (scipy.odr\(^{11}\)), shown as the black dashed and solid lines, respectively. The best-fit results, compared to previous works, are listed in Table 2. The K-S law shows a steeper slope here than in M51a (Kennicutt et al. 2007) and NGC 3521 (Liu et al. 2011) when the applied threshold is \(\Sigma_{\text{H}_2} > 1 M_\odot \, \text{pc}^{-2}\). Furthermore, if we restrict the measurement to \(\Sigma_{\text{H}_2} > 10 M_\odot \, \text{pc}^{-2}\), the slope of the K-S law is roughly consistent with that in M51a (Liu et al. 2011), while it is steeper than in M100 (Azeez et al. 2016). However, our slopes are flatter than the relation derived from the YSOs in the GMCs of the Galaxy. This is in line with the conclusion of Liu et al. (2011) that the spatial resolution affects the shape and slope of these star formation relations.

The inner regions (\(r < 9\, \alpha\)) are found to have an SFE (SFR) about 1.1 (0.4) dex higher than the outer regions, indicating that more intense star formation activities are occurring in the dust lane and the star-forming ring around the AGN. However, there exist dense regions with \(\Sigma_{\text{H}_2} > 100 M_\odot \, \text{pc}^{-2}\) but with significantly lower SFE (\(\sim 10^{-11}\) \(\text{yr}^{-1}\)), indicating suppression of star formation in a number of dense gas regions. In parallel, in the low-density regime, a number of regions show relatively high SFE (\(\sim 10^{-8}\) \(\text{yr}^{-1}\)); they are scattered in both inner and outer locations, indicating remarkably enhanced star formation.

In the right panel of Figure 4, we present the relation between stellar mass surface density and SFR surface density for these molecular regions, color-coded by their distances to the central AGN. The blue, red, and brown solid lines represent the resolved relations in star-forming galaxies from the MaNGA survey (Liu et al. 2018), M51a, and NGC 4254 (Enia et al. 2020), measured at resolutions of 1–2 kpc, 330 pc, and 500 pc, respectively. The gray dashed lines represent different specific SFR (sSFR = \(\text{SFR} / M_\star\)) levels, annotated with three values, 10\(^{-8.5}\), 10\(^{-9.5}\), and 10\(^{-10.5}\) \(\text{yr}^{-1}\). We note that \(\Sigma_{\text{SFR}}\) increases rapidly with increasing \(\Sigma_{\text{SFE}}\). The steeper slope indicates that the accumulation of stellar mass within the nuclear regions of NGC 1365 is significantly faster than in normal star-forming galaxies and spiral galaxies, which might be due to the enhancement of star formation caused by strong bars. High sSFR values (\(\sim 10^{-9.5}\) \(\text{yr}^{-1}\)) are found in both the inner and outer regions, yet the majority of the outer regions possess lower sSFR (\(< 10^{-10.5}\) \(\text{yr}^{-1}\)). This result indicates the coexistence of enhancement and suppression of star formation activities in the nuclear region. However, the underestimated stellar mass as a result of the severe extinction in the central regions (see Figure 5, top right panel) might steepen the main-sequence relation.

### 4.2. Spatial Distribution of SFE

In the strongly barred spiral galaxy NGC 1365, there is an obvious nuclear ring revealed by CO(1–0) (Figure 1), CO(2–1) (Sakamoto et al. 2007), and CO(3–2) (Combes et al. 2019), with a radius about 9\(\prime\) = 770 pc. The position angle of the bar is about 92\(\circ\) (Combes et al. 2019), and the northeastern side is the near side. The location of peak flux in the molecular gas map is consistent with the dust lanes seen in the optical images. The inner Lindblad resonance of the bar corresponds to the nuclear ring (e.g., Sakamoto et al. 2007), where active star formation is taking place.

In Section 4.1, we have presented the K-S relation at a resolution of 180 pc, and found a number of regions of enhanced or suppressed star formation. In this section, we smooth the original \(\Sigma_{\text{SFR}}\) map to match that of the CO(1–0) resolution and investigate the SFE distribution, in order to search for these regions with extraordinary star formation activities. In Figure 5, we show the SFE map overlaid by the [O\text{III}] 5007 flux. The dense gas with log\((\Sigma_{\text{H}_2}/M_\odot \, \text{pc}^{-2}) > 2.4\) is shown by black contours, which roughly depict the morphology of the two dust lanes. The regions with enhanced star formation (log(SFE/\(\text{yr}^{-1}\)) > –8.3) are accompanied by blue solid lines and marked with the letters B–G. The regions with suppressed star formation (log(SFE/\(\text{yr}^{-1}\)) < –11.0) are represented by red solid lines and marked A and H.

Although located in the outer parts of the star formation ring, regions A and H are found to possess high-density molecular gas (log\((\Sigma_{\text{H}_2}/M_\odot \, \text{pc}^{-2}) > 2\)) but weak H\(\alpha\) emission. As seen from the dust attenuation distribution (Figure 5), regions A and H show lower dust attenuation than regions B–G, which, in contrast, are located where local peaks of H\(\alpha\) flux are found but gas surface density is relatively low. As a result, in the outer regions (\(r > 10^9\)), a prominent offset between the H\(\alpha\) arms and CO arms is seen, which can be interpreted as the delay of star formation after the compression of molecular gas in spiral arms (Egusa et al. 2004, 2009). The decorrelation between the star formation and the molecular gas leads to the difference in SFE between the front/leading side and the back/trailing side of spiral rotation, and even probably results in the breaking down of the resolved K-S law at such a high spatial resolution.

The regions C, D, E, and F, situated in the inner star-forming ring, show the highest SFE values. However, the gas density within these four regions is vastly different. Regions C and D are nearly invisible in the optical image, because of the enormous dust attenuation (\(A_v > 4\)). Since the dust/gas column
density \((\log(S_{\text{HI}}/M_\odot \text{ pc}^{-2}) \sim 2.7)\) is extremely high in these two regions, we should note that the extinction correction from the Balmer decrement may not be accurate or even inapplicable (Liu et al. 2013). We defer the comparison of SFR derived from Balmer emission lines and free–free emission of radio continuum to a future work (Y. Gao et al. 2021, in preparation).

In contrast, regions E and F harbor lower gas surface densities \((\log(S_{\text{HI}}/M_\odot \text{ pc}^{-2}) \sim 2.1)\), about 25\% of those in C and D. Previously, these four regions of intense star formation have been detected in the radio (2, 3, 6, 20 cm) and mid-infrared (8.9–12.9 \(\mu\)m) bands (Sandqvist et al. 1982, 1995; Galliano et al. 2005, 2008, 2012; Sakamoto et al. 2007), which will be discussed later in Section 5.1.2.

Furthermore, we note that the SFE in the southwestern (SW) dust lane is lower than that in the northeastern lane by a factor of 5 (\(~0.7\) dex). In the bottom left panel of Figure 5, we plot the velocity dispersion map of CO(1–0) overlaid by the contour of the [O III] \(\lambda5007\) flux. We find the molecular gas velocity dispersion in the SW dust lane to be \(~50–60\) km s\(^{-1}\), higher than that in the NE lane.

The virial parameter, \(\alpha_{\text{vir}} = M_{\text{vir}}/M_{\star}\), is routinely employed to gauge whether or not a molecular gas cloud fragment is stable against collapse (e.g., Krumholz & McKee 2005; Kauffmann et al. 2013; Sun et al. 2018). If \(\alpha_{\text{vir}} \leq 2\), the cloud fragments are supercritical, unstable, and tend to collapse, while \(\alpha_{\text{vir}} > 2\) suggests that the gas motion alone may prevent cloud fragments from collapsing. Following the method in Sun et al. (2018), we calculate \(\alpha_{\text{vir}}\) at the scale of the beam size through the following equation:

\[
\alpha_{\text{vir}} = \frac{5\sigma^2 r_{\text{beam}}}{fGM} = \frac{5}{\pi G} \left(\frac{\sigma}{\text{km s}^{-1}}\right)^2 \times \left(\frac{\sum \rho}{M_\odot \text{ pc}^{-2}}\right) \left(\frac{r_{\text{beam}}}{\text{pc}}\right)^{-1},
\]

where the value of the factor \(f\) is adopted to be 10/9 with a density profile of \(\rho(r) \propto r^{-1}\) (Sun et al. 2018), the gravitational constant \(G\) is \(4.3 \times 10^{-3} \text{ pc} M_\odot^{-1} (\text{ km s}^{-1})^2\), and \(r_{\text{beam}}\) is the radius of the synthesized beam. We note that the determination of \(\alpha_{\text{vir}}\) is affected by the adopted value of \(X_{\text{CO}}\). In Section 3.1, we adopt an \(X_{\text{CO}}\) value lower than that of the Milky Way by a factor of 4, but we emphasize that we focus on the comparison of \(\alpha_{\text{vir}}\) between different sub-galactic regions.

Figure 5. Top left: the SFE map contoured by the [O III] \(\lambda5007\) fluxes (gray lines). We mask the central AGN region \((r < 2.4')\). The black lines represent the dense gas regions with \(\log([\text{H}_\alpha]/M_\odot \text{ pc}^{-2}) > 2.4\), denoting the shape of dust lanes. The blue and red lines represent some high \((\log(SFE/\text{yr}^{-1}) > -8.3)\) and low \((\log(SFE/\text{yr}^{-1}) < -11.0)\) SFE regions, respectively, which are marked with the letters A–H. The black box represents the suppressed star-forming region. The typical uncertainty of \(\log(SFE/\text{yr}^{-1})\) is about 0.13. Top right: the dust attenuation distribution contoured with CO(1–0) fluxes. Bottom left: the moment 2 (velocity dispersion) map of CO(1–0) contoured by the [O III] \(\lambda5007\) fluxes (gray lines). Bottom right: the virial parameter \(\alpha_{\text{vir}}\) distribution of molecular gas. If we adopt the uncertainty of velocity dispersion as 5 km s\(^{-1}\), the typical uncertainty of \(\alpha_{\text{vir}}\) is less than 0.3.
In the bottom right panel of Figure 5, we plot the virial parameter distribution of molecular gas at the spatial scale of the beam size. Among these regions, “C” shows the smallest $\alpha_{\text{vir}}$ in line with with the finding of the highest SFE therein. In addition, $\alpha_{\text{vir}}$ is remarkably larger in regions A and H than in B, C, D, E, and F, suggestive of a low chance for molecular gas to collapse. Furthermore, a significantly high value of $\alpha_{\text{vir}}$ is found in the regions on the SW side of the dust lane that show high velocity dispersion, where molecular gas is probably disturbed and heated by the [O III] $\lambda$5007-emitting outflows driven by the central AGN or starburst activities. This result is in line with negative feedback effects from outflows, even in relatively dense gas. In addition, the $\alpha_{\text{vir}}$ value in the gas fragments located on the edge of the molecular gas disk is evidently high, which is possibly linked to heating processes, and further discussion on the gas kinematics there is deferred to Section 4.3.

4.3. Gas Kinematics

Previous works have delineated the motion of gas in the nuclear region of NGC 1365 (Lindblad 1999; Sakamoto et al. 2007; Elmegreen et al. 2009). The molecular gas in the dust lanes flows into the inner region, leading to the formation of massive star clusters and the high gas accretion rate. The high resolution of CO(1–0), [O III] $\lambda$5007, and H$\alpha$ data now facilitates a scrutiny of the kinematics of the molecular and ionized gas.

In Figure 1, we show the velocity distributions of CO(1–0), [O III] $\lambda$5007, and H$\alpha$ emission. The velocity map in the right panels therein indicates a noncircular motion of molecular gas, and shows complex motion features around the dust lanes and the star-forming ring. With respect to the systemic velocity (1618 km s$^{-1}$), a blueshift in the NE and a redshift in the SW are seen. To model the rotation of molecular gas, we utilize the $^{3}$D$^{3}$BAROLO code (Di Teodoro & Fraternali 2015) to perform a 3D fitting on the CO(1–0) emission line data cube. The position of the central AGN that we adopt is $\alpha = 03^h33^m36^s35.8, \delta = -36^\circ08'25''8$, and the step size of radii ($\Delta r$) is set to be 1″. The systemic velocity, position angle, and inclination are set to be 1618 km s$^{-1}$, 220°, and 40°, following the parameter-setting in Sakamoto et al. (2007). The $^{3}$D$^{3}$BAROLO code fits a pure circular rotation model to the data cube, so that noncircular motions (e.g., radial motion due to spiral arm and bar dynamics, inflows, and outflows) manifest themselves as residuals. The resultant circular rotation model and the residuals are shown in Figure 6 (top left and top right panels, respectively). The residual map shows a redshift in
the NE dust lane (black solid contour), though a blueshift in the SW lane is not evident. As the NW side is the near side of the galaxy (Elmegreen et al. 2009), this indicates streaming inflow motions of molecular gas along the NE dust lane, with a projected velocity of about 10–15 km s\(^{-1}\). Interestingly, blueshifted and redshifted strip components outside the dust lanes are readily observed on the NW and SE sides, respectively, which reach up to approximately ±100 km s\(^{-1}\) in the projected velocity, suggestive of noncircular motion.

Using the velocities derived from emission lines and stellar continuum in Section 3.2, we determine the [O III] λ5007 and H\(\alpha\) velocities relative to the stellar rotation. The stellar rotation is similar to Figure 6 (panel a) in Venturi et al. (2018). The velocity residual maps derived from the [O III] λ5007 and H\(\alpha\) emission lines are shown in the bottom panels of Figure 6, and are consistent with Figure 6 in Venturi et al. (2018). In this figure, we see biconical morphology of the [O III] outflow, with velocities negative (blueshifted) in the SE, and positive (redshifted) in the NW. Similar receding motion is found on the NW side of the H\(\alpha\) velocity map, though the approaching cone in the SE is not obvious. The H\(\alpha\) velocity with respect to the stellar rotation is dominated by a blueshift in the north and redshifted in the south.

We also plot the position–velocity diagrams (PVDs) for CO(1–0) emission in Figure 7, which are obtained along the major axis at PA = 220° and minor axis at 310°. These PVDs help reveal the azimuthal and radial streaming motions along the designated directions (Aalto et al. 1999). The best-fit model derived from \(^{13}\)C\(\text{CO}\) is shown as red contours. The basic directions are also shown as SW, NE, SE, and NW in the plots.

The basic directions are also shown as SW, NE, SE, and NW in the plots.

The observed velocity maps of molecular and ionized gas are shown in Figure 8. The [O III] emitting outflow likely driven by the central AGN and/or starburst is receding on the NW side and approaching on the SE side, and its half-opening angle is as wide as about 50° (Sandqvist et al. 1995; Venturi et al. 2018). The star-forming ring is depicted by the inner gray ellipse, and the molecular disk is located in the region between the two gray ellipses. Dense molecular gas is inflowing to the central AGN along the dust lanes, and is color-coded with red (NW side) and blue (SE side) lines. Along the line of sight, the dust lane on the NW side is in front of the [O III] outflow, while the SE lane is behind the outflow. In Figure 6, the low-density molecular gas in the disk is receding (approaching) on the SE (NW) side,
which is shown as red (blue) arrows in Figure 8. The low-density molecular gas on the surface of the disk may have been swept out by the outflows, and such an interpretation is compatible with their higher virial parameters in Figure 5. The H\textalpha{} kinematics in Figure 6 is predominantly two thick lanes aligned with the molecular gas whose overall motion is similar (approaching in the NW and receding in the SE). The diffuse ionized H\textsuperscript{+} gas is marked with red and blue circles in Figure 8. It is probably created by the photoionization of molecular H\textsubscript{2} gas and seemingly located between the molecular gas disk and [O III] outflows.

5. Discussion

5.1. Star Formation

The high-resolution data of CO(1–0) and H\textalpha{} obtained by ALMA and VLT/MUSE allow for exploring the spatially resolved star formation activities in the nuclear region of NGC 1365. In this section, we will discuss the Kennicutt–Schmidt and main-sequence relations at a resolution of 180 pc, and the feedback effects on star formation from the outflows.

5.1.1. Star Formation Relations at 180 pc

In Section 4.1, we investigate the K-S relations at a resolution of 180 pc. Because of the higher resolution in our data, the greater slopes are consistent with the findings in Liu et al. (2011). However, if we smooth the CO and H\textalpha{} data at a larger scale of 360 pc, we find the correlation coefficients are 0.66 (Pearson) and 0.76 (Spearman), with slopes of 1.64 ± 0.23 (\(\Sigma_{H_\text{II}} > 1 \, M_\odot \, \text{pc}^{-2}\)) and 3.0 ± 0.4 (\(\Sigma_{H_\text{II}} > 10 \, M_\odot \, \text{pc}^{-2}\)). This superlinear slope (\(N \geq 2\)) in our work might indicate the transition between inefficient/normall star formation and starburst sequences (Kennicutt & Evans 2012). Onodera et al. (2010) studied the K-S law in M33 with different resolutions (80, 240, 500 pc, and 1 kpc) when \(\Sigma_{H_\text{II}}\) ranged from 10 to 40 \(M_\odot \, \text{pc}^{-2}\), and found the relation becomes invalid and breaks down at the highest resolution of 80 pc. We also detect the breaking down of the K-S relation, because the SFR density is nearly uncorrelated with the gas density in the low-density regime. One reason is that the large fraction of gas in a regime of low molecular gas density is atomic H\textsuperscript{I} gas, because of the low conversion efficiency from the atomic to molecular phase. The local SFR density is in part uncorrelated with H\textsuperscript{I} density (e.g., Liu et al. 2011; Kennicutt & Evans 2012). Another reason is that the depletion of molecular gas in some inner regions is more efficient, caused by the outflows, starburst, or stellar feedback (Kruisjes et al. 2019). Besides, because of the delay between compression of molecular gas in spiral arms and star formation, the decorrelation between the emission peak regions of CO(1–0) and H\textalpha{} is identified (Egusa et al. 2004, 2009). This might lead to the SFE difference between the front/leading and back/trailing sides of spiral rotation, and even probably contribute to the breakdown in the resolved K-S law at such a high spatial resolution.

In the right panel of Figure 4, we find that the slope of the resolved main-sequence relation in the nuclear region of NGC 1365 is steeper than in normal star-forming galaxies and other spiral galaxies. This difference might arise for a few reasons. One is that star formation in the nuclear region is enhanced by the strong bar-driven gas dynamics. The stellar bar is suggested to drain the molecular gas in the spiral region toward its galactic center, thus triggering gravitational collapse to form gas clumps and lead to intense star formation (e.g., Kormendy & Kennicutt 2004; Chown et al. 2019; Lin et al. 2020). Another is that the coverage of stellar mass density (7.7 < log(\(\Sigma_*/M_\odot \, \text{pc}^{-2}\)) < 9.4) is much narrower than in other studies, which would introduce some bias to the relation.

The extinction correction is not accurate for dusty regions (e.g., dust lanes), and the determination of stellar mass from the SSP fitting might be underestimated at higher densities. Furthermore, the spatial resolution in our work is much higher than in other studies. Enia et al. (2020) derived the resolved main-sequence relations for all pixels in eight nearby spiral galaxies at scales of 280–750 pc, and found the slopes are from 0.54 to 1.1, which is smaller than in our work. These results indicate that the speed of accumulation of stellar mass in the inner region of NGC 1365, such as the star-forming ring, is much faster than in the outer molecular gas spiral arms.

5.1.2. Enhanced and Suppressed Star Formation

In Figure 5, the inner regions C, D, E, and F show the highest SFEs while harboring different gas densities. Regions C and D are nearly invisible in optical bands because they are located at the connection points between the star-forming ring and dust lane. Galliano et al. (2008, 2012) observed three regions (C, D, and another region located to the west with higher dust attenuation), using the instruments VISIR and SINFONI on the VLT in mid-infrared bands. They regarded these two regions as super Young (6–8 Myr) massive (~10\textsuperscript{7} M\odot) star clusters, still embedded in the surrounding dust. Elmegreen et al. (2009) reviewed the environment of these star clusters in NGC 1365. They inferred these clusters are formed at a position where an interbar filament impacts the dust lane, triggered by the higher pressure and spontaneous gravitational instabilities in the dust lane. The regions E and F have been proven to contain mixtures of a few optical super star clusters by Kristen et al. (1997), harboring diffuse molecular gas and the two brightest star clusters. Kristen et al. (1997) found the brightest one is 300 times brighter than the luminous globular star clusters in our Milky Way. Emsellem et al. (2015) provided a detailed simulation about the star formation and gas fueling in the nuclear region of barred galaxies. Their simulation shows that the star clusters would form efficiently at the very edge of the bar and concentrate at its two ends. Because the end regions of the bar are evolved with a high density of molecular gas but with low shear, the molecular gas is expected to collapse and form the star clusters. A large fraction of the molecular gas in regions E and F has probably been consumed by the star formation or disrupted by stellar feedback and AGN outflows.

In Figure 5, we notice that the star formation activities are much more intense in the NE dust lane than in the SW one. The denser molecular gas in the SW dust lane is partly heated by or interacts with the ionized outflows from the central AGN and starburst regions E and F. Furthermore, Sandqvist et al. (1995) and Wang et al. (2009) have reported the existence of a jet in radio and X-ray bands, the features of which are visually extended to the SW dust lane, possibly leading to the larger velocity dispersion and virial parameters. This finding supports the negative feedback of outflows (Fabian 1994), because the energy can prevent the molecular gas, even in the denser clouds, from cooling and can lead to the suppression of star formation. This result is different from the positive effects of outflows on denser molecular gas clouds (e.g., Silk 2013;
Maiolino et al. 2017; Shin et al. 2019), which suggest that the outflows will compress the molecular gas and then trigger the star formation activities. In the future, we will check the existence of negative feedback of outflows on denser molecular gas fragments in other galaxies.

5.2. Noncircular Gas Motion

As seen in Figures 6 and 8, we infer that the low-density molecular gas and diffuse ionized gas on the surface of the disk are swept by the outflows of AGNs. These motions have also been reported in previous observations (e.g., García-Burillo et al. 2014, 2019; Morganti et al. 2015; Salak et al. 2016; Alonso-Herrero et al. 2019; Shin et al. 2019). In barred starburst galaxy NGC 1808, Salak et al. (2016) detected these blueshifted and redshifted components of molecular gas in the residual velocity map, and they are regarded as the combination of bar dynamics and outflows. Shin et al. (2019) reported that the outflows from AGNs in NGC 5728 could sweep out the inflowing gas along the spiral arms, then gave a negative feedback scenario. García-Burillo et al. (2019) and Alonso-Herrero et al. (2019) also detected line-of-sight velocity residuals of about 100–200 km s$^{-1}$ in NGC 1068 and NGC 3227, respectively. They interpreted the radial motions in the galactic plane as nuclear molecular outflows entrained by the AGN wind. Using simulation, Emsellem et al. (2015) found the stellar feedback from a starburst in molecular clumps would expel the gas outside the disk plane to hundreds of parsecs. This feedback will help remove angular momentum from the disk and allow gas to move closer to the inner AGN. Except for the sweeping motion, the inflowing gas along the dust lanes is detected in the CO(1–0) velocity residual map (Figure 6), which is positive in the NE dust lane but is not evident in the SW one, because these components are smaller in terms of velocity residuals than the outflowing components.

Another possibility is that the complex bar dynamics (at least partially) contribute to these noncircular motions (Koda & Sofue 2006). However, to derive an accurate picture of the kinematics of stellar, ionized gas, and molecular gas, we need to perform a simulation of the rotational motions of spiral arms, bar, and star-forming ring (Sakamoto et al. 1999; Koda & Sofue 2006; Emsellem et al. 2015; Li et al. 2015), which will be studied in our future work.

5.3. Mass Outflow Rate and Powering Source

With the spatial distribution of molecular gas and its velocity, it is easy to derive the mass of outflowing molecular gas ($M_{\text{Mol}}$), projected radial size ($R_{\text{out}}$), and projected outflowing velocity ($V_{\text{out}}$). After subtracting the contribution of molecular gas with $-50$ km s$^{-1}$ $< V < V_{\text{model}} < 50$ km s$^{-1}$, we obtain $M_{\text{Mol}}$, $R_{\text{out}}$, and $V_{\text{out}}$. Here, we use the conversion factor $X_{\text{CO}}$ in starburst nuclei, which is the same as in Section 3.1. Following the procedure in previous work (Equations (4), (6), (7) of García-Burillo et al. 2014) and adopting the angle $\alpha$ between the outflow and the line of sight as $40^\circ$, we estimate the mass outflow rate ($dM/dt$), the kinetic luminosity ($L_{\text{kin}}$) of the outflow, and the momentum flux ($dP_{\text{out}}/dt$) of the outflow. The total SFR of NGC 1365 is adopted from the literature and the SFR in the central 5 kpc region is estimated from attenuation-corrected Hα luminosity. We also obtain the momentum ($L_{\text{bol}}/c$) provided by the AGN. All of these parameters are listed in Table 3.

![Table 3](https://example.com/table3.png)

| Parameter | Value | Reference |
|-----------|-------|-----------|
| $M_{\text{Mol}}$ (total) | $\sim 1.91 \times 10^3 M_\odot$ | This work |
| $M_{\text{Mol}}$ (not outflow) | $\sim 1.78 \times 10^3 M_\odot$ | This work |
| $M_{\text{Mol}}$ (outflow) | $\sim 1.37 \times 10^3 M_\odot$ | This work |
| $R_{\text{out}}$ | $\sim 598$ pc | This work |
| $V_{\text{out}}$ | 73$^{+35}_{-17}$ km s$^{-1}$ | This work |
| $dM/dt$ | $35^{+16}_{-8}$ M_\odot yr$^{-1}$ | This work |
| SFR (total) | $\sim 17.0 M_\odot$ yr$^{-1}$ | Combes et al. (1999) |
| SFR (central) | $\sim 4.6 M_\odot$ yr$^{-1}$ | This work |
| $dP_{\text{out}}/dt$ | $2.1^{+4}_{-2} \times 10^{44}$ g cm s$^{-2}$ | This work |
| $L_{\text{bol}}/c$ | $\sim 6.7 \times 10^{42}$ erg s$^{-2}$ | This work |
| $L_{\text{kin}}$ | $1.0^{+2.3}_{-1.3} \times 10^{41}$ erg s$^{-1}$ | This work |
| $L_{\text{bol}}$ | $\sim 2 \times 10^{43}$ erg s$^{-1}$ | Venturi et al. (2018) |

Note. The total molecular gas mass in the central 5 kpc region is represented by $M_{\text{Mol}}$ (total). $M_{\text{Mol}}$ (not outflow) means the molecular gas mass with $-50$ km s$^{-1}$ $< V < V_{\text{model}} < 50$ km s$^{-1}$. The adopted conversion factor $X_{\text{CO}}$ is $0.5 \times 10^{20}$ cm$^{-2}$ (K km s$^{-1}$)$^{-1}$, which is the same as in Section 3.1. SFR (total) in NGC 1365 is derived from the infrared luminosities. SFR (central) means the total SFR in the central 5 kpc region, derived from the attenuation-corrected Hα luminosity.

$L_{\text{kin}}/L_{\text{bol}}$ is about 0.5$^{+1.1}_{-0.5}$%, which is much lower than the required fraction of 5% in the AGN feedback model to produce an outflow in the ISM (Di Matteo et al. 2005; King & Pounds 2015), and similar to the fraction of 0.5% in the two-phase feedback model (Hopkins & Elvis 2010). These results suggest that the energy of the AGN is enough to produce such an outflow. ($dM/dt$)/($L_{\text{bol}}/c$) $\sim 31^{+12}_{-12}$ is nearly consistent with the range of momentum boost factors ($dP_{\text{out}}/dt$)/($L_{\text{bol}}/c$) $\sim 10$–50 in the AGN feedback model with energy-conserving outflows predicted by Faucher-Giguère & Quataert (2012). According to the explanation in Faucher-Giguère & Quataert (2012), these results indicate that the AGN nuclear winds or hot shocked gas are probably the primary driving mechanism of molecular outflow. Furthermore, ($dM/dt$)/SFR is about 2$^{+1.0}_{-0.4}$ and 7.5$^{+3.8}_{-1.7}$ for the global galaxy and the central 5 kpc region, respectively. The consumption of molecular gas via outflow is much faster than star formation, suggesting the negative feedback scenario.

6. Summary

In this work, we perform a spatially resolved analysis of molecular gas and ionized gas in the central 5.4 kpc $\times$ 5.4 kpc region of NGC 1365, using the ALMA band 3 and VLT/MUSE data. We explore the star formation activities and kinematics in dust lanes, circumnuclear ring, and outflow biconical regions. The main conclusions are summarized below.

1. We find the resolved K-S relation is superlinear at a resolution of 180 pc, with steeper slopes than previous studies based on greater spatial resolution. We suggest the large slopes reflect the transition between normal star formation and starburst sequences. The star formation activities are more intense in the inner circumnuclear ring than in the outer regions.

2. The slope of the resolved main-sequence relation in the nuclear region of NGC 1365 is steeper than in normal star-forming galaxies and other spiral galaxies at a smaller spatial resolution. This indicates that the speed...
of accumulation of stellar mass in the inner region, such as the star-forming ring, is much faster than in the outer spiral arms, suggesting the enhancement of star formation by bar dynamics.

3. The regions C, D, E, and F in the inner star-forming ring show the highest star formation efficiency. These regions are thought to harbor massive star clusters and might be caused by cloud–cloud collisions in the denser molecular gas regime.

4. Star formation is much weaker in the SW dust lane than in the NE one, while the former harbors denser molecular gas, larger velocity dispersion, and larger virial parameters. The SW dust lane is also superposed on the region of larger [O III] λ5007 velocity. These results suggest the scenario of negative feedback of outflows, because the radiation energy/outflows from the central AGN and starburst can prevent the molecular gas from cooling even in the denser clouds.

5. After subtracting a circular molecular gas rotation model and the stellar rotation, we find two obvious noncircular motion components of molecular and ionized hydrogen gas, reaching a velocity of up to 100 km s⁻¹. These motions probably indicate the scenario that the outflows from the AGN could sweep out the low-density molecular gas and diffuse ionized gas on the surface of the disk.

6. The molecular outflow is probably driven by AGN nuclear winds or hot shocked gas. The consumption of molecular gas via outflow is faster than star formation, suggesting the negative feedback scenario.

We thank the referee very much for careful reading and valuable suggestions. We acknowledge the grant from the National Key R&D Program of China (2016YFA0400702), the National Natural Science Foundation of China (No. 11673020 and No. 11421303), and the Fundamental Research Funds for the Central Universities, and the Chinese Space Station Telescope (CSST) Project. Y.L.G. gratefully acknowledges support from the China Scholarship Council (No. 201906340095). F.E. is supported by JSPS KAKENHI grant No. 17K14259. K.M.M. is supported by JSPS and the Fundamental Research Funds for the Central Universities, and the National Natural Science Foundation of China (No. 2016YFA0400702), the National Natural Science Foundation of China (No. 11673020 and No. 11421303), and the Fundamental Research Funds for the Central Universities, and the Chinese Space Station Telescope (CSST) Project. Y.L.G. gratefully acknowledges support from the China Scholarship Council (No. 201906340095). F.E. is supported by JSPS KAKENHI grant No. 17K14259. K.M.M. is supported by JSPS KAKENHI grant No. 2016YFA0400702.

References

Aalto, S., Hubinsteiner, S., Scoville, N. Z., & Thaddeus, P. 1999, ApJ, 522, 165
Agostino, C. J., & Salim, S. 2019, ApJ, 876, 12
Alonso-Herrero, A., García-Burillo, S., Pereira-Santaella, M., et al. 2019, A&A, 628, A65
Azouz, J. H, Hwang, C.-Y., Abidin, Z. Z., & Ibrahim, Z. A. 2016, NatSr, 6, 26896
Bacon, R., Accardo, M., Adjali, L., et al. 2010, Proc. SPIE, 7735, 773508
Bacon, R., Piqueras, L., Conseil, S., Richard, J., & Shepherd, M. 2016, MPDAF: MUSE Python Data Analysis Framework, Astrophysics Source Code Library, ascl:1611.003
Baldwin, A., Phillips, M. M., & Terlevich, R. 1981, PASP, 93, 817
Bigiel, F., Leroy, A., Walter, F., et al. 2008, AJ, 136, 2846
Bolatto, A. D., Wolire, M., & Leroy, A. K. 2013, ARA&A, 51, 207
Bruzual, G., & Charlot, S. 2003, MNRAS, 344, 1000
Calzetti, D., Armus, L., Bohlin, R. C., et al. 2000, ApJ, 533, 682
Chabrier, G. 2003, PASP, 115, 763
Cheung, E., Bundy, K., Cappellari, M., et al. 2016, Natur, 533, 504
Chown, R. Li, C., Athanassoula, E., et al. 2019, MNRAS, 484, 5192
Cid Fernandes, R., Mateus, A., Soddé, G., & Gomes, J. M. 2005, MNRAS, 358, 363
Combes, F., García-Burillo, S., Audibert, A., et al. 2019, A&A, 623, A79
Cresci, G., Marconi, A., Zibetti, S., et al. 2015, A&A, 582, A63
Davies, R. L., Groves, B., Kewley, L. J., et al. 2016, MNRAS, 462, 1616
Di Matteo, T., Springel, V., & Hernquist, L. 2005, Natur, 433, 604
Di Teodoro, E. M., & Fraternali, F. 2015, MNRAS, 451, 2021
Dobbs, C. L. 2008, MNRAS, 391, 844
Durrey, M., & Mould, J. 2018, ApJ, 867, 149
Eden, D. J., Moore, T. J. T., & Morgan, L. K. 2013, MNRAS, 431, 1587
Eden, D. J., Moore, T. J. T., Plume, R., & Morgan, L. K. 2012, MNRAS, 422, 3178
Elmegreen, B. G., & Elmegreen, D. M. 1983, MNRAS, 203, 31
Elmegreen, B. G., & Elmegreen, D. M. 2019, ApJS, 245, 14
Elmegreen, B. G., Galliano, E., & Aalto, S. 2009, ApJ, 703, 1297
Emsellem, E., Renaud, F., Bournaud, F., et al. 2015, MNRAS, 446, 2468
Enia, A., Rodighiero, G., Morselli, L., et al. 2020, MNRAS, 493, 4107
Evans, N. J. I., Heiderman, A., & Vutisalchatvakan, N. 2014, ApJ, 782, 114
Fabian, A. C. 1994, ARA&A, 32, 277
Fabian, A. C. 2012, ARA&A, 50, 455
Fauscher-Giguère, C.-A., & Quataert, E. 2012, MNRAS, 425, 605
Fazio, N., Busch, G., Valencia-S., M., et al. 2019, A&A, 622, A128
Federrath, C., & Klessen, R. S. 2005, Natur, 433, 604
Gallagher, R., Maiolino, R., Belore, E., et al. 2008, MNRAS, 385, 1870
Gao, Y., & Solomon, P. M. 2004, ApJ, 606, 271
García-Burillo, S., Combes, F., Ramos Almeida, C., et al. 2019, A&A, 628, A65
Gao, Y., & Solomon, P. M. 2004, ApJ, 606, 271
Gao, Y., Bao, M., Yuan, Q., et al. 2018, ApJ, 869, 15
Gao, Y., & Solomon, P. M. 2004, ApJ, 606, 271
García-Burillo, S., Cointes, F., Ramos Almeida, C., et al. 2019, A&A, 628, A61
García-Burillo, S., Cointes, F., Ramos Almeida, C., et al. 2019, A&A, 628, A61
García-Burillo, S., Combes, F., Usero, A., et al. 2014, A&A, 567, A125
García-Burillo, S., Usero, A., Alonso-Herrero, A., et al. 2012, A&A, 539, A38
Genzel, R., Price, S. H., Übler, H., et al. 2020, ApJ, 902, 98
Harrison, C. M., Costa, T., Tadhunter, C. N., et al. 2018, NatAs, 2, 198
Hopkins, P. F., & Elvis, M. 2010, MNRAS, 401, 7
Jeffreson, S. M. R., & Kuijken, J. M. D. 2018, MNRAS, 476, 3688
Kennicutt, R. C., Jr. 1998, ARA&A, 36, 189
Kennicutt, R. C., Jr. 2012, ARA&A, 50, 531
Kennicutt, R. C., Jr., Calzetti, D., & Evans, N. J. 2012, ARA&A, 50, 531
Kewley, L. J., Dopita, M. A., Sutherland, R. S., Heisler, C. A., & Trevena, J. 2001, ApJ, 566, 121
King, A., & Pounds, K. 2015, ARA&A, 53, 115
Koda, J., & Sofue, Y. 2006, PASJ, 58, 299
