

Mechanisms of Star Formation Suppression in the Strongly Barred Galaxy NGC 1300

(棒渦巻銀河 NGC1300 における星形成抑制メカニズムの解明)

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Abstract

In order to understand galaxy formation and evolution, it is essential to understand the star formation process, i.e. the conversion process from molecular gas to stars, in galaxies. Recent observations show the star formation activity appears to have a wide variety depending on galactic-scale environments; Star formation efficiency (SFE), which is the star formation rate per unit molecular gas mass, strongly depends on the galactic structure such as spiral arms, bar, and nucleus. In particular, SFE in the bar regions tends to be lower than that in other regions. Therefore, it is crucial to figure out how the galactic environments set the conditions for star formation within the molecular gases.

To unveil the impact of the galactic environment on the properties of molecular gas and star formation activity, we focus on the nearest strongly barred galaxy NGC 1300 as an ideal laboratory. This is because significant differences in star formation activity are seen; While HII regions (i.e. massive star formation) are seen in arm regions, prominent HII regions are mostly not seen in the strong bar despite the presence of molecular gas. In this galaxy, the physical mechanism(s) of the low SFE (i.e. star formation suppression) in the bar regions is(are) expected to be clearly seen.

Firstly, we investigate the properties of giant molecular clouds (GMCs). GMCs are the stellar nurseries in a galaxy, which are the most important components for understanding the galactic-scale star formation. In particular, comparing the GMC properties among environments with different SFEs is necessary. To do this, using Atacama Large Millimeter/submillimeter Array (ALMA) 12-m array, we carried out CO(1 – 0) observations toward NGC 1300 at a high angular resolution of ~ 40 pc. We detected GMCs associated with the dark lanes not only in the arm and bar-end regions but also in the bar region, where massive star formation is not seen. Using the CPROPS algorithm, we identified and characterized 233 GMCs across the observed regions. Based on the Kolmogorov-Smirnov test, we find that there is hardly any significant variations in GMC physical properties (e.g., radius, velocity dispersion, molecular gas mass) among the environments. A marginally significant difference is only seen in the distribution of molecular gas mass between the bar and bar-end regions, and the arm and bar-end regions. This result suggests that systematic differences in the physical properties of the GMCs are not the cause for SFE differences with environments. In particular, we find that there is no clear difference in the distribution of the virial parameter, which is a measure for gravitational binding of molecular clouds, between the GMCs in the bar region and those in the arm and bar-end regions. This result suggests that the star formation suppression in the strong bar of NGC 1300 cannot be explained by a systematic difference of the gravitational bounding and that there should be other mechanisms that control the galactic-scale SFE.

Another possible mechanism is that the presence of a large amount of diffuse molecular gas, which would not contribute to the star formation, makes the SFE in the bar regions low in appearance. To test this scenario, we examine the relationship between the SFE and the diffuse molecular gas fraction (f_{dif}), which is derived using the $^{12}\text{CO}(1 - 0)$ flux obtained from the interferometer of ALMA 12-m array, which has no sensitivity on diffuse (extended; $\text{FWHM} \gtrsim 700$ pc) molecular gases due to the lack of Atacama Compact Array, and the total $^{12}\text{CO}(1 - 0)$ flux obtained from

Nobeyama 45-m single-dish telescope. We find that the SFE decreases with increasing f_{dif} . The f_{dif} and SFE are $0.74 - 0.91$ and $(0.06 - 0.16) \text{ Gyr}^{-1}$ in the bar regions, and $0.28 - 0.65$ and $(0.23 - 0.96) \text{ Gyr}^{-1}$ in the arm and bar-end regions. This result supports the idea that the presence of a large amount of diffuse molecular gas makes the SFE low. The suppression of the SFE in the bar has also been seen even when we exclude the diffuse molecular gas components. This suggests that the low SFE appears to be caused not only by a large amount of diffuse molecular gases but also by other mechanisms that control the SFE of GMCs.

Although the galactic environments seem not to affect the physical properties of GMCs (i.e. α_{vir}) in NGC 1300, there is a possibility that the interaction of GMCs is affected. Cloud–cloud collision (CCC) has been suggested as a mechanism to induce massive star formation. Recent simulations suggest that a CCC speed is different among galactic-scale environments, which is responsible for observed differences in star formation activity. In particular, a high-speed CCC is proposed as a cause of star formation suppression in the bar regions in barred spiral galaxies. Thus, we investigate the CCC speed in NGC 1300. We find the CCC speed in the bar and bar-end tend to be higher than that in the arm. The estimated CCC speed is $\sim 20 \text{ km s}^{-1}$, $\sim 16 \text{ km s}^{-1}$, and $\sim 11 \text{ km s}^{-1}$ in the bar, bar-end, and arm, respectively. Although the star formation activity is different in the bar and bar-end, the CCC speed and the number density of high-speed CCC with $> 20 \text{ km s}^{-1}$ are high in both regions, implying the existence of other parameters that control the star formation. The difference of molecular gas mass (average density) of the GMCs between the bar (lower mass and lower density) and bar-end (higher mass and higher density) may be the causes for the different star formation activity.

Considering our studies, the leading candidates of causes for the star formation suppression in the bar in NGC 1300 are the presence of a large amount of diffuse molecular gases and high-speed CCCs between low mass GMCs; the physical parameters which control the observed galactic-scale SFE would be at least the diffuse molecular gas fraction and the CCC speed. Our results lay the foundation for future observations toward other galaxies/environments (e.g. weakly barred galaxies, interacting galaxies, central regions, high- z galaxies, etc.) to figure out more general physical conditions for star formation to occur in galaxies, which leads to our better understanding of galaxy formation and evolution.

Contents

1	Introduction	1
1.1	ISM in Galaxies	3
1.1.1	Organization of the ISM: Characteristic phases	3
1.1.2	Giant molecular clouds: Stellar nurseries	4
1.2	Star Formation in Galaxies	9
1.2.1	Diversity of star formation activity in galaxies	9
1.2.2	Star-formation suppression in bar regions	11
1.2.3	Recent CO observations toward strongly barred galaxies	15
1.3	Aims of This Thesis	18
2	Properties of Giant Molecular Clouds in NGC 1300	20
2.1	Scope of This Chapter	20
2.2	Observations with ALMA 12-m Array and Data Reduction	20
2.3	GMC Scale Molecular Gas Distribution in NGC 1300	22
2.4	GMC Identification and Characterization	23
2.4.1	GMCs identification	23
2.4.2	Derivation of basic properties	24
2.5	Basic Properties of GMCs	25
2.5.1	Variation of GMC physical properties with environment	27
2.5.2	The reliability of the measurements	31
2.6	Scaling Relations	32
2.6.1	Size-velocity dispersion relation	33
2.6.2	Virial equilibrium	33
2.6.3	Size-mass relation	34
2.6.4	Relationship between σ_v^2/R and Σ_{mol}	35
2.7	GMC Mass Spectra	36
2.8	Discussion: Examination of Gravitationally Unbound GMCs Scenario	38
2.9	Conclusions of This Chapter	40
3	Diffuse Molecular Gases in NGC 1300	42
3.1	Scope of This Chapter	42
3.2	Observations and Data Reduction	43
3.2.1	CO(1 – 0) emission from the NRO 45-m observations	43
3.2.2	CO(1 – 0) emission from ALMA observations	47
3.2.3	Archival data	48
3.3	Conversion to Physical Parameters	53
3.3.1	Molecular gas surface density	53
3.3.2	Star formation rate	54
3.3.3	Stacking Analysis	58

3.4	Star Formation Efficiency and Recovery Fraction	60
3.4.1	Star formation efficiency	60
3.4.2	Diffuse molecular gas fraction	62
3.4.3	SFE vs. diffuse molecular gas fraction	63
3.5	Discussion	63
3.5.1	Trends with $R_{21/10}$	63
3.5.2	Can the low SFE in the bar region be explained by only the difference of the fraction of diffuse molecular gas?	66
3.6	Conclusions of This Chapter	68
4	Environmental dependence of cloud-cloud collision speed in NGC 1300	70
4.1	Introduction and Scope of This Chapter	70
4.2	Estimated CCC Speed	72
4.2.1	Velocity Field Model	72
4.2.2	Estimation of the cloud-cloud collision speed	76
4.2.3	Results	79
4.2.4	Comparison of estimated CCC speeds with the simulation	81
4.3	Velocity Deviation	82
4.4	Discussion	85
4.4.1	Biases and caveats on our analyses	85
4.4.2	The cause for the different star formation activity between bar and bar-end with the same high CCC speed	87
4.4.3	The cause of the low SFE in the bar region	88
4.5	Conclusions of This Chapter	89
5	Summary and Future Prospects	91
5.1	Summary	91
5.2	Future Prospects	93
A	A Hydrodynamical Simulation of a Strongly Barred Galaxy	95
A.1	Scope of This Appendix	95
A.2	Numerical Methods	95
A.2.1	The code	95
A.2.2	The structure of the galactic disk	97
A.3	Results	101
A.3.1	Global structure and disk evolution	101
A.3.2	Cloud definition and classification	103
A.3.3	Cloud properties	103
A.3.4	Cloud-cloud collisions	105
A.4	Discussion	109
A.4.1	The physical mechanism of the fast collision	109
A.4.2	Why does not the fast collision affect global distributions of cloud properties?	113
A.4.3	Cloud properties: comparison with observations	114
A.5	Summary of the Simulation	116
B	CPROPS bias on the GMC properties	118
C	Supplementary results of CO observations with Nobeyama 45-m telescope	122
D	Catalog of the GMCs in NGC 1300	125

Chapter 1

Introduction

Galaxies, the fundamental building blocks of the universe, are gravitationally bound systems that are composed of a large number of stars, gas, dust, and dark matter. There are several hundred billion galaxies in the observable universe, each containing tens to hundreds of billions of stars. The Milky Way, the galaxy in which we live, is one of them, and the Sun and most of the objects in the night sky are components of the galaxy. Understanding the general properties of galaxies and theories of their formation and evolution leads to a better understanding of how the universe came to be as we currently observe it.

Galaxies have been evolving by converting gas into stars. The stellar nurseries are aggregations of cold gas known as the giant molecular clouds (GMCs). Most gas in the GMC is in the molecular phase. Their masses are $\sim 10^5 - 10^6 M_{\odot}$ and sizes are $\sim 10 - 100$ pc (Solomon et al. 1987). Within the GMCs, stars form in the region with higher density, called dense core. Once massive stars form, the parent cloud is dispersed by stellar feedback (e.g. photoionization, stellar winds, and supernovae). In this process, energy, momentum, metal, and dust are deposited into the surrounding medium. The dispersed metal-enriched gas and dust will become the cradle of the next generation of stars through the process of compression and cooling again. Through the cycle of matter between gas and stars the properties of the galaxies change; the stellar mass, metallicity, and dust mass increase with time. Therefore, it is essential to understand the physical process of the matter cycle in the galaxies to understand galaxy evolution.

Recent observations show that star formation activity appears to have a wide variety depending on galactic-scale environments. Observations of nearby galaxies with kpc/sub-kpc scale resolution have revealed a large scatter in star formation efficiency (SFE), which is the star formation rate (SFR) per unit molecular gas mass (e.g. Leroy et al. 2013). In particular, the SFE strongly depends on the galactic structure such as spiral arms, bar, and nucleus (e.g. Momose et al. 2010; Hirota et al. 2014). These observational facts suggest that the physical processes of the matter cycle (especially star formation) depend on the galactic environments. Therefore, it is required to unveiling how the galactic environments set the conditions for star formation within the molecular gases.

To figure out the issue, we argue that observations toward galaxies in which the SFE is dramatically different among the galactic-environments. This is because the larger the difference in SFE, the clearer the differences in the physical conditions that control star formation are expected to be observed. From this perspective, a strongly barred galaxy is considered to be a suitable laboratory because we can see significant differences in star formation activity among environments compared to the previously observed galaxies; the absence of star formation is clearly seen in bar regions. Figure 1.1 shows an optical image of NGC 1300, which is the nearest (~ 21 Mpc) strongly barred galaxy with significant differences in star formation activity. Remarkable dust lane is seen in the bar regions without prominent HII regions (red regions in the figure), while in the arm regions HII

regions are associated with dust lanes. Focusing on NGC 1300, in this thesis, we investigate the cause of the differences in the SFE through the CO observations toward NGC 1300 using Atacama Large Millimeter/submillimeter Array (ALMA) and Nobeyama 45-m single-dish telescope.



Figure 1.1: NGC 1300 observed with the Advanced Camera for Surveys (ACS) on Hubble Space Telescope (HST) on September 2004, through the filters of F435W (close to B), F555W (V), F658N ($H\alpha$), and F814W (I).

Although the scope of this thesis lies in better understanding the cycle of matter between gas and stars at cloud scales, it is necessary to mention that matter cycles on a galactic scale is also important in understanding galaxy evolution. Galactic interactions and gas flow into the galactic nucleus usually induce exceptionally high rates of star formation (i.e. starburst). At the same time, galactic outflows (e.g. supernovae-driven winds, active galactic nucleus jets) work as feedback processes by blowing away the gas and quenching star formation. While part of outflow metal-enriched gases are blown out of the halo, others cool and accrete back to the galaxy as recycling gases to form new stars. Besides the recycling gases, inflow of pristine gas (low-metal gas) from the outside (e.g. circumgalactic medium and/or intergalactic medium) is considered to be necessary to continue star formation for a long time. The existence of cold stream, which is filamentary accretion from the intergalactic medium into the galactic disk of star-forming galaxies without heating, has been suggested (e.g. Dekel et al. 2009; Stewart 2017). The large-scale balance between the inflow and outflow of the gas set the global inter-stellar medium (ISM) properties (e.g. gas content, SFR), which would influence the efficiency of local star formation processes (e.g. Tumlinson et al. 2017). Therefore, the ultimate goal of galactic astronomy is to comprehensively understand the physical processes of the multi-scale matter cycle in galaxies.

In the following, we briefly overview the basic properties of the ISM and star formation in nearby galaxies, to provide the background of this thesis.

1.1 ISM in Galaxies

1.1.1 Organization of the ISM: Characteristic phases

The ISM accounts for at most 10% of total baryonic mass of spiral galaxies like the Milky Way in the present-day universe (e.g. Saintonge et al. 2011; Boselli et al. 2014). In terms of galaxy evolution, however, the ISM is the most important component of galaxies as it is responsible for forming stars. Controlled by various physical factors (e.g. self-gravity, spiral arms, magnetic field, galaxy interaction), the ISM is accumulated into cold molecular gas as the birthplace of the new stars. At the same time, stars change the surrounding ISM structure and composition. Evolved stars produce and inject recycled gas with metal and dust into the ISM by stellar winds. Moreover, massive stars destroy and disperse the surrounding molecular gas through stellar feedback. That way, the properties of ISM change as galaxies evolve.

The ISM consists of gas and dust, with a mass ratio of $\sim 100:1$ in galaxies with the same metallicity as the Milky Way (e.g. Rémy-Ruyer et al. 2014)¹. Main components of the gas are hydrogen and helium, and those of the dust are heavy elements like C, Si, O, Fe. The temperature of the gas is determined by the balance of heating and cooling, and the density is determined by the balance of the several factors acting on the ISM (e.g. stellar potential, shock wave, self-gravity). Thus, the temperature and density of the gas cover a wide range, but the ISM can fall into some characteristic phases; Figure 1.2 shows the multi-phase of the ISM. (1) Warm Neutral Medium (WNM, or inter-cloud gas) of $\sim 10^4$ K and $\sim 10^{-2} - 10^0 \text{ cm}^{-3}$, (2) Cold Neutral Medium (CNM, or HI cloud) of $\sim 10^1 - 10^3$ K and $\sim 10^0 - 10^2 \text{ cm}^{-3}$, (3) Coronal gas of $\sim 10^6$ K and $\sim 10^{-2} \text{ cm}^{-3}$, (4) GMC of $\sim 10 - 100$ K and $\sim 10^2 - 10^5 \text{ cm}^{-3}$, and (5) HII region of $\sim 10^3 - 10^4$ K and $\sim 10^1 - 10^4 \text{ cm}^{-3}$.

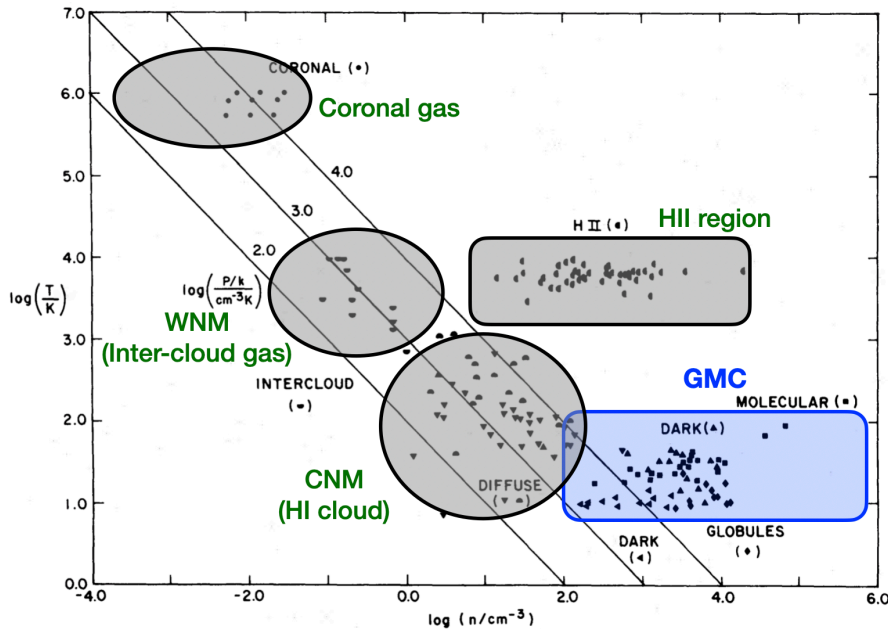


Figure 1.2: Phase diagram of the ISM. The diagonal straight lines denote constant pressures. Figure taken from Myers (1978).

WNM is warm phase of atomic hydrogen gas, which fills a significant fraction of the volume

¹Gas-to-dust mass ratio decreases with decreasing the metallicity and ranges over a 2 dex in local galaxies.

of the galactic disk $\sim 40\%$. CNM is cold phase of atomic hydrogen gas, which has a cloud-like structure filling $\sim 1\%$ of the volume of the galactic disk. Both are in approximate pressure equilibrium. The theoretical two-phase model can describe them as a stable high-temperature ($\sim 10^4$ K), low-density phase and a low-temperature ($\sim 10^2$ K), high-density phase (e.g. Field et al. 1969; Wolfire et al. 1995; Inoue et al. 2009). Coronal gas is hot gas ionized that is likely heated by supernova explosions. Most of the coronal gas has low density, filling approximately half of the volume of the galactic disk. Three-phase model (McKee & Ostriker 1977) can explain that the ISM has three thermally stable phases at 10^6 K (Coronal gas), 10^4 K (WNM), and 10^2 K (CNM).

HII region and GMC are components that are located out of the pressure equilibrium in the phase diagram. The HII region is a short-lived nebula where ionized gas is expanding. The GMC is an aggregation of cold dense gas and most GMCs are gravitationally bound systems (we will review the GMC in the next subsection). In the HII region, the hydrogen is photoionized by ultraviolet photons from recently formed massive stars (O-type and early B-type stars). The HII region is observed through hydrogen recombination lines such as $H\alpha$, $H\beta$. Since their intensity is proportional to the number of ionizing photons in the ultraviolet, which in turn depends on the number of the massive stars, the SFR of a galaxy can be estimated from the luminosity of the lines by assuming the initial mass function and escape fraction (e.g. Kennicutt 1998a).

1.1.2 Giant molecular clouds: Stellar nurseries

GMCs are the stellar nurseries in a galaxy, which are the most important components for understanding the galactic-scale star formation. The molecular hydrogen is the dominant component of the GMC. However, dipole rotational transitions are strongly forbidden because the molecular hydrogen has no permanent electric dipole moment due to its symmetric structure. The quadrupole rotational transitions are hardly observable because they are very weak. Moreover, its vibrational or electric emission lines are unobservable due to the low temperature. For these reasons, GMC is usually observed by rotational lines of carbon monoxide (CO), the second most abundant molecule in it. Since the first detection of CO(1–0) lines in 1970 (Wilson et al. 1970), our knowledge of the GMCs (especially those in the Milky Way) has advanced rapidly. In recent years, thanks to the high angular resolution observations with interferometries, such as the ALMA and NOthern Extended Millimeter Array (NOEMA), the observations of extragalactic GMCs up to $z = 1 \sim 3$ are actively progressing. In the following, we review the GMC properties.

Scaling relations

In the Milky Way, mass M , size R , and velocity dispersion σ_v of GMCs are typically $\sim 10^4\text{--}10^6 M_\odot$, $\sim 20\text{--}100$ pc, and $2\text{--}10$ km s $^{-1}$, respectively (e.g. Solomon et al. 1987; Heyer et al. 2009). Observations of GMCs revealed approximate scaling relations among M , R , and σ known as Larson’s laws (Larson 1981). Figure 1.3 shows the size-velocity dispersion relation in the Milky Way; $\sigma_v/\text{km s}^{-1} = 0.72(R/\text{pc})^{0.5}$. Heyer & Brunt (2004) found a somewhat steeper power law index of 0.59. It is notable that the σ_v of the GMCs exceeds the isothermal sound speed of $0.19 \times (T/10\text{ K})^{1/2}$ km s $^{-1}$, which indicates the internal gas in the GMC is in supersonic turbulence.

Scaling relation between M and σ_v is also seen; $\sigma_v/\text{km s}^{-1} = 0.15(M/M_\odot)^{0.25}$ (Solomon et al. 1987). These scaling relations also directly yield a mass-radius relation: $M/M_\odot = 540(R/\text{pc})^2$. This result implies that the GMCs in the Milky Way have constant molecular gas surface density: $\Sigma = M/(\pi R^2) = 170 M_\odot \text{ pc}^{-2}$. Heyer et al. (2009) reexamined the same GMC sample but using ^{13}CO emission and found the same tendency but a different value of $\Sigma = 42 M_\odot \text{ pc}^{-2}$. Note that this value merely shows the average value and observed surface density ranges one order of magnitude.

Moreover, recent observations of extragalactic GMCs show the surface density ranges at least four orders of magnitude (see below; e.g. Sun et al. 2018).

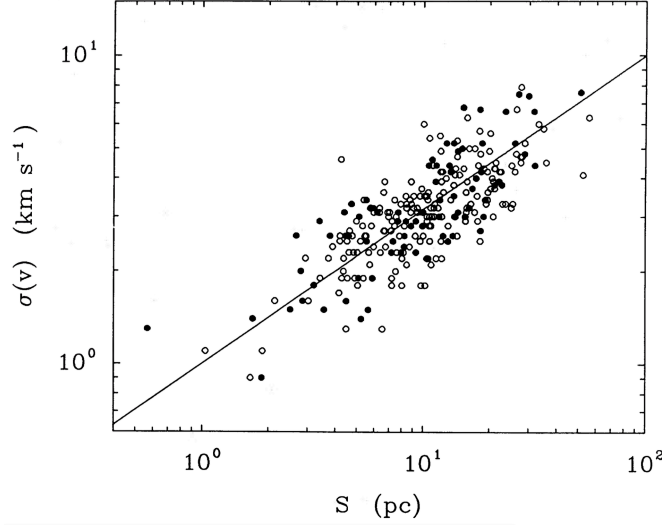


Figure 1.3: Size-velocity dispersion relation of the GMCs in the Milky Way. Size parameter S is defined as $S = D \tan(\sqrt{\sigma_l \sigma_b})$, where D is the distance to a GMC, σ_l and σ_b are rms dispersions in the galactic coordinate. The radius is related to the size parameter by $R = 3.4/\sqrt{\pi} S = 1.92S$. Figure taken from Solomon et al. (1987).

Virial parameter

Here, we briefly summarize the virial parameter, α_{vir} , which is a measure for the gravitational binding of a GMC. Neglecting effects of magnetic field and rotation of the cloud, the total internal energy of the GMC, E , is represented as the sum of the kinetic energy, T , and the gravitational potential energy, Ω ;

$$E = T + \Omega. \quad (1.1.1)$$

We assume a spherical cloud of mass M , radius R , velocity dispersion σ , density $\rho(r)$, where r is the distance from the center of the GMC. Here, we assume a power-law density profile of $\rho(r) \propto r^{-n}$. The kinetic energy is

$$T = \frac{1}{2} M \sigma^2. \quad (1.1.2)$$

Since the mass within r is $M(r) = M(R/r)^{n-3}$, we obtain

$$\Omega = - \int_0^R G \frac{M(r) \rho(r) 4\pi r^2}{r} dr = - \frac{3-n}{5-2n} \frac{GM^2}{R}. \quad (1.1.3)$$

If the GMC is in the virial equilibrium, we obtain

$$2T + \Omega = 0 \quad (1.1.4)$$

$$M = \frac{5-2n}{3-n} \frac{R\sigma^2}{G} = \frac{3(5-2n)}{3-n} \frac{R\sigma_{1D}^2}{G}, \quad (1.1.5)$$

where the one-dimensional velocity dispersion is defined by $\sigma_{1D} = \sigma/\sqrt{3}$. As equation (1.1.5), the mass obtained from the observed velocity dispersion and radius assuming virial equilibrium is called virial mass M_{vir} .

The virial parameter, α_{vir} , is defined as the ratio of virial mass to mass, and the formula for $n = 0$ is usually used (Bertoldi & McKee 1992):

$$\alpha_{\text{vir}} = \frac{M_{\text{vir}}}{M} = \frac{5R\sigma_{\text{1D}}^2}{GM} = 1163 \left(\frac{R}{\text{pc}} \right) \left(\frac{\sigma_{\text{1D}}}{\text{km s}^{-1}} \right)^2 \left(\frac{M}{M_{\odot}} \right)^{-1}. \quad (1.1.6)$$

The $\alpha_{\text{vir}} = 1$ shows the GMC is in the virial equilibrium. The prerequisite for a GMC to be gravitationally bound is $E < 0$. This becomes

$$\begin{aligned} T + \Omega &< 0 \\ \alpha_{\text{vir}} &< 2. \end{aligned} \quad (1.1.7)$$

Thus, $\alpha_{\text{vir}} < 2$ indicates the cloud is a bound system while $\alpha_{\text{vir}} > 2$ gravitationally unbound. From the scaling relations obtained by Solomon et al. (1987), the virial parameter of the GMCs in the Milky Way is $\alpha_{\text{vir}} \sim 1.6$, which suggests most of the GMCs are gravitationally bound systems.

Extragalactic GMC observations

Observations of GMCs in the Local Group galaxies and nearby dwarf galaxies have been actively carried out since the end of the 1980s; e.g. M33 (Wilson & Scoville 1990; Engargiola et al. 2003; Rosolowsky et al. 2003, 2007), M31 (Vogel et al. 1987; Sheth et al. 2008; Rosolowsky 2007), LMC (Cohen et al. 1988; Israel et al. 1993; Fukui et al. 1999, 2008), SMC (Rubio et al. 1991, 1993, 1996; Israel et al. 2003), IC10 (Wilson & Reid 1991; Ohta et al. 1992), other dwarfs (Ohta et al. 1993; Bolatto et al. 2008) (see also a review by Fukui & Kawamura 2010). For example, Ohta et al. (1992) showed that the size, velocity dispersion, and mass of GMCs in IC10 are consistent with those in the Milky Way, M31, and M33. Bolatto et al. (2008) investigated the scaling relations of GMCs in 13 local dwarf and spiral galaxies (within 5 Mpc) and compared the relations with that in the Milky Way using a consistent analysis manner. They found that extragalactic GMC properties measured across a wide range of environments were compatible with those in the Galaxy: $\sigma_v/\text{km s}^{-1} = 0.44(R/\text{pc})^{0.6}$.

In recent years, thanks to high sensitivity interferometers, extragalactic GMCs can be observed at a high angular resolution of 20~50 pc toward nearby galaxies within ~ 20 Mpc; e.g. M51 (Koda et al. 2009; Colombo et al. 2014), M64 (Rosolowsky & Blitz 2005), M83 (Freeman et al. 2017; Hirota et al. 2018), M101 (Rebolledo et al. 2015), NGC 253 (Leroy et al. 2015), NGC 300 (Faesi et al. 2018), NGC 628 (Rebolledo et al. 2015; Kreckel et al. 2018), NGC 1068 (Tosaki et al. 2017), NGC 2403, 3031, 4736, 4826 (Donovan Meyer et al. 2013), NGC 6946 (Rebolledo et al. 2012; Donovan Meyer et al. 2013; Rebolledo et al. 2015; Wu et al. 2017), NGC 4526 (Utomo et al. 2015), NGC 4567/8 (Kaneko et al. 2018). PHANGS survey observed $\sim 100,000$ GMCs toward more than 70 nearby disk galaxies with ALMA (A. K. Leroy et al., in preparation). These observations have revealed that the properties of the GMC change among the type of galaxies and environment in the galaxies.

The PdBI Arcsecond Whirlpool Survey (PAWS), which is a large program of IRAM, mapped the CO(1 – 0) emission in the inner disk of the massive spiral galaxy of M51 (distance of ~ 7.6 Mpc) with a high angular resolution of ~ 40 pc (Schinnerer et al. 2013). Using this map, Colombo et al. (2014) generated the GMC catalog, containing ~ 1500 GMCs. Interestingly, a strong correlation between the GMC size and velocity dispersion like that in the Milky Way is not seen. The majority of the GMCs have larger velocity dispersion than in the Milky Way, and $\sim 30\%$ of the GMCs are gravitationally unbound ($\alpha_{\text{vir}} > 2$). Decorrelation between size and the velocity dispersion is also seen in other galaxies (e.g. Hughes et al. 2013). Note that these results may be the result of overestimation of the velocity dispersion and radius.

Surveys of extragalactic GMCs show the large spans of velocity dispersion and surface density in nearby galaxies. Figure 1.4 shows the relation between the CO line width, $\sigma_{120 \text{ pc}}$, and the surface density, $\Sigma_{120 \text{ pc}}$, at a common resolution of 120 pc for the 15 nearby galaxies (Sun et al. 2018). The $\sigma_{120 \text{ pc}}$ and $\Sigma_{120 \text{ pc}}$ span ~ 2 and ~ 4 orders of magnitude, respectively. This figure shows molecular gas dynamical state (i.e. virial parameter; $\alpha_{\text{vir}} \propto \sigma_{120 \text{ pc}}^2 / \Sigma_{120 \text{ pc}}$) and internal turbulent pressure ($P_{\text{turb}} \propto \Sigma_{120 \text{ pc}} \sigma_{120 \text{ pc}}^2$) clearly depend on the type of galaxies: In normal star forming galaxies (i.e. main sequence galaxies; blue region), α_{vir} and P_{turb} are $1.5 - 3.0$ and $10^4 - 10^6 \text{ K cm}^{-3}$, respectively. The central regions of the galaxies show higher P_{turb} . In the more quiescent galaxies of M31 and

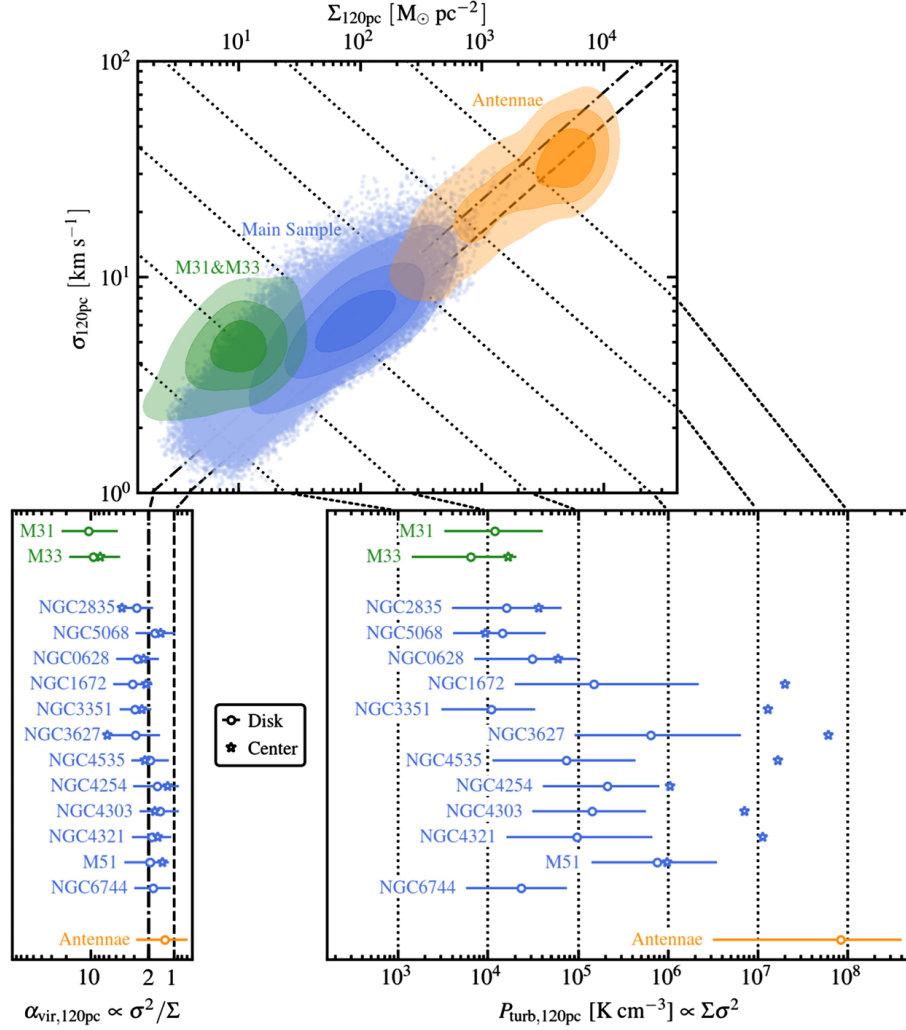


Figure 1.4: Top panel shows the relation between the CO line width and the gas surface density at a common resolution of 120 pc for the disks of 15 nearby galaxies. The bottom left panel presents the mass-weighted distribution of the virial parameter and the bottom right panel the distribution of turbulent pressure for the disk (circles) and center (star symbols). Figure taken from Sun et al. (2018).

M33 (green region), higher α_{vir} of $2 - 10$ is observed. Such higher α_{vir} is often seen in galaxies with low gas fraction (e.g. Schruba et al. 2019). The most extreme high value of P_{turb} is found in the Antennae galaxies (orange region), which are famous interacting galaxies. In there, the gas is experiencing high external pressure caused by the merger (Sun et al. 2018) and is undergoing violent compression, which can lead to gravitational collapse (e.g. Elmegreen 2018; Vanzella et al. 2019). Like the interacting galaxies, high velocity dispersion are seen in starburst (e.g. Leroy

et al. 2015), the nearby ultra luminous infrared galaxies (e.g. Saito 2019), and in high-redshift star-forming galaxies (e.g. Dessauges-Zavadsky et al. 2019), which suggest the internal GMC velocity dispersion increases for clouds forming in gas with high external pressures and densities.

GMC mass spectrum

As a useful way to study the GMC formation and destruction processes, the GMC mass spectrum has been measured (e.g. Solomon et al. 1987) and semi-analytical models for the evolution of the GMC mass spectrum have been constructed (e.g. Kwan 1979; Inoue & Inutsuka 2009; Kobayashi et al. 2017). The mass spectrum is usually expressed in a differential form known to follow a power-law relation as

$$\frac{dN}{dM} \propto M^\gamma, \quad (1.1.8)$$

where M is the molecular gas mass of a GMC, N is the number of molecular clouds and γ is an index of the power-law relation.

Integration of this expression gives a cumulative mass distribution. Several studies reported the GMC mass spectra steepens at higher masses (e.g. Williams & McKee 1997; Fukui et al. 2001, 2008; Rosolowsky et al. 2007; Gratier et al. 2012). In this case, it can be useful to model the mass spectra using a truncated power-law (Williams & McKee 1997):

$$N(> M) = -\frac{N_u}{\gamma + 1} \left[\left(\frac{M}{M_u} \right)^{\gamma+1} - 1 \right], \quad (1.1.9)$$

where M_u is an upper cutoff mass of GMCs and N_u is a measure of the number of GMCs at the upper cutoff mass. The index γ shows how the GMC mass is distributed. If γ is larger than -2 , massive GMCs dominate the total cloud mass.

The parameters of the mass spectrum (γ and M_u) are considered to be determined in the balance between the formation and destructive processes of GMCs. Enhance of the formation process of massive GMCs (e.g. agglomeration of small clouds and self-gravity; Dobbs 2008) leads to a flatter mass spectrum and a higher M_u . On the contrary, the destruction process (e.g. stellar feedback, cloud-cloud collision, and large-scale shear motion) plays a role to make the mass spectrum steeper and decrease the M_u . Adopting the continuity equation of GMCs in mass space, Inutsuka et al. (2015) showed the slope γ could be described as $\gamma = -(1 + T_f/T_d)$, where T_f and T_d are the time scales for the formation and destruction processes of GMCs, respectively. They predicted $T_f \lesssim T_d$ (i.e. $-2 \lesssim \gamma < -1$) in typical of spiral arm regions, which agrees with observations (e.g. Solomon et al. 1987). In quiescent regions (e.g. inter-arm regions), γ may be less than -2 because T_f is expected to be larger than in spiral arms due to a limited amount of dense material.

Previous observations toward such as the Milky Way and M33, γ is considered to be universal of $-2.0 \sim -1.6$ (e.g. Kennicutt & Evans 2012). However, recent observations show the presence of environmental dependence on the slope γ as expected above discussion. It is reported that differences in galactic dynamics, molecular gas abundance, and its spatial distribution cloud be causes of the differences in the mass spectrum (Hughes et al. 2013). In M51, Colombo et al. (2014) found γ and M_u vary with galactic environments: the γ is steeper in the inter-arm region than in the spiral arms and exhibits a sharp truncation at high masses in the nuclear bar region. They suggested this difference is a consequence of the combined action of large-scale dynamical processes and feedback from high-mass star formation. Hughes et al. (2016) found that the slope γ becomes steeper as the surface density of molecular gas and stellar component increase. As suggested by the diversity of the scaling relations and the mass spectra, physical mechanisms of GMC formation

and evolution would depend on the environment (i.e. galactic properties and structure), which have been keen interest recently (e.g. Chevance et al. 2020b).

1.2 Star Formation in Galaxies

1.2.1 Diversity of star formation activity in galaxies

Empirical relation of galactic-scale star formation

It is important to investigate the relation between SFR and molecular gas density in the context of galaxy evolution. This relation describes how efficiently galaxies convert their gases into stars. In 1959, Schmidt hypothesized that the SFR is proportional to the n th power of the volume density of the gas (Schmidt 1959):

$$\rho_{\text{SFR}} \propto \rho_{\text{gas}}^n. \quad (1.2.1)$$

Index n is related to the mechanism of the star formation. If the n is close to 1, it implies a simple picture in which stars form in proportion to the density of the gas, i.e. SFE ($= \rho_{\text{SFR}}/\rho_{\text{gas}}$) is constant. On the other hand, if the n is close to 2, the SFR can be considered to be proportional to the square of the number density of molecular clouds. In this case, collision between molecular clouds may play a central role in the star formation process. Although the index n was expected to be between 1 and 2, this hypothesis was not tested for a long time because the observing techniques for measuring molecular gas mass had not been developed and the derivation of SFRs had not been established yet. As the first statistical test, Kennicutt (1989) combined the measurements of the distribution of H α emission in galaxies with published H I and CO(1 – 0) data, and found that the power law relation holds. Kennicutt (1998b), the revised paper of Kennicutt (1989), found the relation between the SFR surface density and molecular gas surface density (Figure 1.5(a)) as

$$\left(\frac{\Sigma_{\text{SFR}}}{\text{M}_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}} \right) = (2.5 \pm 0.7) \times 10^{-4} \left(\frac{\Sigma_{\text{gas}}}{\text{M}_{\odot} \text{ pc}^{-2}} \right)^{1.4 \pm 0.5}. \quad (1.2.2)$$

Here, the Σ_{SFR} and Σ_{gas} are derived by dividing the total SFR and gas (H₂ + H I) mass by the area of the galaxy, respectively. This is often referred to as the Kennicutt-Schmidt (Schmidt-Kennicutt) law. One can explain $n \sim 1.4$ by assuming that the SFR volume density is proportional to the ratio of the volume density of the gas to its free-fall time (τ_{ff}) as $\rho_{\text{SFR}} \propto \rho_{\text{gas}}/\tau_{\text{ff}} \propto \rho_{\text{gas}}/(1/\sqrt{G\rho_{\text{gas}}}) \propto \rho_{\text{gas}}^{1.5}$. If the gas scale height is constant, $\Sigma_{\text{SFR}} \propto \Sigma_{\text{gas}}^{1.5}$ is given. This scenario is simple and straightforward, however, it should be noted that the actual star formation process is not as simple as this scenario because there are orders of magnitude gap between the scale of galaxies and the scale of star formation. Nonetheless, in many theoretical simulations of galaxy formation and evolution, SFR is parameterized with the gas density and the free-fall time.

Diversity of star formation activity in galaxies

Recent CO observations show the different star formation laws. Figure 1.5(b) shows the Kennicutt-Schmidt plot for different types of galaxies presented by Daddi et al. (2010). This figure suggests the existence of two different star formation regimes: a long-lasting mode for disk galaxies (low SFE; $\sim 1 \text{ Gyr}^{-1}$) and a more rapid mode for starburst galaxies (high SFE; $\sim 10 - 100 \text{ Gyr}^{-1}$). The former includes BzK galaxies, $z \sim 0.5 - 2.3$ normal galaxies, and local spiral galaxies. The latter includes the SMGs, QSOs, local ULIRGs, and local starburst galaxies, probably under major mergers or in dense nuclear star formation regions.

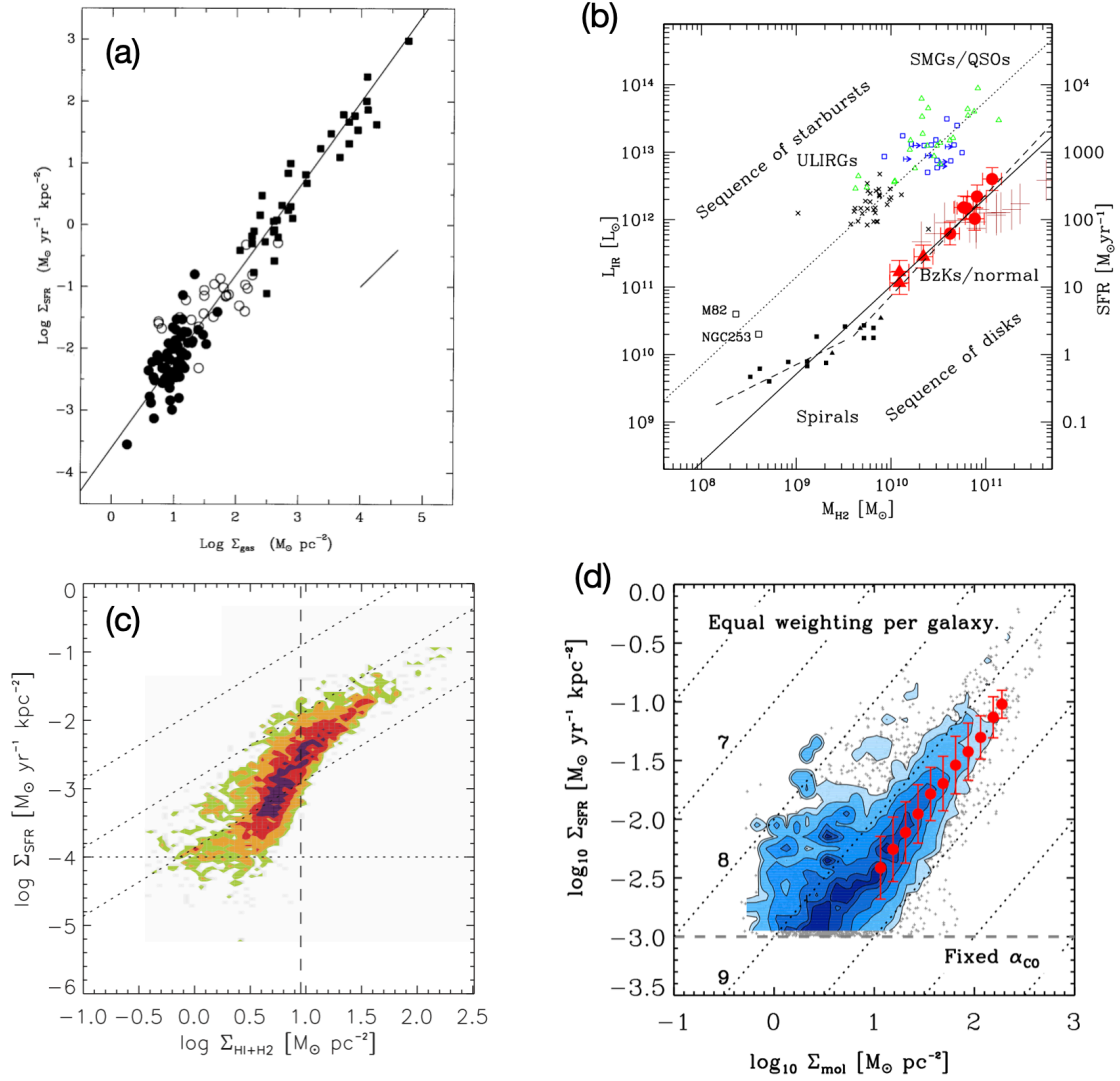


Figure 1.5: **(a)** Global Kennicutt-Schmidt law of nearby galaxies. Filled circles and squares show the normal disk galaxies and starburst galaxies, respectively. Open circles show the centers of the normal disk galaxies. The line shows the equation (1.2.2). Figure taken from Kennicutt (1998b). **(b)** Global Kennicutt-Schmidt law for many types of galaxies: BzK galaxies (Daddi et al. 2010, red filled circles), $z \sim 0.5$ disk galaxies (Salmi et al. 2012, red filled triangles), $z = 1 - 2.3$ normal galaxies (Tacconi et al. 2010, brown crosses), SMGs (Greve et al. 2005; Frayer et al. 2008; Daddi et al. 2009a,b, blue empty squares), QSOs (Riechers et al. 2006, green triangles), local ULIRGs (Solomon et al. 1997, black crosses), and local spirals (Leroy et al. 2009; black filled squares, Wilson et al. 2009; black filled triangles). The two nearby starbursts M82 and the nucleus of NGC 253 are also shown (data from Weiß et al. 2001; Houghton et al. 1997; Kaneda et al. 2009). The solid line is a fit to local spirals and BzK galaxies and the dotted line is the same relation shifted in normalization by 1.1 dex. The dashed line is a possible double power-law fit to spirals and BzK galaxies. Figure taken from Daddi et al. (2010). **(c)** Resolved Kennicutt-Schmidt law (Σ_{SFR} vs. Σ_{H_2}) of nearby spiral galaxies at the resolution of 750 pc. H_2 gases were measured from $\text{CO}(2-1)$ with an intensity ratio $I_{\text{CO}(2-1)}/I_{\text{CO}(1-0)} = 0.8$. The sensitivity limit of star formation tracer is indicated by a horizontal dotted line. The vertical dashed line indicates the transition from the low-density regime to the high-density regime (see text). Figure taken from Bigiel et al. (2008). **(d)** Resolved Kennicutt-Schmidt law at 1-kpc resolution for 30 nearby disk galaxies. H_2 gases were measured from $\text{CO}(2-1)$ with an intensity ratio $I_{\text{CO}(2-1)}/I_{\text{CO}(1-0)} = 0.7$. Figure taken from Leroy et al. (2013).

Although Figure 1.5(a) and (b) show the global star formation laws, there have been some studies on the spatial resolved Kennicutt-Schmidt law in nearby galaxies. For example, Bigiel et al. (2008) measured the Kennicutt-Schmidt law at the resolution of 750 pc in a sample of 18 nearby non-barred spiral galaxies, using $^{12}\text{CO}(2-1)$ line as a molecular gas tracer. They find a clear correlation as $\Sigma_{\text{SFR}} \propto \Sigma_{\text{H}_2}^{1.0 \pm 0.2}$. Further, they investigated the relation between Σ_{SFR} and $\Sigma_{\text{H}_2} + \Sigma_{\text{HI}}$ at the resolution shown as Figure 1.5(c). In this figure, the presence of two distinct regimes are clearly seen; (1) A low-density regime ($\Sigma_{\text{HI}+\text{H}_2} \lesssim 10 \text{ M}_\odot \text{ pc}^{-2}$ or $N(\text{HI}) \lesssim 10^{21} \text{ cm}^{-2}$) where the star formation activity is low, and the dependence of the SFR density on gas density is very steep (or not so well correlated). The low-density regime is mostly observed in the outer disks of spiral galaxies and the gas in this regime is HI-dominated ($\Sigma_{\text{HI}} > \Sigma_{\text{H}_2}$), though local concentrations of molecular gas are often found. (2) A high-density regime ($\Sigma_{\text{HI}+\text{H}_2} \gtrsim 10 \text{ M}_\odot \text{ pc}^{-2}$ or $N(\text{HI}) \gtrsim 10^{21} \text{ cm}^{-2}$) where the SFR is high and is strongly correlated with the gas density. The gas in this regime is dominated by the molecular gas ($\Sigma_{\text{H}_2} > \Sigma_{\text{HI}}$). The picture of two distinct regimes suggests the existence of the threshold density for the star formation. Similar star formation thresholds have been observed previously (e.g. Davies et al. 1976; Nakano et al. 1987; Ohta et al. 1988; Kennicutt 1989, 1998b). Although the threshold gas density for the star formation is thought to be universal (e.g. Gao & Solomon 2004), recent spatial resolved HCN, which is one of the dense gas tracers, observations suggest the threshold density depends on the environments (e.g. Bigiel et al. 2016; Gallagher et al. 2018).

Figure 1.5(d) shows the 1-kpc resolution Kennicutt-Schmidt law for nearby 30 disk galaxies by Leroy et al. (2013). They used $^{12}\text{CO}(2-1)$ maps from the HERACLES survey. They demonstrated a first-order linear correspondence ($\Sigma_{\text{SFR}} \propto \Sigma_{\text{mol}}^{1.00 \pm 0.15}$) but also found important second-order systematic variations in the apparent molecular gas SFE. This result suggests an environmental dependence of star formation activities within a galaxy exists. Such variations of the SFE with environments are reported for other nearby galaxies and the Milky Way (e.g. Longmore et al. 2013; Usero et al. 2015; Gallagher et al. 2018).

Note that the slopes of the resolved Kennicutt-Schmidt law described here (Bigiel et al. 2008; Leroy et al. 2013) are somewhat shallower than that obtained by Kennicutt (1998b). This difference may be due to the different molecular gas tracers. Bigiel et al. (2008) and Leroy et al. (2013) used not $\text{CO}(1-0)$ but $\text{CO}(2-1)$ and assumed a constant line ratio of $\text{CO}(2-1)/\text{CO}(1-0)$ to measure the molecular gas surface density. However, there is a positive correlation between the line ratio and the gas surface density, and it is shown that the assumption of the constant line ratio tends to make the slope shallow (Morokuma-Matsui & Muraoka 2017).

1.2.2 Star-formation suppression in bar regions

Environmental dependence of star formation activity can be seen just by looking at the optical images of galaxies. Figure 1.6 shows M51 observed by HST. Stars form mostly in spiral arms as well as in the central region of the galaxy. In spiral arms, stars form in GMCs, which coexist with dust lanes. HII regions, which are represented as red regions, are associated with the dust lanes. This is usually interpreted in terms of the spiral density wave; the gases go into the spiral density wave, then dense shocked gas regions form in the spiral arms which result in the formation of GMCs. In the GMCs, stars form and the massive stars produce HII regions. However, star formation in bar regions of typical strongly barred galaxies is different from that in spiral arms (Figure 1.1). Although there are remarkable dust lanes along the stellar bar, prominent HII regions are often not seen. The presence of the dust lane implies the existence of molecular clouds. Nevertheless, (massive) star formation is notably absent.

Star formation suppression in the bar regions is reported by a lot of observations. In the radial

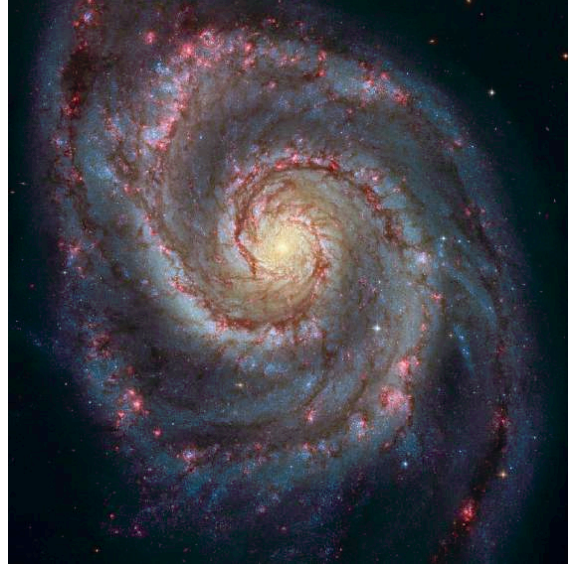


Figure 1.6: M 51 observed with ACS on HST on January 2005, through the filters of F435W (close to B), F555W (V), F658N ($H\alpha$), and F814W (I).

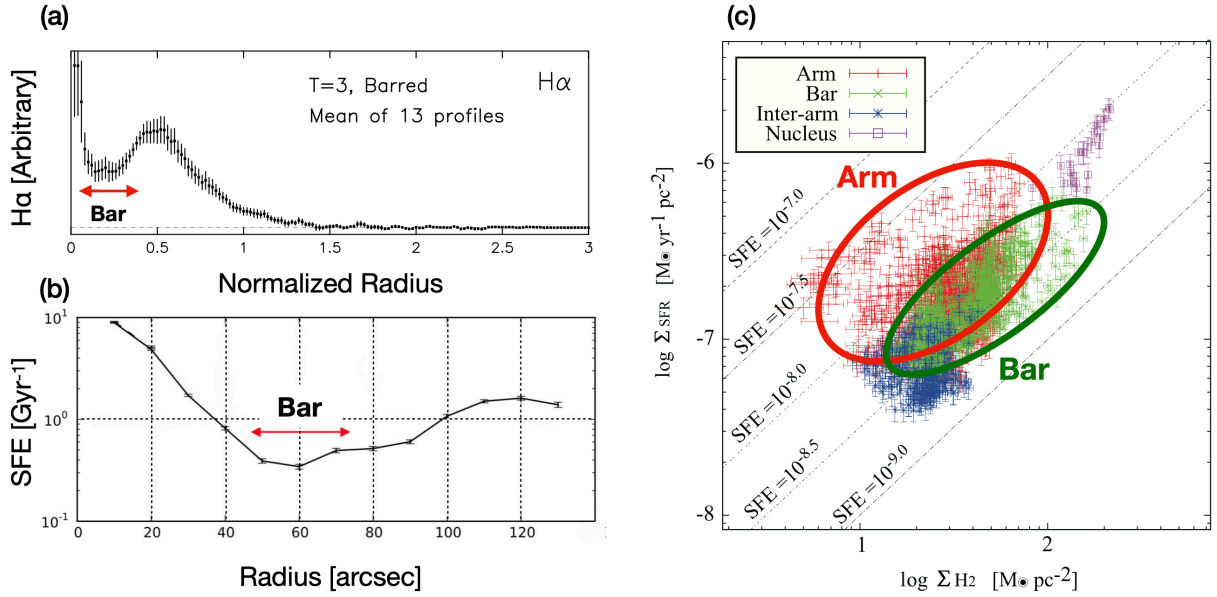


Figure 1.7: **(a)** The average radial $H\alpha$ profile for 13 SBb galaxies. Figure taken from James et al. (2009). **(b)** Solid line shows the radial distribution of SFE in M 83. Figure taken from Hirota et al. (2014). **(c)** Resolved Kennicutt-Schmidt law for NGC 4303 at the angular resolution of ~ 500 pc. Figure taken from Momose et al. (2010).

profile of $H\alpha$ line emission, which is one of the massive star formation tracers, there is a strong dip near the bar regions of early-type barred galaxies (James et al. 2009, Figure 1.7(a)). In galaxies with bars of intermediate strength, the $\text{SFE} (= \Sigma_{\text{SFR}}/\Sigma_{\text{H}_2})$ in the bar region is 2 $\sim$ 3 times lower than that in the arm region (e.g. M83; Hirota et al. 2014, Figure 1.7(b), NGC 4303; Momose et al. 2010, Figure 1.7(c)). In strongly barred galaxies, the absence of massive star formation along the bars is clearly seen as described above. Another evidence for the massive star formation suppression was provided from an independent analysis by Hakobyan et al. (2016). They found that the radial distribution of core-collapse supernovae in barred galaxies is different from that of unbarred galaxies, while the distributions of Type Ia supernovae are not significantly different.

These results can be explained by the suppression of massive star formation in the radial range of the bars. However, physical mechanisms that suppress the massive star formation in the bar regions are still unclear.

Cause of the star formation suppression in the bar regions

This question is a long-standing problem, and several explanations have been proposed in observational and theoretical studies. Tubbs (1982) made numerical hydrodynamic simulations of a strongly barred galaxy, NGC 5383 to test the destruction of dense gas clouds in the gravitational field by the strong bar. Tubbs (1982) suggested the molecular clouds may be destroyed by shock due to the high velocity of the gases relative to the bar structure. Hydrodynamic simulations by Athanassoula (1992) showed that the density of the gas in the bar region is low, except for the loci of shocks. Along with the shocks, there is a high shear which probably suppresses the molecular cloud formation (see also Zurita et al. 2004). The role of shear for the suppression of star formation within the bar regions is also suggested in recent Milky Way-like simulation at sub-pc resolution (Emsellem et al. 2015). CO observations toward NGC 1530 suggest intense shock with high-velocity jumps and a large shear suppress the star formation by destroying the molecular clouds (Reynaud & Downes 1998). It was proposed that gas in the bar regions is efficiently depleted due to the formation of the bar structure (e.g. Spinoso et al. 2017; James & Percival 2018).

Recent studies proposed other scenarios and physical mechanisms that could suppress the star formation fall into the following three scenarios.

Scenario 1: Gravitationally unbound molecular clouds in bar regions. This scenario means that GMCs in the bar regions have $\alpha_{\text{vir}} > 2$. Sorai et al. (2012) made $^{12}\text{CO}(1-0)$ map of the barred spiral galaxy Maffei 2 at an angular resolution of 200 pc with a single-dish telescope and investigated the physical properties of the molecular gas in the bar regions. They found that the distribution of the peak temperature, velocity width, and integrated intensity of the CO emission lines in the bar region is quite different from those in the arm region. They determined the physical properties of the molecular gas to reproduce the resulting distribution based on the large velocity gradient approximation and found that molecular gas in the bar regions may be gravitationally unbound and hard to form stars (Figure 1.8(a)). Nimori et al. (2013) performed a 2D hydrodynamical simulation and also found the unbound clouds in the bar regions.

Scenario 2: A large amount of diffuse molecular gases in bar regions. Molecular gas traced by $^{12}\text{CO}(1-0)$ would consist of two components: One is GMCs in which star formation occurs. The other is the extended diffuse component which is distributed on scales larger than sub-kpc. Presence of such diffuse component is reported by Pety et al. (2013) and Caldú-Primo et al. (2015); they found that about half of the $^{12}\text{CO}(1-0)$ emission arises mostly from spatial scales larger than 1.3 kpc in M51 and 1.0 kpc in NGC 4736, respectively. In the SFE calculation using $^{12}\text{CO}(1-0)$ emission, the diffuse molecular gas, which would not directly contribute to the current star formation activity, is included in the Σ_{H_2} . This scenario proposes that the diffuse gas greatly contributes to the Σ_{H_2} in the bar regions and that the SFE becomes low in appearance. Single-dish CO observations toward barred galaxies show gas density in the bar regions is lower than that in the arm regions using non-LTE analysis (e.g. NGC 2903; Muraoka et al. 2016, and NGC 4303; Yajima et al. 2019). This suggests that a large amount of diffuse molecular gases exists in the bar. In the Milky Way, a dense gas fraction in the Galactic bar region is smaller than that in the Galactic arm region, which would imply the presence of a large amount of diffuse gases in the bar (Torii et al. 2019, Figure 1.8(b)).

Scenario 3: High-speed cloud–cloud collisions (CCCs) in bar regions. CCCs induce clump formation by shock compressions and have been suggested as the mechanism of massive star formation (e.g. Habe & Ohta 1992; Fukui et al. 2014; Renaud et al. 2015). Recent hydrodynamical

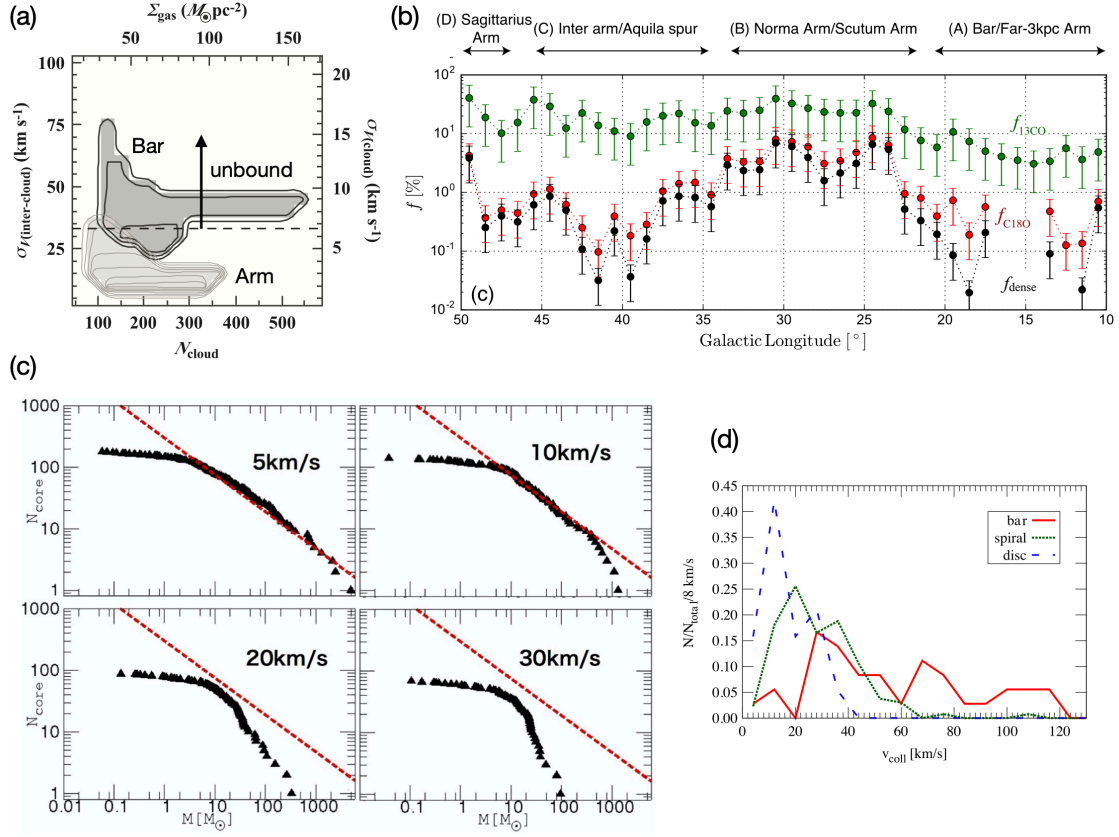


Figure 1.8: **(a)** Distribution of the number of clouds in the beam and inter-cloud velocity dispersion required to reproduce the observed peak temperature, velocity width, and velocity-integrated intensity of the CO(1 – 0) line profiles in Maffei 2 with Nobeyama 45-m telescope. Molecular gas in the bar regions distributes in the region colored dark gray, while that in the arm regions distributes in the light-gray region. A simple model of a clouds ensemble is assumed here; Each cloud is uniform and spherical with the same radius of 10 pc, density of $1 \times 10^3 \text{ cm}^{-3}$, and kinematic temperature of 15 K, and that the clouds are randomly distributed within a beam. Broken lines represent the boundaries between gravitationally bound and unbound molecular cloud. Figure taken from by Sorai et al. (2012). **(b)** The longitudinal distribution of dense gas mass fraction f_{dense} (black filled circles) by Torii et al. (2019). The f_{dense} is defined as the fraction of molecular gas with $A_V > 8$ mag to total molecular gas. $f_{^{13}\text{CO}}$ ($f_{\text{C}^{18}\text{O}}$) shows the fraction of the molecular gas mass traced by ^{13}CO (C^{18}O) to the total molecular gas mass. The f_{dense} in the bar region in the Milky Way is $\sim 0.1 \%$. **(c)** The cumulative core mass distribution of the collision between two clouds for the four collision speeds 5, 10, 20, and 30 km s^{-1} , at the converging point. The red dashed line shows $N_{\text{core}} = 300 M^{-0.6}$. The number of high mass core decreases with increasing the collision speed. Figure taken from Takahira et al. (2018). **(d)** Distribution of collision speeds of clouds in bar, arm, and disk regions by Fujimoto et al. (2014a). In the arm and disk regions, the collision speed is 10 – 40 km s^{-1} , while in the bar regions larger ($> 50 \text{ km s}^{-1}$) collision speed is seen.

simulations of the CCCs suggest that star formation activity strongly depends on the relative speed of the two colliding clouds. Takahira et al. (2014, 2018) show a high-speed CCC can shorten the gas accretion phase of the cloud cores formed, leading to suppression of core growth and massive star formation (Figure 1.8(c)). Further, a high-resolution ($\sim$ a few pc) 3D hydrodynamical simulation of an intermediate-type barred galaxy performed by Fujimoto et al. (2014b) found that CCC speed in the bar regions is larger than in the arm regions (Figure 1.8(d)). Based on this simulation, Fujimoto et al. (2014a) proposed that difference in CCC speed between the arm and bar is responsible for the observed low SFE in the bar.

However, it is still unclear which scenario is the most dominant cause for the low SFE in the bar regions. Moreover, none of the above studies have directly observed GMCs. Therefore, in order to understand the star formation suppression in the bar regions, we need to identify the individual GMCs in the bar regions with high angular resolution observations and investigate each scenario to figure out which scenario is the most dominant cause of the suppression.

1.2.3 Recent CO observations toward strongly barred galaxies

CO observations toward nearby barred galaxies have been made: e.g. M83 (Handa et al. 1990; Lord & Kenney 1991; Rand et al. 1999; Lundgren et al. 2004; Sakamoto et al. 2004; Muraoka et al. 2007, 2009; Hirota et al. 2014, etc.), NGC 1097 (Gerin et al. 1988; Hsieh et al. 2011, etc.), NGC 1300 (Regan et al. 1999), NGC 1365 (Sandqvist et al. 1995; Sandqvist 1999), NGC 1530 (Regan et al. 1999; Reynaud & Downes 1997, 1999), NGC 2903 (Regan et al. 1999; Muraoka et al. 2016), NGC 3627 (Regan et al. 1999), NGC 4303 (Momose et al. 2010), NGC 4314, NGC 5135 (Regan et al. 1999), NGC 5383 (Ohta et al. 1986; Regan et al. 1999; Sheth et al. 2000), NGC 7479 (Sempere et al. 1995; Laine et al. 1999), and other barred galaxies in CO surveys (Regan et al. 2001; Kuno et al. 2007; Bolatto et al. 2017). However, almost all of these observations were made with large beam sizes even with the interferometer, corresponding to physical size of typically 1 kpc or more. Further, many of the observations focused on the central regions and the arm regions in the barred galaxies, and high resolution and high sensitivity observations of the bar regions have been very much limited. Unfortunately, these galaxies previously observed are not necessarily suitable targets to study the cause for the suppression of star formation activity in the bar regions, because many of them have an intermediate-type bar (classified as SAB or even SA) and do have star forming regions associated with the bar or bar-like region.

In order to understand the cause for the suppression of the star formation in the bar regions, prototype strongly barred galaxy NGC 1300 is a very suitable laboratory to examine the properties of the GMCs to test the scenarios described above. Again, in NGC 1300, a remarkable dust lane is seen in the bar region without prominent HII regions, while in the arm region HII regions are associated with dust lanes (Figure 1.1). Since NGC 1300 is comparatively near to us (~ 20 Mpc), we can achieve a high spatial resolution of ~ 50 pc, corresponding to the typical GMC size with the ALMA. However, CO emission line was not detected toward the bar regions of NGC 1300 (e.g. Regan et al. 1999).

Recent CO observations toward NGC 1300 with Nobeyama 45-m telescope

To confirm the presence of the molecular gas in the bar region of NGC 1300, we observed CO(1 – 0) line toward the galaxy with the 45-m telescope of Nobeyama Radio Observatory (NRO)². The details were presented by Maeda et al. (2018). The purposes of the observations are (1) to detect molecular gases in the bar regions and arm regions in NGC 1300 and to derive masses of the molecular gases to make further investigations with ALMA, and (2) to derive velocity widths of CO emissions in a beam size ($\sim 1 - 2$ kpc) of the 45-m telescope, and compare the velocity widths in the bar regions and arm regions. The purpose (2) intends to examine *Scenario 3* described above; Figure 1.9 illustrates line profiles of the gases ($n \geq 100 \text{ cm}^{-3}$) in the bar and arm regions in the simulation by Fujimoto et al. (2014b). The bar (arm) regions are selected from both sides with respect to the center of the galaxy. Each region is taken to represent the beam size of NRO 45-m telescope, i.e. a circular region with a diameter of 1.0 kpc, and we set the viewing angle to the same

²Nobeyama Radio Observatory (NRO) is a branch of the National Astronomical Observatory of Japan, National Institutes of Natural Sciences.

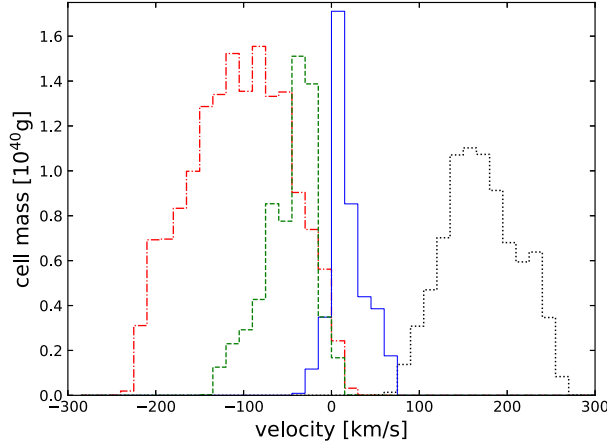


Figure 1.9: Line profiles of the gases in the bar regions (black solid line and red dash-dotted line) and the arm regions (blue dotted line and green dashed line) in the simulation by Fujimoto et al. (2014b) and Fujimoto et al. (2014a). The bar (arm) regions are selected from both sides with respect to the center of the galaxy. Each region is a circular region with a diameter of 1.0 kpc and the viewing angle is set to the same as that of NGC1300. The width of each bin is 15 km s^{-1} . The offset of the velocity is just reflection of the velocity field (rotation curve). Figure taken from Maeda et al. (2018).

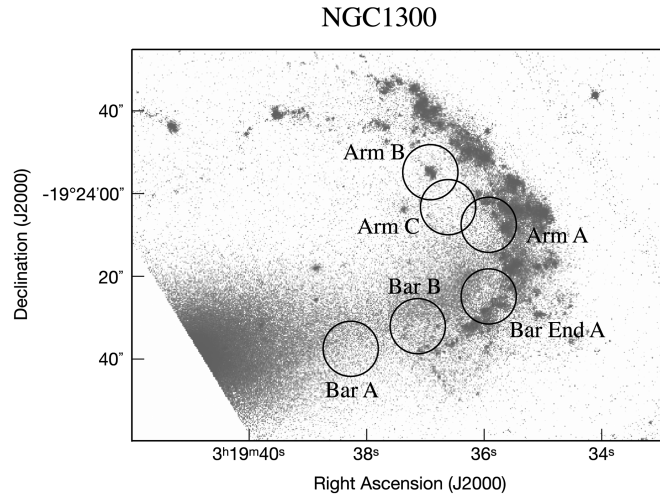


Figure 1.10: NGC 1300 taken with HST (F658N : $\text{H}\alpha$ emission + continuum) Observed positions are superimposed. Circles show the beam size of $13.5''$ of the NRO 45-m telescope. Figure taken from Maeda et al. (2018).

as the inclination of NGC1300. Since the relative velocity among the clouds in the bar regions is larger than that in the arm regions, the profiles in the bar regions (black and red) are much wider (Full Width at Zero Intensity, FWZI $\sim 250 \text{ km s}^{-1}$) than those in the arm regions (blue and green) ($\sim 130 \text{ km s}^{-1}$). Although the galaxy in this simulation was modeled based not on a strongly barred galaxy but an intermediate-type one (M83), we investigated whether the same tendency is qualitatively seen in observed profiles or not.

We carried out CO(1 – 0) line observations of NGC 1300 on 2015/16 and 2016/17 seasons. The observed positions are shown with circles in Figure 1.10. We observed six regions in NGC 1300. Bar A and Bar B are in the bar region where the dust lane is most clearly seen and there are no HII regions associated with it. Arm A and Arm B are in the arm region where a clear dust lane

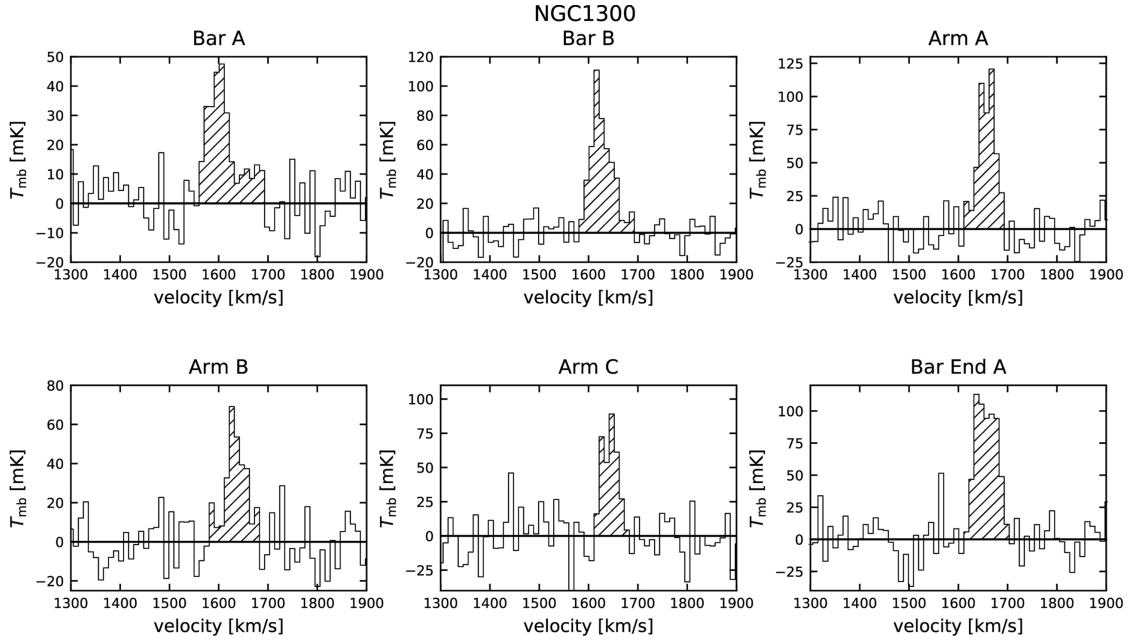


Figure 1.11: CO emission profiles in NGC 1300 obtained with Nobeyama 45-m telescope. The observed positions are shown in Figure 1.10 with black circles. Velocity refers to LSR velocity. The CO emission line is shown as a hatched region. Figure taken from Maeda et al. (2018).

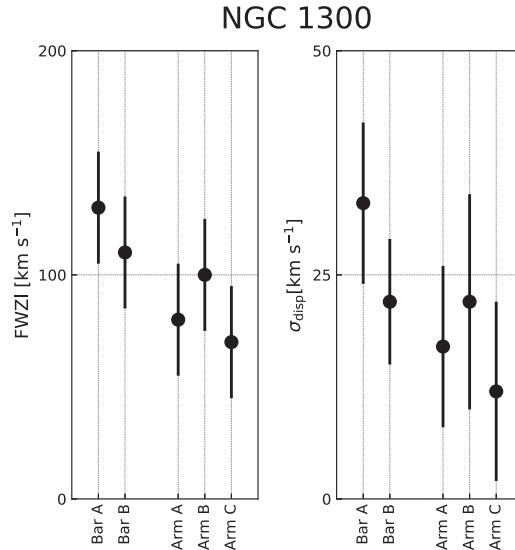


Figure 1.12: Velocity widths (Full Width at Zero Intensity, FWZI, and intensity-weighted velocity dispersion, σ_{disp}) in the bar and arm regions of NGC 1300. Error bars shown for the FWZI are 25 km s^{-1} . Figure taken from Maeda et al. (2018).

associated with HII regions is seen. Arm C is also in the arm region but with no HII regions. We additionally observed a bar end region (Bar End A) where HII regions are seen. The half-power beam width (HPBW) was $\sim 13.5''$ which corresponds to 1.34 kpc at the distance of NGC 1300 (20.7 Mpc). The frequency resolution was 488.28 kHz, corresponding to 1.27 km s^{-1} at 115 GHz. The line intensity was calibrated by the chopper wheel method. The T_{sys} was 350 – 600 K for NGC 1300. The observed data were analyzed using the NRO reduction software, NEWSTAR. After flagging and the baseline subtraction, we smoothed the spectrum by binning to 10 km s^{-1} . We

converted the antenna temperature (T_A^*) into the main beam brightness temperature (T_{mb}) using the main beam efficiency of $\eta_{\text{mb}} = 0.42$, where $T_{\text{mb}} = T_A^* / \eta_{\text{mb}}$.

We detected CO emission lines from all the regions observed (Figure 1.11). Significant emissions were seen in all the bar regions in NGC 1300, indicating that the molecular gases do exist in the bar regions. For the bar regions, most of the spectra show asymmetric shapes similar to the results of the simulation (Figure 1.9) and some of them show double peak structure (Bar A). The molecular gas surface density in the bar and arm regions are comparable; $\sim 10 \text{ M}_\odot \text{ pc}^{-2}$, which corresponds to the molecular gas masses in the beam size of $\sim 2.0 \times 10^7 \text{ M}_\odot$. Here, we adopted a canonical CO-to- H_2 conversion factor of $4.36 \text{ M}_\odot (\text{K km s}^{-1} \text{ pc}^2)^{-1}$ including a factor of 1.36 to account for the presence of helium.

Figure 1.12 shows the derived velocity widths. Here, we used FWZI and intensity-weighted velocity dispersion (σ_{disp}). We find FWZI and σ_{disp} in the bar regions are larger than those in the arm regions on average in each galaxy, which is qualitatively consistent with the simulation (Figure 1.9). Maeda et al. (2018) observed another strongly barred galaxy of NGC 5383 and the same tendency is seen. However, the trend is not so clear; the velocity width in Bar B region is comparable to that in Arm B region, and in the Arm C region, where no clear HII region is seen, the velocity width is smaller than those in the Arm A, B, and the bar regions. Larger velocity widths in the bar region are seen in the previous and recent observations with the single-dish telescope toward other intermediate-type barred galaxies (Regan et al. 1999; Sorai et al. 2012; Morokuma-Matsui et al. 2015; Muraoka et al. 2016; Yajima et al. 2019). However, the velocity width is also affected by the velocity field and molecular cloud distribution in the beam besides relative velocity among clouds. Therefore, although our results are broadly consistent with *Scenario 3*, concluding that the results support *Scenario 3* is premature. Further, it is difficult to investigate *Scenario 1 and 2* using only single-dish observations. Therefore, to detect individual GMCs, observations of higher angular resolution with ALMA are necessary.

1.3 Aims of This Thesis

The scope of this thesis is to investigate the physical mechanisms that make star formation activity suppressed in the bar regions through high angular resolution molecular gas observations, which leads to better understanding how the galactic environments set the conditions for star formation within the molecular gas. Throughout this thesis, we target the prototype strongly barred galaxy NGC 1300. As described in Section 1.2.3, this galaxy is very suitable laboratory because physical mechanism(s) of the suppression is(are) expected to be clearly seen and is close enough to detect GMCs using ALMA. Our work can be a seed research for future observations toward other type of galaxies to understand the matter cycle as galaxy evolution.

As described in Section 1.2.2, three scenarios are proposed as the causes of the star formation suppression in the bar regions; *Scenario 1*: Gravitationally unbound molecular clouds in bar regions. *Scenario 2*: A large amount of diffuse molecular gases in bar regions. *Scenario 3*: High-speed CCCs in bar regions. However, no one has comprehensively examine these theories through the high angular molecular gas observations which can detect individual GMCs. Therefore, in this thesis, we examine each scenario using CO(1 – 0) observation at a high angular resolution of $\sim 40 \text{ pc}$ toward NGC 1300. In examining *Scenario 2* and *3*, we also use the CO mapping data with Nobeyama 45-m telescope and ALMA archival data. The main parts of this thesis is organized as follows: In Chapter 2, we measure the properties of GMCs and investigate environmental dependence of the properties, especially, virial parameter to examine *Scenario 1*. We describe the details of the ALMA CO observations here. In Chapter 3, we examine *Scenario 2* by investigating the relation between

the SFE and the diffuse molecular gas fraction, which is derived using the CO(1 – 0) flux obtained from the interferometer of ALMA, which has no sensitivity on diffuse molecular gases, and the total CO(1 – 0) flux obtained from Nobeyama 45-m telescope. In Chapter 4, we estimate the CCC speed using GMC data created in Chapter 2 to examine *Scenario 3*. Although brief conclusions of each topic are given in each Chapter, we summarize our new points of view regarding the star formation suppression in the bar regions in Chapter 5. Finally, Chapter 6 describes future prospects. Table 1.1 summarizes the parameters of NGC 1300 adopted throughout this thesis. The main part of this thesis is based on my refereed papers "Properties of giant molecular clouds in the strongly barred galaxy NGC 1300"(Maeda et al. 2020a) and "A large amount of diffuse molecular gases in the bar of the strongly barred galaxy NGC 1300: cause of the low star formation efficiency"(Maeda et al. 2020b), and submitted paper "Connection among environment, cloud-cloud collision speed, and star formation activity"(Maeda et al. submitted to MNRAS). My contributions are planning, preparation and performing of observations, data reduction and other analyses, and a large part of discussions.

It is important to examine the proposed scenarios not only observationally, but also theoretically. In particular, since it is impossible to track the GMCs by observations, simulations of GMC motion in the galaxy are essential to study the CCC speeds. Therefore, besides the CO observations, we carry out a hydrodynamical simulation of a strongly barred galaxy, using a stellar potential which is taken from observational results of NGC 1300, to examine the GMC properties and the CCC speeds as shown in Appendix A. In the main parts of this thesis, we compare the observation and the simulation. The result of the simulation was published as "Fast cloud–cloud collisions in a strongly barred galaxy: suppression of massive star formation "(Fujimoto, Maeda, et al. 2020). My contributions to this work are data reduction of the CO archival data for model constructions and part of discussions.

Table 1.1: Properties of NGC 1300

Parameter	Value
Morphology*	SB(s)bc
Center position (J2000.0) [†]	03 ^h 19 ^m 41 ^s .036 –19°24′40″.00
Inclination [§]	50°.2
PA of the line of nodes [§]	274°.5
PA of the bar [§]	281°
Distance [‡]	20.7 Mpc
Linear scale	100 pc arcsec ^{–1}

* Sandage & Tammann (1981)

[†] The peak of V-band image.

[§] England (1989b)

[‡] We adopted the systemic velocity with corrections for the Virgo cluster, the Great Attractor, and the Shapley concentration of 1511 km s^{–1} (Mould et al. 2000) and the Hubble constant of 73 km s^{–1} Mpc^{–1}.

Chapter 2

Properties of Giant Molecular Clouds in NGC 1300

Part of this Chapter was published as Maeda et al. 2020, MNRAS, 493, 5045

2.1 Scope of This Chapter

In this chapter, we report $^{12}\text{CO}(1-0)$ observations toward the western bar, arm, and bar-end regions in NGC 1300 at a high angular resolution of ~ 40 pc with ALMA. Our aims are to measure the properties of GMCs and investigate whether there are differences in the properties with environments. In addition, we compare the properties of GMCs in NGC 1300 with those in a normal spiral galaxy. As pointed out by Hughes et al. (2013), for comparison with different data cubes, it is essential to match the spatial and spectral resolution and line sensitivity to minimize observational bias. In this chapter, we compare the properties of GMCs in spiral arms of proto-type spiral galaxy of M51 by Colombo et al. (2014, C14) because the spatial resolution and line sensitivity are mostly comparable to those of our observations.

This chapter is structured as follows: In Section 2.2, we describe the $\text{CO}(1-0)$ observations and data reduction. The resultant $\text{CO}(1-0)$ distribution is presented in Section 2.3. In Section 2.4, we summarize the method used to identify GMCs. The basic properties of the GMCs and examination of the variations of GMC physical properties with environments are described in Section 2.5. In Sections 2.6 and 2.7, we examine scaling relations and mass spectra of the GMCs. In Section 2.8, we discuss what physical mechanism controls the SFE of the GMC. Conclusions in this chapter are presented in Section 2.9.

2.2 Observations with ALMA 12-m Array and Data Reduction

We carried out $^{12}\text{CO}(1-0)$ line observations of NGC 1300 on 2017 December 30 and 2018 January 6, 7, 13, and 16 with ALMA (program ID: 2017.1.00248.S, PI = F. Maeda). To cover the regions observed with $^{12}\text{CO}(1-0)$ by Maeda et al. (2018), two pointings were centered at (RA, Dec) = ($3^{\text{h}}19^{\text{m}}37^{\text{s}}.435$, $-19^{\circ}24'33''.24$) and ($3^{\text{h}}19^{\text{m}}36^{\text{s}}.326$, $-19^{\circ}24'01''.42$) in J2000 as shown with the green circles in Figure 2.1. The ALMA primary beam for the 12-m array is $54''$ at HPBW.

The ALMA observations were taken during five separated periods with seven execution blocks in total. Table 2.1 summarizes the details of the ALMA observations. The total on-source time was 5.31 hours (2.65 hours for each position). For all observations, we used about 44 antennas

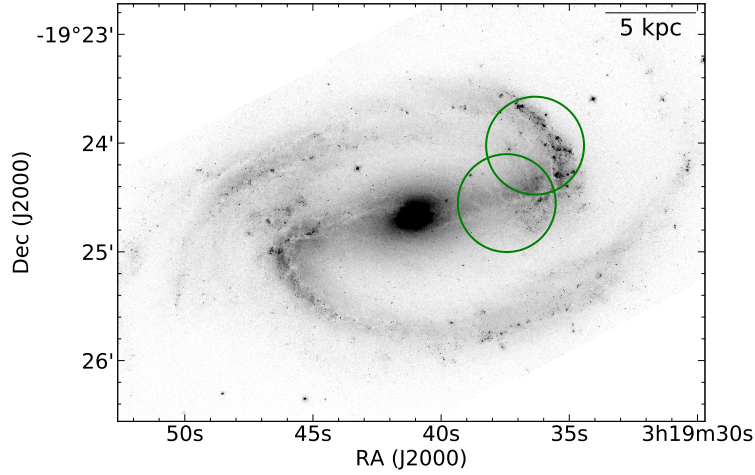


Figure 2.1: V-band image of NGC 1300 taken with F555W filter on ACS of HST. We obtained this image from the Hubble Legacy Archive (HLA). Green circles represent field of views (FoVs; HPBW = $54''\phi$) observed with ALMA (see Section 2.2).

with C43-5 configuration. The projected baseline length ranged from 15.1 m to 2.5 km, which corresponds to a maximum recoverable scale (MRS) of $\sim 21.4''$ at 115 GHz. We used the Band 3 receiver with the central frequency of 114.664 GHz, channel width of 244.1 kHz ($\sim 0.64 \text{ km s}^{-1}$), and bandwidth of 468.8 MHz ($\sim 1225 \text{ km s}^{-1}$). Bandpass and phase were calibrated with J0423-0120 and J0340-2119, respectively. J0423-0120 was also used as a flux calibrator. The T_{sys} and PWV were typically 100–150 K and 1–5 mm during the observations, respectively.

We calibrated raw visibility data using the Common Astronomy Software Applications (CASA) ver. 5.1.1. and the observatory-provided calibration script. We reconstructed the two-field mosaic image using CASA ver. 5.4.0. First, we combined the calibrated visibility data of the 2 pointing positions using `concat` task. Then, we imaged the concatenated visibility using the multiscale CLEAN algorithm (Cornwell 2008), which models an image by a collection of multiple Gaussians with different FWHM values. As shown by Rich et al. (2008), this method works well in reducing the depth of negative emission features (so-called ‘negative bowl’) and recovering extended emission in comparison to the standard CLEAN algorithm, which models an image by a collection of point sources. We used the task `tclean` for imaging by adopting the factors of 1, 2, and 5 times the synthesized beam as multiscale parameter and Briggs weighting with `robust = 0.5`. To ensure

Table 2.1: Observation settings

Execution Block	Start time (UTC)	On source time (min)	Number of antennas	Baseline range
uid__A002_Xc889b6_X21a3.ms	2017/12/30 02:27:10	45.55	46	15.1m–2.5km
uid__A002_Xc889b6_X2691.ms	2017/12/30 03:36:38	45.53	46	15.1m–2.5km
uid__A002_Xc8d560_X4fa.ms	2018/01/06 23:17:13	45.55	44	15.1m–2.5km
uid__A002_Xc8d560_X9e4.ms	2018/01/07 00:26:35	45.48	44	15.1m–2.5km
uid__A002_Xc8d560_X9737.ms	2018/01/07 22:10:49	45.50	43	15.1m–2.5km
uid__A002_Xc91189_X727.ms	2018/01/13 01:59:20	45.52	44	15.1m–2.5km
uid__A002_Xc92fe3_X8e21.ms	2018/01/16 22:21:23	45.50	44	15.1m–1.4km

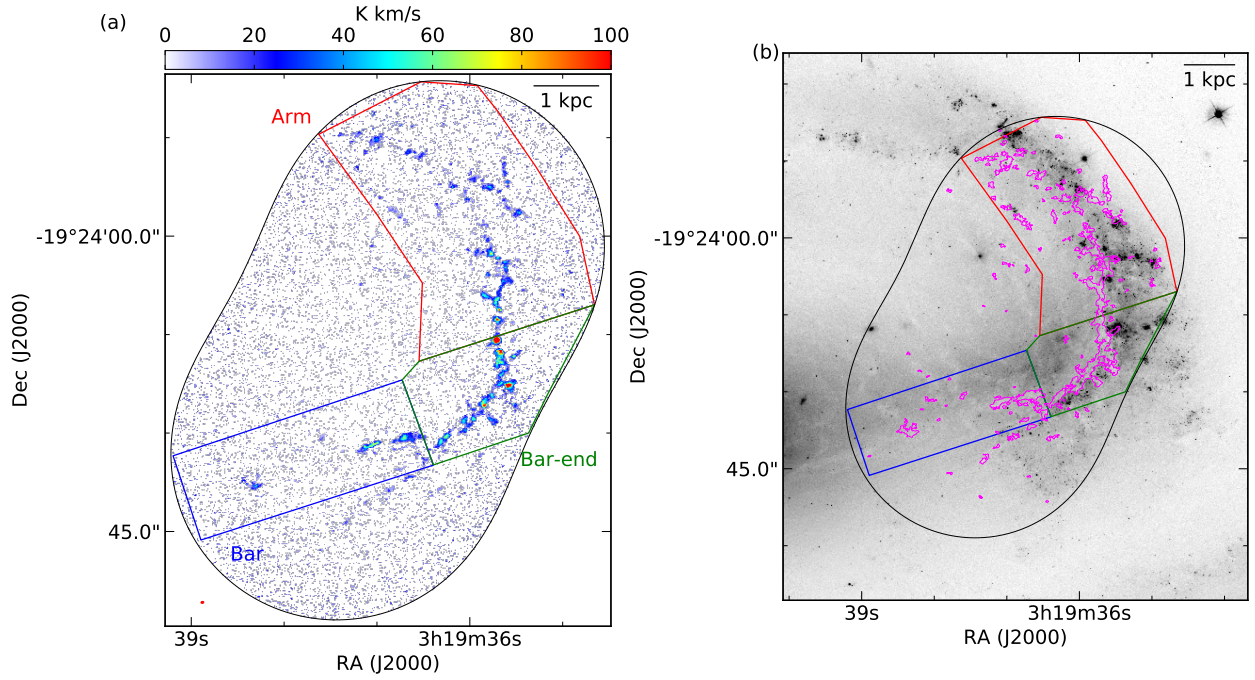


Figure 2.2: (a) Velocity integrated intensity $^{12}\text{CO}(1-0)$ image of NGC 1300 generated from the ALMA data cube. We used channel maps within the velocity range $1540 - 1690 \text{ km s}^{-1}$ clipped at 3σ ($1.53 \text{ mJy beam}^{-1}$). The black line represents the FoV of $\text{CO}(1-0)$ observations with ALMA. Color solid lines indicate the definition of the environmental mask. *Bar*, *arm*, and *bar-end* are indicated with blue, red, and green lines, respectively. (b) CO contours in magenta are superimposed on the F555W image obtained from HST archive data. CO contours are created from the significant emission identified by CPROPS. The contour level of the CO map is 8.0 K km s^{-1} .

consistency with C14 and to achieve a reasonable S/N, we choose a velocity resolution of 5 km s^{-1} and a pixel size of $0.''12$. The resultant rms noise is $0.51 \text{ mJy beam}^{-1}$, corresponding to 0.36 K . Finally, we applied the primary beam correction on the output restored image. In this thesis, we used the region within the primary beam correction factor smaller than 2.0. The final data cube has an angular resolution of $0.44'' \times 0.30''$.

2.3 GMC Scale Molecular Gas Distribution in NGC 1300

Figure 2.2(a) shows a map of the velocity-integrated intensity (I_{CO}). This map is created from channel maps within the LSR velocity range $1540 - 1690 \text{ km s}^{-1}$ clipped at 3σ ($= 1.53 \text{ mJy beam}^{-1}$). The clipping is only for visualization purpose. We detected $^{12}\text{CO}(1-0)$ emission from the western arm to the bar region. Thanks to the high angular resolution of $\sim 40 \text{ pc}$, the CO emission is resolved into GMC scale. Figure 2.2(b) compares the CO distribution with the map of HII regions and dust lanes. The gray scale image is the V-band image (same as Figure 2.1). The magenta contours in Figure 2.2(b) show the CO emission with 8.0 K km s^{-1} . These contours are created from the significant emission identified by CPROPS (so-called ‘island’ regions; see section 2.4.1).

In this thesis, to compare physical properties of GMCs among galactic environments, we separated NGC 1300 into *bar*, *arm* and *bar-end* regions, according to Figure 2.2. Blue rectangle is defined as the *bar* region, which covers the dark lane and associated spurs that are connected almost perpendicularly to the dark lane. The *arm* region is defined as a red polygon. Green polygon that

covers the intersection region of the bar and the arm is defined as the *bar-end* region. These color codes will be kept throughout this paper. The deprojected area is 5.1, 9.9, and 3.6 kpc² in *bar*, *arm* and *bar-end*, respectively.

Here we see the feature of the CO emissions in each region. In *arm* and *bar-end*, the mean I_{CO} within the region we detected significant emission is 20 and 32 K km s⁻¹ in *arm* and *bar-end*, respectively. These values correspond to 55 and 90 M_⊙ pc⁻² assuming the standard CO-to-H₂ conversion factor (α_{CO}) of 4.4 M_⊙ (K km s⁻¹ pc²)⁻¹. In these regions, most of CO emissions are associated with H α emissions and coexist with dust lanes. This good correspondence of the CO emissions to the dust lanes and displacement of the H α and CO emissions are often seen in spiral galaxies at a high angular resolution of ~ 50 pc (e.g. M51; Schinnerer et al. 2013). This is naturally interpreted with respect to the spiral density wave; the gases go into the spiral density wave, then dense shocked gas regions form in the spiral arms which result in the formation of GMCs. In the GMCs, stars form, and massive stars born produce HII regions. The stellar feedback (e.g. stellar wind, supernova) would disperse the molecular gas, thus contributing to the observed offset.

In *bar*, we detected GMC-like CO emissions on the dust lanes. The mean I_{CO} is 22 K km s⁻¹, corresponding to 60 M_⊙ pc⁻². Unlike *arm*, however, no prominent HII region is associated with the CO emissions. This result indicates that massive star formation in the bar region of the strongly barred galaxy is suppressed despite the presence of GMC-like molecular gases. Note that we did not detect significant CO emission above 4σ of $T_{\text{peak}} = 1.44$ K, corresponding to an average surface density of 20 M_⊙ pc⁻² for a single pixel and spectral channel, in part of the dust lane in the bar region.

2.4 GMC Identification and Characterization

2.4.1 GMCs identification

The choice of an algorithm for identifying GMCs can be the largest source of uncertainty in measuring and comparing GMC properties. In this thesis, we used 3-D clumps finding algorithm CPROPS (Rosolowsky & Leroy 2006) which is designed to identify GMCs well even at low sensitivities. The spatial resolution and line sensitivity of our data cube are comparable to those of the data cube of M51 by Schinnerer et al. (2013) which was observed with the Plateau de Bure Interferometer and IRAM 30-m telescope at a spatial resolution of ~ 40 pc and a line sensitivity of 0.4 K at 5 km s⁻¹ bin. Using CPROPS, C14 identified GMCs in M51 from the data cube. Therefore, we adopt almost the same CPROPS parameters adopted in C14 to make a proper comparison and minimize systematics.

Here, we provide a brief summary of CPROPS. CPROPS has been fully described by Rosolowsky & Leroy (2006). This algorithm begins with the identification of regions with significant emissions within the data cube (called the ‘islands’ in CPROPS). CPROPS identifies pixels in which the signal is above $t\sigma_{\text{rms}}$ in at least two adjacent velocity channels, where σ_{rms} is the rms noise of the data cube. Since the data cube is corrected for the primary beam pattern, the noise in the map is non-uniform. Thus, we calculated a spatially varying of the rms noise in the map by calling NONUNIFORM flag in CPROPS. CPROPS then grows these regions to include adjacent pixels in which the signal is above $e\sigma_{\text{rms}}$. The t and e are the THRESHOLD and EDGE parameters in CPROPS, respectively. We chose $t = 4.0$ and $e = 1.5$ to ensure consistency with C14.

After the identification of the islands, the islands are divided into individual GMCs using a modified watershed algorithm. CPROPS searches for local maxima within a box of three times the beam and channel width, corresponding to ~ 120 pc $\times$ 120 pc $\times$ 15 km s⁻¹. All local maxima are required to lie at least $2\sigma_{\text{rms}}$ above the merge level with another maximum. Only emission that is

uniquely associated with each local maximum is given an assignment (i.e. only that emission which is above all merge levels with other local maxima).

For every pair of local maxima in an island, CPROPS compares the values of the moments at contour levels just above and just below the merge level. If the moments jump by more than a user-defined fraction, called SIGDISCONT parameter, the two local maxima are categorized as distinct, otherwise they are merged into a single cloud. The default parameter of SIGDISCONT = 1.0 requires 100% or more fractional change. As described in C14, however, setting of SIGDISCONT > 0.0 does not work well for the CO bright regions where a lot of local maxima are connected at a very low contour level; CPROPS misses objects that visual inspection suggests are GMCs (see Appendix B in C14). In our data cube, some GMCs are missed with SIGDISCONT > 0.0 in Bar-End where CO emission is the brightest. To avoid this failure, we set SIGDISCONT to 0.0 which makes no attempt to merge the two local maxima into a single cloud. In other words, each local maximum is assigned to an individual independent cloud. The remainder of the emission is considered to be in the watershed, and CPROPS does not assign it to any cloud.

A large number of objects were found whose peak temperature is above $4\sigma_{\text{rms}}$ but temperature of the adjacent pixels in the velocity axis is lower than $4\sigma_{\text{rms}}$. These objects seem to be GMCs because their size, velocity dispersion, and luminosity are similar to those in M51 spiral arms. However, they are missed by CPROPS because CPROPS does not identify objects which do not contain two consecutive pixels above $4\sigma_{\text{rms}}$ in the velocity axis. Therefore, to identify such GMCs for which signal above $4\sigma_{\text{rms}}$ is detected in only a single channel, we allowed CPROPS to identify an island which has pixels above $4\sigma_{\text{rms}}$ in only one channel. As we will discuss in Section 2.5, the possibility that these GMCs are spurious is very low.

2.4.2 Derivation of basic properties

Size, velocity width and CO luminosity

CPROPS determines the size, velocity width and flux of GMCs using moment methods. CPROPS corrects for the sensitivity by extrapolating GMC properties to those we would expect to measure with perfect sensitivity (i.e. 0 K) and the resolution by deconvolution for the beam and channel width. Details of the measurement method of CPROPS are described in Rosolowsky & Leroy (2006).

The effective radius of the GMC is defined as $R = (3.4/\sqrt{\pi})\sigma_r$, where σ_r is geometric mean of the second intensity-weighted moments along the major and minor axis (i.e. rms size) and $3.4/\sqrt{\pi}$ is an empirical factor defined by Solomon et al. (1987). If the extrapolated rms size is smaller than the beam size of 15.4 pc, we set this value as an upper limit of the rms size. The velocity width, σ_v , is computed as the intensity-weighted second moment of the velocity after the deconvolution to correct the velocity resolution (ΔV_{chan}). CPROPS approximates the shape of the channel as a Gaussian with an integral area equal to that of the channel width (i.e. $\Delta V_{\text{chan}}/\sqrt{2\pi}$). The CO luminosity, L_{CO} , is derived from

$$\left(\frac{L_{\text{CO}}}{\text{K km s}^{-1} \text{ pc}^2} \right) = \left(\frac{F_{\text{CO}}}{\text{K km s}^{-1} \text{ arcsec}^2} \right) \left(\frac{D}{\text{pc}} \right)^2 \left(\frac{\pi}{180 \times 3600} \right)^2, \quad (2.4.1)$$

where F_{CO} is the zeroth moment of the intensity and the D is the distance to NGC 1300 of 20.7 Mpc.

The median ratio of the extrapolated (i.e. without deconvolution) radius and velocity dispersion to the directly measured (i.e. without deconvolution and extrapolation) are 1.5 and 1.4, respectively. For the CO luminosity, the median ratio of the extrapolated value to the directly measured value is 2.1. These correction factors are comparable to those of the GMCs in M51 (C14).

Derived Properties

The molecular gas mass of a GMC, M_{mol} , is converted from the CO luminosity by adapting an α_{CO} :

$$\left(\frac{M_{\text{mol}}}{M_{\odot}}\right) = \alpha_{\text{CO}} \left(\frac{L_{\text{CO}}}{\text{K km s}^{-1} \text{ pc}^2}\right). \quad (2.4.2)$$

We adopt the standard α_{CO} of $4.4 M_{\odot} (\text{K km s}^{-1} \text{ pc}^2)^{-1}$ to ensure consistency with C14. Note that this α_{CO} includes a factor of 1.36 to account for the presence of helium.

Assuming a spherical GMC with the power-law density profile of $\rho \propto r^{-n}$, we calculate the virial mass of a GMC, M_{vir} , from the size and velocity dispersion as

$$\begin{aligned} M_{\text{vir}} &= \frac{3(5-2n)}{3-n} \frac{R\sigma_v^2}{G} \\ &= 1040 \left(\frac{R}{\text{pc}}\right) \left(\frac{\sigma_v}{\text{km s}^{-1}}\right)^2 [M_{\odot}]. \end{aligned} \quad (2.4.3)$$

We adopt the profile of $n = 1$ to ensure consistency with previous studies. We assume that magnetic fields and external pressure are negligible.

The average molecular gas surface density, Σ_{mol} , is defined as

$$\Sigma_{\text{mol}} = \frac{M_{\text{mol}}}{\pi R^2}. \quad (2.4.4)$$

The virial parameter, α_{vir} , which is explained in Section 1.1.2, is defined as

$$\alpha_{\text{vir}} = \frac{5\sigma_v^2 R}{GM_{\text{mol}}}. \quad (2.4.5)$$

This definition assumes $n = 0$, but the impact of the difference between $n = 0$ and 1 is only about 10%.

The scaling coefficient, c , characterizes the scaling between the size and the velocity dispersion of a GMC as

$$c \equiv \frac{\sigma_v}{R^{0.5}}. \quad (2.4.6)$$

For a GMC with $\alpha_{\text{vir}} = 1$, c can be related to the molecular gas surface density as $c = (\pi G \Sigma_{\text{mol}} / 5)^{0.5}$.

CPROPS estimates the uncertainty of these GMC properties using a bootstrapping method, and the final uncertainty is the standard deviation of the bootstrapped values scaled up by the square root of the oversampling rate. The oversampling rate is equal to the number of pixels per beam, which accounts for the nonindependence of the pixels. C14 found that 50 bootstrapping measurements provided a reliable estimation of the uncertainty, thus we adopted this number.

2.5 Basic Properties of GMCs

CPROPS identified 233 GMCs in the data cube. 166 of the GMCs have at least two consecutive pixels above $4\sigma_{\text{rms}}$ in the velocity axis direction. The remaining 67 GMCs have pixels above $4\sigma_{\text{rms}}$ in only one channel. Figure 2.3 shows GMC distribution in NGC 1300. We detected 34, 119, and 49 GMCs in *bar*, *arm*, and *bar-end*, respectively. 31 GMCs are outside the three regions (i.e. in interarm regions). The GMC catalog in NGC 1300 is presented in Appendix D.

We inspected the CO line profiles from each GMC CPROPS identified visually, and an obvious

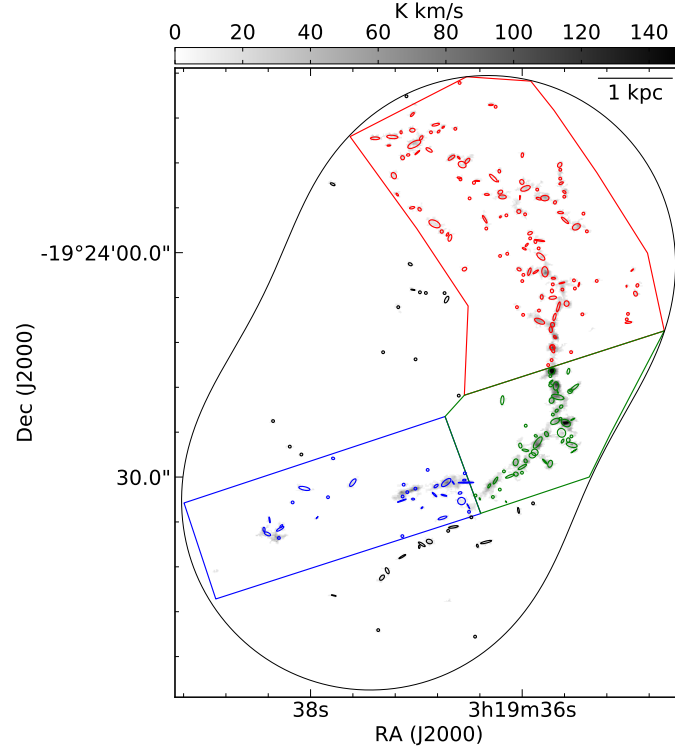


Figure 2.3: GMC distribution in NGC 1300 superimposed on the velocity integrated CO map (gray scale). The GMCs are represented as ellipses with the extrapolated and deconvolved major and minor axes, oriented according to the measured position angle. The black line represents the FoV of CO(1 – 0) observations with ALMA. Colors indicate the environment defined in Figure 2.2.

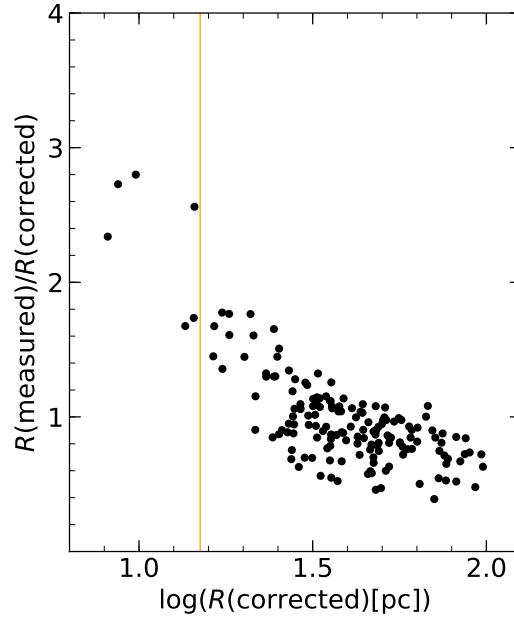


Figure 2.4: Ratio of measured radius to corrected (i.e. with deconvolution and extrapolation) radius for all resolved GMCs against corrected radius. Vertical orange line indicates 15 pc.

spurious signal was not found. To check contamination by spurious sources, we counted the number of local maxima in the data cube scaled by -1 with the same settings described in Section 2.4.1. We found no false positives which have two consecutive pixels above $4\sigma_{\text{rms}}$ in the velocity axis direction. For the 166 GMCs, therefore, we believe there is no contamination by spurious sources. On the other hand, CPROMS identified three false positives which have pixels above $4\sigma_{\text{rms}}$ in only one channel. Thus, ~ 3 of the 67 ($\sim 4\%$) GMCs for which signal above $4\sigma_{\text{rms}}$ is detected in only a single channel are expected to be spurious.

With the adopted parameters for CPROMS, GMCs with $T_{\text{peak}} > 4\sigma_{\text{rms}}$, which corresponds to ~ 1.44 K, were detected. The mass completeness limit is estimated to be $2.0 \times 10^5 M_{\odot}$ by assuming that a minimum detectable GMC has a size and a velocity width comparable to the beam size and the channel width, respectively, and α_{CO} is $4.4 M_{\odot} (\text{K km s}^{-1} \text{ pc}^2)^{-1}$. We find that 154 of these 233 GMCs are resolved by the synthesized beam. When the observed size is similar to the beam size, uncertainties of R are greatly magnified by the deconvolution process (e.g. Faesi et al. 2018). Figure 2.4 shows the ratio of directly measured radius to the corrected radius (i.e. with extrapolation and deconvolution) as a function of the corrected radius. Below 15 pc ($\log R = 1.17$), the ratio is often larger than a factor of 2, or even higher. Further, we find only 47 % of the GMCs with $M_{\text{mol}} < 5.0 \times 10^5 M_{\odot}$ are resolved, while 95 % of the GMCs with $M_{\text{mol}} \geq 5.0 \times 10^5 M_{\odot}$ are resolved. Therefore, we defined the GMCs with $M_{\text{mol}} \geq 5.0 \times 10^5 M_{\odot}$ and $R > 15$ pc as a resolved sample for the investigation of R , M_{vir} , Σ_{mol} , α_{vir} , and c , and defined the GMCs with $M_{\text{mol}} > 2.0 \times 10^5 M_{\odot}$ as a mass completed sample for the investigation of T_{peak} , σ_v , and M_{mol} .

2.5.1 Variation of GMC physical properties with environment

Figure 2.5 shows the distribution of GMC properties. We use a box and whiskers plot as C14 used for M51. In this plot, the ends of the box represent the upper and lower quartiles (Q_1 and Q_3 , respectively). The median value or Q_2 is marked by a vertical line in the box. The upper whisker expands to the largest data point below $Q_3 + 1.5\Delta Q$ and the lower whisker expands to the smallest data point above $Q_1 - 1.5\Delta Q$, where ΔQ is the box length or $Q_3 - Q_1$. For a Gaussian distribution, the region within the whiskers contains 99.3 % ($\pm 2.7\sigma$) of the population. The data points outside the whiskers are considered to be outliers. Except for T_{peak} , σ_v , and M_{mol} , we show a box and whiskers plot for the resolved sample. The orange lines and bands in Figure 2.5 show the median value and the range from Q_1 to Q_3 of those in M51 spiral arms from the catalog of C14. The median value and the range from Q_1 to Q_3 of each physical property are listed in Table 2.2.

We investigated the environmental variation of GMC properties in NGC 1300 and compared to the GMC properties in M51 spiral arms. We used the two-sided Kolmogorov-Smirnov (K-S) test to statistically evaluate differences in GMC property distributions for different environments in NGC 1300. We used `stats.ks_2samp` function of python's Scipy package, which calculates p -value based on the approximately formula given by Stephens (1970). To estimate the uncertainties of the p -values, we made resampling with 100 realizations. In one realization, random values of a given property were generated within the bootstrap uncertainties CPROMS calculated. The most likely p -value and its uncertainty are the median and the median absolute deviation (MAD) of 100 realizations, respectively. Table 2.3 shows the results for each GMC physical parameter. Since CPROMS does not provide uncertainties of the T_{peak} , we applied rms noise of the data cube, 0.36 K as the uncertainty. We also show the p -value for the observed value in parentheses. Following the conventional criteria, the two cumulative distribution functions are considered to be significantly different if the p -value is less than 0.01. A p -value within 0.01 to 0.05 indicates that the difference is marginally significant.

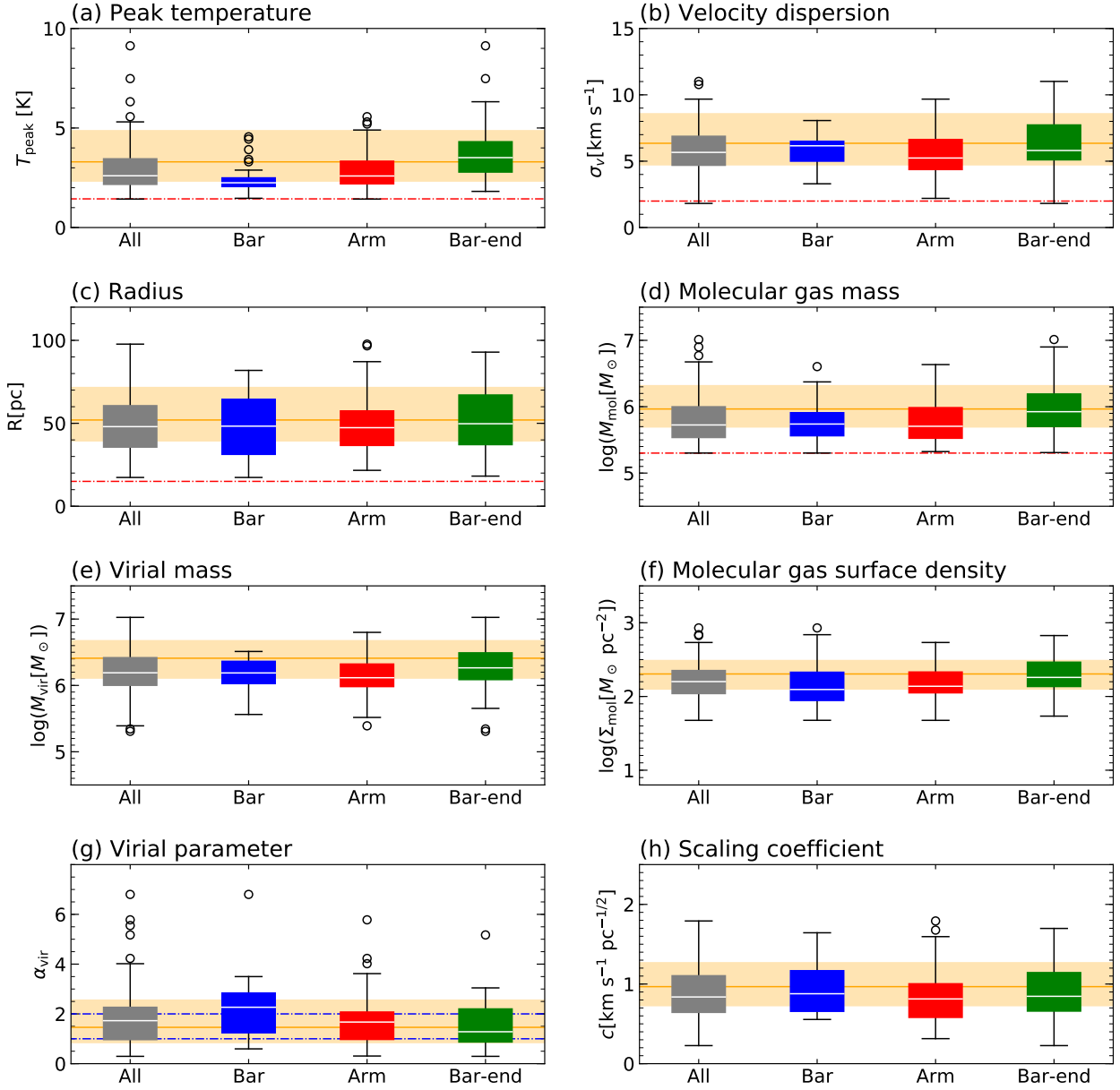


Figure 2.5: Box-and-whisker plots for GMC's (a) peak temperature (T_{peak}), (b) velocity dispersion (σ_v), (c) radius (R), (d) molecular gas mass (M_{mol}), (e) virial mass (M_{vir}), (f) molecular gas surface density (Σ_{mol}), (g) virial parameter (α_{vir}), and (h) scaling coefficient (c) in the whole region (gray) and each environment (*bar*: blue, *arm*: red, and *bar-end*: green) of NGC 1300. We used the GMCs with $M_{\text{mol}} \geq 2.0 \times 10^5 M_{\odot}$ for T_{peak} , σ_v , and M_{mol} and the GMCs with $M_{\text{mol}} \geq 5.0 \times 10^5 M_{\odot}$ and $R \geq 15 \text{ pc}$ for other properties. The median value is represented as a white horizontal line within each box. Upper and lower edges of each box indicate the upper and lower quartile, respectively (Q_1 and Q_3 , respectively). The upper whisker expands to the largest data point below $Q_3 + 1.5\Delta Q$ and the lower whisker expands to the smallest data point above $Q_1 - 1.5\Delta Q$. The data points outside the whiskers are considered outliers and shown as open circles. The orange solid line and bands show the median value and the range from Q_1 to Q_3 of each property of GMCs in M51 spiral arms (C14). Horizontal red dash-dotted lines indicate 1.44 K ($= 4 \sigma$), 2.0 km s^{-1} ($= \Delta V_{\text{chan}} / \sqrt{2\pi}$), 15 pc , and $2.0 \times 10^5 M_{\odot}$. Horizontal blue dash-dotted lines in panel (g) indicate $\alpha_{\text{vir}} = 1.0$ and 2.0 .

Table 2.2: GMC properties in the different environments of NGC 1300

Envir.	Area (kpc ²)	# [*]	$T_{\text{peak}}^{\dagger}$ (K)	$\sigma_v^{\dagger}$ (km s ⁻¹)	$R^{\ddagger}$ (pc)	$M_{\text{mol}}^{\dagger}$ (10 ⁵ M _⊙)	$M_{\text{vir}}^{\ddagger}$ (10 ⁵ M _⊙)	$\Sigma_{\text{mol}}^{\ddagger}$ (M _⊙ pc ⁻²)	$\alpha_{\text{vir}}^{\ddagger}$	$c^{\ddagger}$ (km s ⁻¹ pc ^{-0.5})
All	37.9	203(104)	2.6 ^{+0.9} _{-0.4}	5.2 ^{+1.3} _{-0.8}	48.0 ^{+12.6} _{-12.4}	5.3 ^{+4.7} _{-1.9}	15.5 ^{+10.7} _{-5.5}	159.2 ^{+65.9} _{-49.7}	1.7 ^{+0.5} _{-0.8}	0.8 ^{+0.3} _{-0.2}
Bar	5.1	28(12)	2.2 ^{+0.2} _{-0.2}	5.7 ^{+0.8} _{-0.9}	48.3 ^{+16.2} _{-17.0}	5.5 ^{+2.7} _{-1.8}	15.4 ^{+7.8} _{-4.7}	125.5 ^{+87.9} _{-36.8}	2.3 ^{+0.6} _{-1.0}	0.9 ^{+0.3} _{-0.2}
Arm	9.9	108(55)	2.6 ^{+0.7} _{-0.4}	5.0 ^{+1.5} _{-0.8}	47.4 ^{+10.1} _{-10.7}	5.1 ^{+4.6} _{-1.7}	13.1 ^{+8.0} _{-3.5}	137.5 ^{+77.3} _{-25.5}	1.7 ^{+0.4} _{-0.7}	0.8 ^{+0.2} _{-0.2}
Bar-end	3.6	43(31)	3.5 ^{+0.8} _{-0.7}	5.6 ^{+2.0} _{-0.9}	49.7 ^{+17.3} _{-12.6}	8.4 ^{+7.1} _{-3.4}	18.4 ^{+12.6} _{-6.2}	181.4 ^{+111.3} _{-45.0}	1.3 ^{+0.9} _{-0.4}	0.8 ^{+0.3} _{-0.2}
M51 SA [★]	14.6	584(365)	3.3 ^{+1.6} _{-1.0}	6.3 ^{+2.3} _{-1.7}	52.0 ^{+20.0} _{-13.0}	9.2 ^{+12.0} _{-4.4}	25.7 ^{+22.6} _{-13.1}	202.0 ^{+111.7} _{-78.5}	1.5 ^{+1.1} _{-0.6}	1.0 ^{+0.3} _{-0.2}

^{*} The number of the GMCs with $M_{\text{mol}} \geq 2.0 \times 10^5 M_{\odot}$. In parentheses, we show the number of the GMCs with $M_{\text{mol}} \geq 5.0 \times 10^5 M_{\odot}$ and $R \geq 15$ pc.

[†] For the GMCs with $M_{\text{mol}} \geq 2.0 \times 10^5 M_{\odot}$.

[‡] For the GMCs with $M_{\text{mol}} \geq 5.0 \times 10^5 M_{\odot}$ and $R \geq 15$ pc.

[★] For M51 spiral arms (SA) (C14). We extract GMCs with the same selection criteria as described in Section 2.5.

Peak temperature (Figure 2.5 (a)): The T_{peak} in *bar-end* is the highest (2.8 – 4.3 K), followed by *arm* (2.2 – 3.4 K) and *bar* (2.0 – 2.4 K). The K-S test indicates that the differences between *bar-end* and *arm* or *bar* are significant, and that between *bar* and *arm* is marginally significant. Thus we conclude that the T_{peak} in *bar-end* is significantly higher than those in *arm* and *bar*. This result does not change for the resolved sample. The ΔQ of T_{peak} distribution in *arm* and *bar-end* is within that in M51 spiral arm, but that in *bar* is lower.

Velocity dispersion (Figure 2.5 (b)): We find no environmental variations based on the K-S test: 4.8 – 6.5 km s⁻¹ in *bar*, 4.2 – 6.5 km s⁻¹ in *arm*, and 4.7 – 7.6 km s⁻¹ in *bar-end*. In *bar-end*, some GMCs have a σ_v larger than 10 km s⁻¹. The ΔQ of σ_v distribution in each region is roughly within those in M51 spiral arm. One caveat of measurement of σ_v is that we may overestimate σ_v of GMCs. We discuss this bias in section 2.5.2 and appendix B.

Radius (Figure 2.5 (c)): There are no environmental variations of R (31.3 – 64.5 pc in *bar*, 36.7 – 57.5 pc in *arm*, and 37.1 – 67.0 pc in *bar-end*) and, the ΔQ of R distribution in each region is roughly within those in M51 spiral arms. Note that we evaluate differences in radius without deconvolution for all sample using the K-S test, and we find no environmental variations.

Molecular gas mass (Figure 2.5 (d)): Molecular gas mass is proportional to a combination of brightness temperature, velocity dispersion, and size: $M_{\text{mol}} \propto L_{\text{CO}} \propto \langle T \rangle R^2 \sigma_v$, where $\langle T \rangle$ is an average brightness temperature. Since the R and σ_v are roughly equal in each region, M_{mol} is mainly proportional to $\langle T \rangle$ in NGC 1300. Therefore, M_{mol} in *bar-end* is expected to be larger than those in *arm* and *bar* like the T_{peak} . In fact, the M_{mol} in *bar-end* is higher ((5.0 – 15.5) $\times 10^5 M_{\odot}$) than those in *bar* ((3.7 – 8.2) $\times 10^5 M_{\odot}$) and *arm* ((3.4 – 9.7) $\times 10^5 M_{\odot}$). The median value in *bar-end* is by a factor of 1.6 larger than those in *bar* and *arm*. The K-S test indicates that the difference between *bar-end* and *arm* (*bar*) is significant (marginally significant), and there is no significant difference between *bar* and *arm*. The median M_{mol} in *bar-end* is comparable to that in M51 spiral arms, but those in *arm* and *bar* are about 2 times lower.

Virial mass (Figure 2.5 (e)): Since the R and σ_v are roughly equal in each region, $M_{\text{vir}} \propto R \sigma_v^2$ is expected to be equal. In fact, we find no significant environmental variation: (1.1 $\times$ – 2.3) $\times 10^6 M_{\odot}$ in *bar*, (1.0 $\times$ – 2.1) $\times 10^6 M_{\odot}$ in *arm*, and (1.2 $\times$ – 3.1) $\times 10^6 M_{\odot}$ in *bar-end*.

Molecular gas surface density (Figure 2.5 (f)): Because S_{mol} is proportional to $\langle T \rangle \sigma_v$, S_{mol} is expected to show the same tendency as T_{peak} . In fact, S_{mol} in *bar-end* is the highest (138.5 – 317.6 $M_{\odot} \text{ pc}^{-2}$), followed by *arm* (112.0 – 214.8 $M_{\odot} \text{ pc}^{-2}$) and *bar* (88.8 – 213.4 $M_{\odot} \text{ pc}^{-2}$). Based on K-S test, however, we do not find the significant difference.

Virial parameter (Figure 2.5 (g)): Because α_{vir} is proportional to $\sigma_v / (\langle T \rangle R)$, α_{vir} is expected to show a reverse tendency of T_{peak} . In fact, α_{vir} in *bar* is the highest (1.3 – 2.9), followed by *arm* (1.0 – 2.1) and *bar-end* (0.9 – 2.2). Based on the resampling method, 58 $\pm$ 8 % of the GMCs in *bar* is gravitationally unbound ($\alpha_{\text{vir}} > 2$). This percentage is larger than that in *arm* and *bar-end* (33 $\pm$ 4 % and 29 $\pm$ 3 %), and in M51 spiral arm (35 %). However, the K-S test gives high p -value which indicates there is no significant environmental variation in α_{vir} . Note that the K-S test for the observed value shows the marginally significant difference between *arm* and *bar*. But based on the resampling method, it is rare that K-S test gives a p -value less than or equal to 0.05. In conclusion, there is no significant environmental variations in α_{vir} in NGC 1300.

Scaling coefficient (Figure 2.5 (h)): As expected from the fact that $c = \sigma_v / R^{0.5}$ is a combination of σ_v and R , we find no environmental variation in c . The c in NGC 1300 is comparable to that in M51 spiral arms.

In summary, there is a significant environmental variation in the T_{peak} ; the highest value in *bar-end* followed by *arm* and *bar*. Since σ_v and R do not exhibit environmental variation, the variation of T_{peak} is mainly responsible for the variation of median value of M_{mol} , S_{mol} , and α_{vir} . But based on the two-sided K-S tests, the (marginally) significant differences are only seen in the distribution

Table 2.3: p -values of the Kolmogorov-Smirnov Test for GMC properties

Prop.	Bar vs. Arm	Bar vs. Bar-end	Arm vs. Bar-end
T_{peak}^*	$0.019 \pm 0.013(0.008)$	$\ll 0.01(\ll 0.01)$	$\ll 0.01(\ll 0.01)$
σ_v^*	$0.350 \pm 0.186(0.281)$	$0.756 \pm 0.165(0.667)$	$0.181 \pm 0.083(0.142)$
$R^\dagger$	$0.672 \pm 0.167(0.746)$	$0.726 \pm 0.167(0.896)$	$0.479 \pm 0.153(0.552)$
M_{mol}^*	$0.876 \pm 0.074(0.954)$	$0.027 \pm 0.017(0.037)$	$0.007 \pm 0.004(0.004)$
$M_{\text{vir}}^\dagger$	$0.794 \pm 0.148(0.613)$	$0.545 \pm 0.167(0.698)$	$0.133 \pm 0.067(0.117)$
$\Sigma_{\text{mol}}^\dagger$	$0.588 \pm 0.183(0.355)$	$0.206 \pm 0.102(0.221)$	$0.123 \pm 0.068(0.128)$
$\alpha_{\text{vir}}^\dagger$	$0.183 \pm 0.114(0.050)$	$0.206 \pm 0.106(0.172)$	$0.813 \pm 0.135(0.938)$
$c^\dagger$	$0.655 \pm 0.172(0.778)$	$0.886 \pm 0.092(0.978)$	$0.430 \pm 0.130(0.592)$

In parentheses, we show the p -value for observed values.

* For the GMCs with $M_{\text{mol}} \geq 2.0 \times 10^5 M_\odot$.

† For the GMCs with $M_{\text{mol}} \geq 5.0 \times 10^5 M_\odot$ and $R \geq 15$ pc.

of M_{mol} between *bar* and *bar-end*, and *arm* and *bar-end*; there is virtually no significant difference in GMC physical properties among the *bar*, *arm* and *bar-end*. In addition, we find the properties of GMCs in NGC 1300 are roughly comparable to those in M51 spiral arms. In particular, the properties in *bar-end* are very similar.

2.5.2 The reliability of the measurements

CPROPS bias

As described in section 2.4.2, the extrapolated (but non-deconvolved) R , σ_v and L_{CO} is typically 1.5 ~ 2.0 times higher than the directly measured values. The accuracy of the CPROPS correction (i.e. extrapolation and deconvolution) depends on the sensitivity, spatial resolution and velocity resolution (Rosolowsky & Leroy 2006). In order to assess the reliability of the measurements of GMC properties, we simulated ALMA observation of mock GMCs, which are three-dimensional Gaussian clouds in position-position-velocity space with a given masses, sizes, and velocity dispersions, in CASA under the same condition of our observations (Section 2.2). After reconstructing the image from the simulated visibility, we identify the GMCs using CPROPS with the same parameters described in Section 2.4 and compare the input and output values. The details of the simulation method and results are described in Appendix B, and we briefly describe the results and discussion here.

We find that the corrected σ_v is overestimated by ~ 50 % if the directly measured velocity width, $2.35\sigma_v$, is less than half the channel width of 5.0 km s^{-1} . Such GMC accounts for 56 %, 64 %, and 64 % in *bar*, *arm*, and *bar-end*, respectively. Therefore, a large number of cataloged GMCs may be overestimated in the σ_v by a factor of ~ 1.5. The CPROPS algorithm performs relatively well for the measurements of the M_{mol} and R in comparison to σ_v . We find that the corrected M_{mol} is mostly equal to the input M_{mol} for the GMC with higher S/N ($7 \leq \text{S/N} \leq 10$), but the corrected M_{mol} is typically underestimated by ~ 10 % for the GMC with lower S/N ($4 \leq \text{S/N} < 7$). The corrected R is typically underestimated by ~ 20 % and ~ 10 % for the GMC with lower S/N and higher S/N, respectively. We retested the environmental variation of the GMC properties using the catalog

corrected for the over/underestimation factor. As a result of the K-S test, p -values do not change much (see Table B.2). Thus we concluded that the over/underestimation of the measurements does not influence on the discussion about the environmental variations described in Section 2.5.1.

Impact of the missing flux

Measurements of GMC properties may be affected by the missing flux (e.g. Rosolowsky & Leroy 2006; Pan & Kuno 2017). Our ALMA observations did not recover the total CO(1 – 0) flux due to the lack of Atacama Compact Array (ACA) measurements. To estimate the recovery fraction of the total CO(1 – 0) flux, we compared the CO(1 – 0) flux obtained from ALMA with those from Nobeyama 45-m single-dish telescope by Maeda et al. (2018), which presented single-pointing observations of several regions in NGC 1300. First, we convolved the CO(1 – 0) data cube to $13''.5$, the beam size of the Nobeyama 45-m telescope at 115 GHz. We then obtained spectra at the pointing positions of the 45-m telescope and measured the recovery fraction (i.e. the ratio of the two flux). We find that the average recovery fraction is 54 % with typical uncertainty of 5 %; about half of the total flux was missed, which could affect the measurements of GMC properties.

To investigate the relationship between the spatial scale of the gas distribution and missing flux, we simulated ALMA observation of a mock Gaussian component. We created a fits image of a circular Gaussian component with total flux of 1.0 Jy and given FWHM. The FWHM was set from 100 pc to 1500 pc every 100 pc. In order to extract the effect originated from the uv-distribution, we simulated the observation under the same configuration and noise-free condition by using the task of `simobserve` in CASA. After reconstructing the image with `tclean` task, we measured the flux of the component and recovery fraction. Figure 2.6 shows the recovery fraction of the Gaussian component as a function of the FWHM. We find that the recovery fraction of the Gaussian component with $\text{FWHM} \leq 300$ pc is ~ 1.0 and that with $\text{FWHM} > 300$ pc is under 1.0. For the large Gaussian component with the $\text{FWHM} \geq 700$ pc, more than half of the flux is missed.

According to the simulation results, total flux of a GMC smaller than ~ 300 pc can be recovered in our observations. Since the radius of the GMCs we identified is smaller than 300 pc (the maximum is ~ 100 pc), their properties would not be affected by the missing flux and the over/underestimates described in 2.5.2 would be mainly due to the sensitivity. In our observations, a molecular gas structure larger than ~ 700 pc is mostly resolved out. This result would mainly be responsible for the missing flux in our data and imply the presence of the large scale gas structures such as diffuse molecular gas components, as have been seen in other galaxies (e.g. M51; Pety et al. 2013). Note that the missing flux would also depend on shape of the GMCs and distribution of them. Thus it is difficult to figure out the real impact of the missing flux on the GMC properties by simulations. This issue will be expected to be clear by the new ACA observations of NGC 1300 in Cycle 7 (PI: F. Maeda).

2.6 Scaling Relations

In this section, we present the analysis of the scaling relations for the GMCs, which are commonly referred to as Larson’s laws (Larson 1981). Here, we investigate the size-velocity dispersion relation, the virial-luminous mass relation, the size-mass relation, and the relationship between σ_v^2/R and Σ_{mol} for the resolved GMCs ($M_{\text{mol}} \geq 5.0 \times 10^5 M_\odot$ and $R > 15$ pc) in NGC 1300. In each analysis, we calculate the Spearman’s rank correlation coefficient (r_s) to evaluate the strength of a link between two sets of data. Considering the number of GMCs, we regard $r_s \geq 0.8$ as a sign of strong correlation and $0.5 < r_s < 0.8$ as that of moderate correlation.

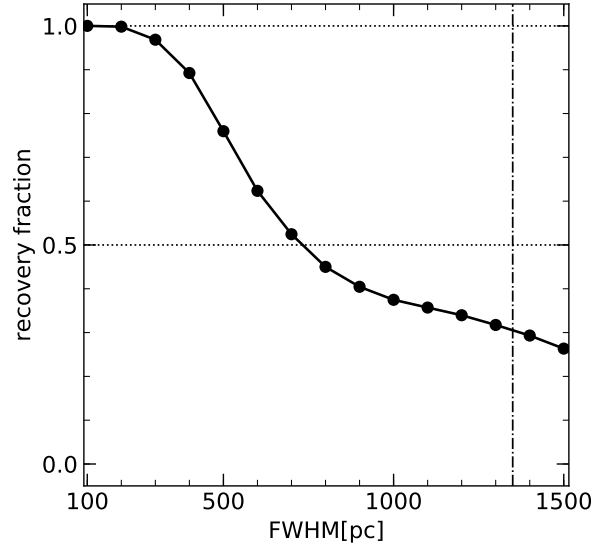


Figure 2.6: Recovery fraction of the Gaussian component as a function of the FWHM. We simulated ALMA observation of the mock Gaussian component with a given FWHM under the same configuration and noise-free condition. Horizontal dashed lines indicate the recovery fraction of 1.0 and 0.5. Vertical dash-dotted line indicates 1350 pc, corresponding to the beam size of Nobeyama 45-m telescope.

2.6.1 Size-velocity dispersion relation

Figure 2.7 shows the size-velocity dispersion relation in NGC 1300. The relation in M51 spiral arms from C14 is shown as gray squares. In panel (a), although the majority of the data points lies around the Galactic fit (Solomon et al. 1987), the correlation is not seen ($r_s = -0.04$) which is also observed in M51 spiral arms ($r_s = 0.16$). Even with division into subregions, the correlations are not seen ($|r_s| < 0.3$).

The existence of the size-velocity dispersion relation has been discussed. In M51, there was no correlation in not only spiral arms but also center and inter-arm regions (C14). Hirota et al. (2018) reported the apparent lack of correlation in the various environments including arm and bar regions of M83. On the contrary, Bolatto et al. (2008) found a correlation of $\sigma_v \propto R^{0.60 \pm 0.10}$ for the multigalaxy GMC population including spiral galaxies and dwarf galaxy. Faesi et al. (2018) found also a correlation of $\sigma_v \propto R^{0.48 \pm 0.05}$ in NGC 300. In section 2.6.4, we will discuss the cause for the weak correlation in NGC 1300.

2.6.2 Virial equilibrium

Upper panels in Figure 2.8 show the relation between virial mass and the molecular gas mass derived from CO luminosity in NGC 1300. We find moderate correlations for all GMCs ($r_s = 0.52$) in *arm* (0.53) and in *bar-end* (0.70), while there is no apparent correlation in *bar* (0.25). In the panels with $r_s \geq 0.5$, a magenta solid line represents the best-fitted line determined by the ordinary least-squares method: $M_{\text{vir}} \propto M_{\text{mol}}^{0.70 \pm 0.35}$ in the whole region, $M_{\text{vir}} \propto M_{\text{mol}}^{0.65 \pm 0.55}$ in *arm*, and $M_{\text{vir}} \propto M_{\text{mol}}^{0.90 \pm 0.53}$ in *bar-end*. These relationships agree with that in M51 spiral arms shown as orange solid line ($M_{\text{vir}} \propto M_{\text{mol}}^{0.74}$). In lower panels of Figure 2.8, we plot the virial parameter (α_{vir}) as a function of M_{mol} . As inferred from the slope lower than 1.0 in upper panels in Figure 2.8, $\alpha_{\text{vir}} \cong M_{\text{vir}}/M_{\text{mol}}$ decreases with increasing M_{mol} . This suggests that the high mass GMCs tend to be more strongly bound than low mass GMCs in *arm* and *bar-end* of NGC 1300 as seen in M51.

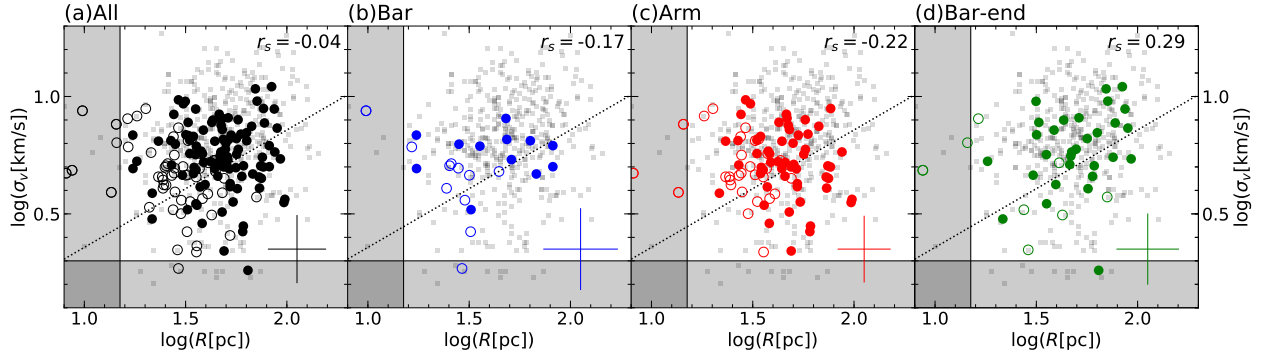


Figure 2.7: (a) Size-velocity dispersion relation for the GMCs in the whole region in NGC 1300. (b) - (d) Same as panel (a) but for the different environments in NGC 1300. We show the GMCs with $M_{\text{mol}} \geq 5.0 \times 10^5 M_{\odot}$ and $R \geq 15$ pc in filled circles and the rest in open circles. The average error bars are indicated as a cross in the bottom right corner of each panel. The range below the spatial (15 pc) and spectral (2.0 km s^{-1}) sensitivity limit is indicated as shaded regions. The Spearman's correlation rank, r_s , for the filled circle is given in the top right corner of each panel. Gray squares show the relationship for GMCs in M51 spiral arms (C14). Black dotted line indicates the Galactic fit, $\sigma_v = 0.72R^{0.5}$ (Solomon et al. 1987).

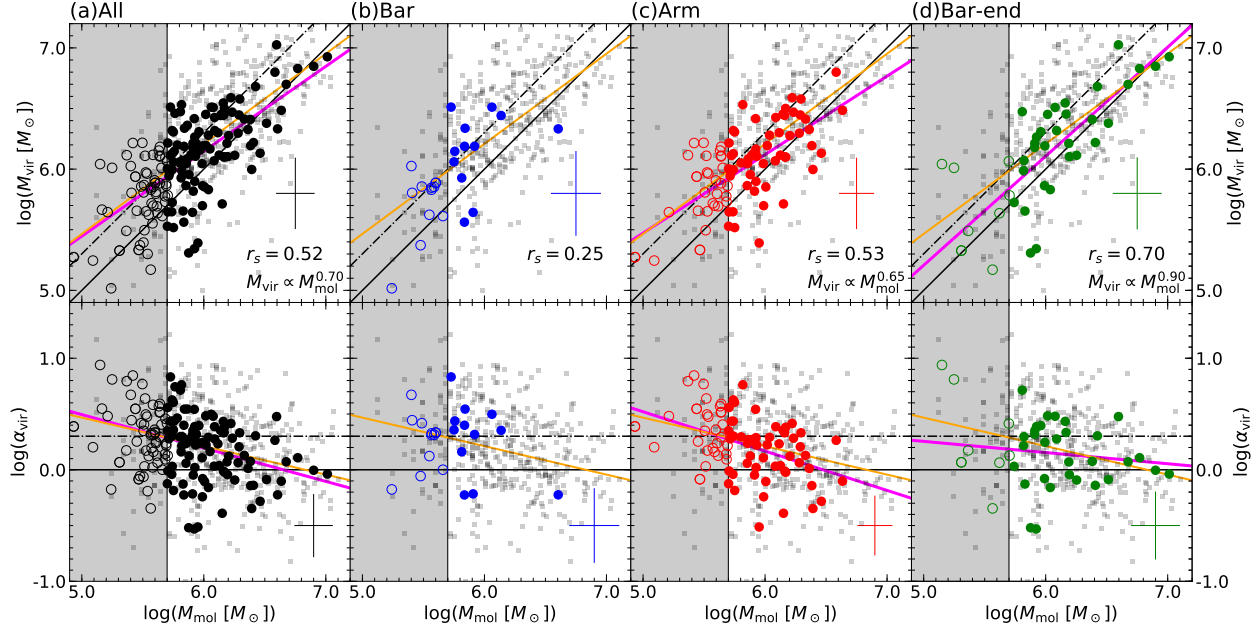


Figure 2.8: (a) Virial mass-luminosity based mass relation (upper) and virial parameter-luminosity based mass relation (lower) for the GMCs in the whole region of NGC 1300. (b) - (d) Same as panel (a) but for the different environments in NGC 1300. We show the GMCs with $M_{\text{mol}} \geq 5.0 \times 10^5 M_{\odot}$ and $R \geq 15$ pc in filled circles and the rest in open circles. The average error bars are indicated as a cross in each panel. The range below $M_{\text{mol}} = 5.0 \times 10^5 M_{\odot}$ is indicated as a shaded region. Black solid and dotted line indicate the line for $\alpha_{\text{vir}} = 1.0$ and $\alpha_{\text{vir}} = 2.0$, respectively. For upper panels, the Spearman's correlation rank, r_s , for the filled circle is given in the bottom right corner (BRC) of each panel. If r_s is larger than 0.5, we show the best fitted line as a magenta solid line and its slope is given in the BRC. Gray squares and orange solid line show the relationship and the best fitted line for GMCs in M51 spiral arms (C14), respectively.

2.6.3 Size-mass relation

Figure 2.9 shows the size-mass relation in NGC 1300. There is a moderate correlation in each panel ($0.60 < r_s < 0.75$). Magenta solid line represents the best fit line determined by the ordinary least-squares method. The slope of the relation in *bar* (0.57) is the shallowest, followed by *arm* (1.00)

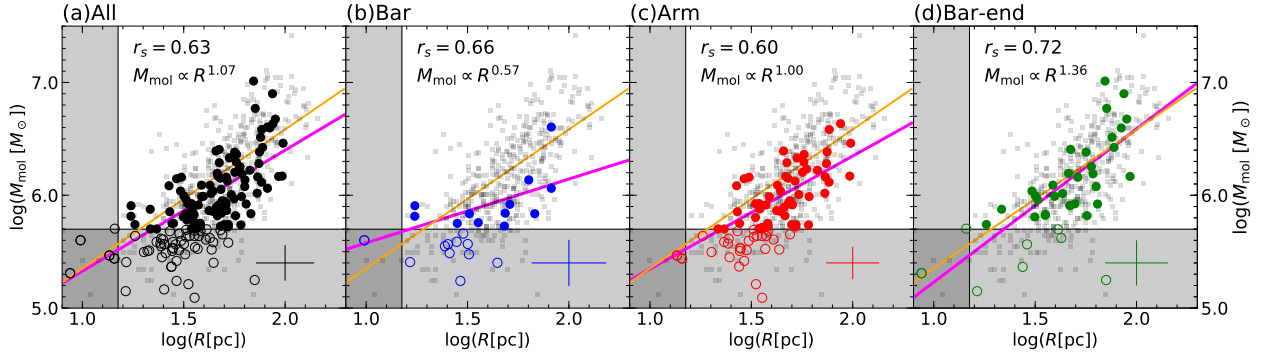


Figure 2.9: (a) Size-molecular gas mass relation for the GMCs in the whole region of NGC 1300. (b) - (d) Same as panel (a) but for the different environments in NGC 1300. We show the GMCs with $M_{\text{mol}} \geq 5.0 \times 10^5 M_{\odot}$ and $R \geq 15$ pc in filled circles and the rest in open circles. The average error bars are indicated as a cross in each panel. The range below $M_{\text{mol}} = 5.0 \times 10^5 M_{\odot}$ and $R = 15$ pc is indicated as shaded regions. The Spearman's correlation rank, r_s , for the filled circle is given in the top left corner (TLC) of each panel. We show the best fitted line as a magenta solid line and its slope is given in the TLC. Gray squares and orange solid line show the relationship and the best fitted line for GMCs in M51 spiral arms (C14), respectively.

and *bar-end* (1.36). The fact that the index is smaller than 2.0, the molecular gas surface density (Σ_{mol}) of GMCs is not roughly constant but decreases with increasing GMC size in NGC 1300. The difference in the index shows that the molecular gas surface density (Σ_{mol}) in *bar* is lower than GMCs with similar size in *arm* and *bar-end*, which is consistent with the tendency of Σ_{mol} (Figure 2.5 (g)). Orange solid line represents the best fit line for the GMCs ($M_{\text{mol}} \geq 5.0 \times 10^5 M_{\odot}$ and $R \geq 15$ pc) in M51 spiral arms and slope is 1.23. The Σ_{mol} in *bar* and *arm* is lower than GMCs with similar size in M51 spiral arms.

2.6.4 Relationship between σ_v^2/R and Σ_{mol}

Recent studies on molecular gas at GMC scale argued that the relationship between $\sigma_v^2/R = c^2$ and Σ_{mol} is useful to investigate the physical state of the GMCs (e.g. Heyer et al. 2009; Leroy et al. 2015; Sun et al. 2018). This is because the position of the GMC in σ_v^2/R - Σ_{mol} space gives information about not only virial parameter, α_{vir} , but also internal turbulent pressure, P_{int} of the GMC. Here, the P_{int} can be expressed as

$$\begin{aligned} \frac{P_{\text{int}}}{k} &= \frac{\rho \sigma_v^2}{k} \\ &= 3695 \left(\frac{\Sigma_{\text{mol}}}{M_{\odot} \text{ pc}^{-2}} \right) \left(\frac{c}{\text{km s}^{-1} \text{ pc}^{-0.5}} \right)^2 [\text{cm}^{-3} \text{ K}], \end{aligned} \quad (2.6.1)$$

where ρ is the molecular gas volume density of the GMC.

Figure 2.10 plots the σ_v^2/R - Σ_{mol} relation of NGC 1300. The $\alpha_{\text{vir}} = 1$ and 2 are represented by a black solid and dotted line, respectively, and magenta dotted lines indicate constant P_{int} . Note that the σ_v^2/R - Σ_{mol} relation is mathematically equivalent to the M_{vir} - M_{mol} relation (Figure 2.8). We can see a moderate correlation in the whole region ($r_s = 0.63$), *bar* (0.66), *arm* (0.60), and *bar-end* (0.72) in NGC 1300, which shows the scaling coefficient, c , increases with increasing Σ_{mol} . The same tendency is seen in Milky Way; Heyer et al. (2009) pointed out that c is proportional to $\Sigma_{\text{mol}}^{1/2}$.

As shown in panel (a), P_{int} of the GMCs in NGC 1300 is spread about 3 dex ($10^4 \leq P_{\text{int}}/k/[\text{cm}^{-3} \text{ K}] \leq 10^7$). The median values and the ΔQ of P_{int}/k are roughly constant across

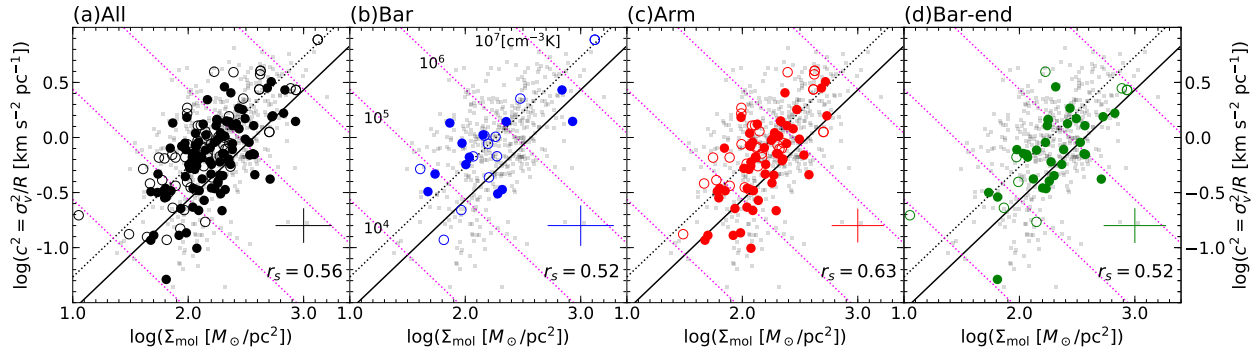


Figure 2.10: (a) Scale coefficient as a function of molecular gas surface density in the whole region of NGC 1300. (b) - (d) Same as panel (a) but for the different environments in NGC 1300. We show the GMCs with $M_{\text{mol}} \geq 5.0 \times 10^5 M_{\odot}$ and $R \geq 15$ pc in filled circles and the rest in open circles. The average error bars are indicated as a cross in each panel. The Spearman's correlation rank, r_s , for the filled circle is given in the BRC of each panel. Gray squares show the relationship for the GMCs in M51 spiral arms (C14). Black solid and dotted line indicate the line for $\alpha_{\text{vir}} = 1.0$ and 2.0 , respectively. Magenta dotted lines indicate the line for $P_{\text{int}}/k = 10^4, 10^5, 10^6$, and 10^7 [cm^{-3} K].

the different environments: $2.2^{+6.2}_{-1.4}$, $2.9^{+4.6}_{-2.5}$, and $3.3^{+10.5}_{-1.6} \times 10^5 \text{ cm}^{-3} \text{ K}$ in *bar*, *arm*, and *bar-end*, respectively. The K-S tests give high p -values of > 0.1 . These values are slightly lower than that in M51 spiral arms of $6.7^{+8.3}_{-4.3} \times 10^5 \text{ cm}^{-3} \text{ K}$.

Figure 2.10 can be interpreted to explain the cause for weak correlation between size and velocity dispersion (Figure 2.7). The GMCs in NGC 1300 cover a wider range of Σ_{mol} (~ 1.5 dex) than those in Milky Way (~ 1.0 dex; Solomon et al. 1987). Therefore, the range of c in NGC 1300 becomes wider than that in Milky Way, leading to a decorrelation between σ_v and R . The dependence of the c on the Σ_{mol} also may be the part of the cause of weak correlation seen in M51 and M83 (see Hirota et al. 2018). Note that the limited dynamic range of the size parameter and the errors in the measurements with CPROPS could be responsible for the weak correlation.

2.7 GMC Mass Spectra

Figure 2.11 shows the cumulative GMC mass spectrum in different environments in NGC 1300 (panel (a) - (d)) and in M51 spiral arms (panel (e); C14). The y-axis shows the GMC number density. The number density of high mass GMC ($M_{\text{mol}} \geq 1.0 \times 10^6 M_{\odot}$) in *bar-end* is the highest (5.2 kpc^{-2}), followed by in *bar* (1.2 kpc^{-2}) and *arm* (2.6 kpc^{-2}). Although these values depend on the definition of the environmental mask, there is no doubt that the number densities of high mass GMC with $\geq 1.0 \times 10^6 M_{\odot}$ in *bar* (5.1 kpc^{-2}) and *arm* (9.9 kpc^{-2}) are lower than that in *bar-end* (3.6 kpc^{-2}). In particular, GMCs more than $5.0 \times 10^6 M_{\odot}$ are only observed in *bar-end*. Note that the number density in M51 spiral arms is 18.2 kpc^{-2} , and is the factor of $4 \sim 10$ larger than that in any environments of NGC 1300.

We fitted the cumulative GMC mass spectrum with equation (1.1.9). Although the mass completeness limit is expected to be $2.0 \times 10^5 M_{\odot}$ in uncrowded regions (see section 2.5), the completeness limit might be effectively raising in a crowded region like *bar-end* (e.g. Colombo et al. 2014; Hirota et al. 2018). Thus, we fitted the mass spectrum using the GMCs with $M_{\text{mol}} \geq 5.0 \times 10^5 M_{\odot}$ indicated as a vertical black dash-dotted line in Figure 2.11. To estimate the fitting uncertainties, we made resampling with 100 realizations. In one realization, random values of a molecular gas mass were generated within the uncertainties CPROPS calculated. The median and the MAD of 100 realizations for each parameter were adopted as the best-fitted value and the

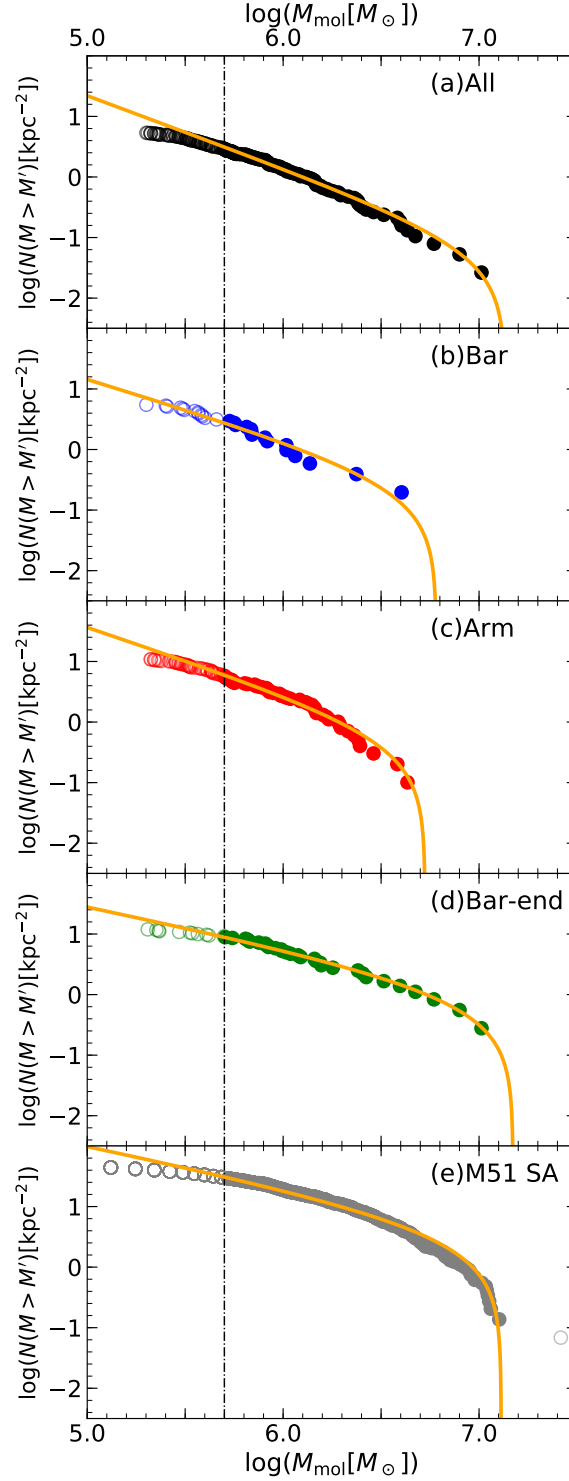


Figure 2.11: (a) Cumulative mass spectrum for GMCs in the whole region of NGC 1300. (b)-(d) Same as panel (a), but for the different environments in NGC 1300. (e) Same as panel (a), but for GMCs in M51 spiral arms (C14). In each plot, filled and open circles indicate the GMCs that are and are not used for fitting the spectrum with equation (1.1.9), respectively. The orange solid line indicates the best-fitted function. The dash-dotted vertical line indicates the lower mass limit, $5 \times 10^5 M_\odot$, for the fitting of mass spectra.

Table 2.4: Truncated Power-law Fits to the GMC Mass Spectra in Different Environments in NGC 1300

Envir.	γ	M_u ($10^6 M_\odot$)	N_u	p -value
All	-2.20 ± 0.04	13.6 ± 0.67	2.74 ± 0.40	0.22
Bar	-1.97 ± 0.20	6.26 ± 3.04	1.36 ± 0.97	0.59
Arm	-2.08 ± 0.10	5.31 ± 0.36	5.45 ± 1.07	0.40
Bar-end	-1.66 ± 0.07	14.8 ± 0.93	2.56 ± 0.42	0.85
M51 SA	-1.70 ± 0.03	13.0 ± 0.34	35.6 ± 2.46	10^{-4}

Note. Slopes γ , upper cutoff mass M_u , and a measure of the number of GMCs at the upper cutoff mass N_u of the truncated power-law fits to the GMC mass spectra of the different environments in NGC 1300. The error are obtained through 100 resampling interaction. In the last column, we list the p -values of the K-S tests as an indication of the goodness-of-fit.

confidence interval (Table 2.4). The orange solid line in Figure 2.11 shows the best-fitted cumulative mass function. We list the p -values of the K-S tests as an indication of the goodness-of-fit in the last column of Table 2.4. Here we fitted the mass spectrum of GMCs in M51 spiral arms in the same way.

No clear difference was found in the shape of mass spectra between in *bar* and *arm*: the slope and upper mass limit is $\gamma \sim -2.0$ and $M_u \sim 5.0 \times 10^6 M_\odot$, respectively. However, the mass spectrum in *bar-end* is obviously different from those in *bar* and *arm*. The slope in *bar-end* is flatter than -2 , which indicates that massive GMCs account for a large population of total cloud mass in *bar-end*. The upper mass limit in *bar-end* of $M_u = (1.3 \pm 3.4) \times 10^7 M_\odot$ is twice as large as that in Bar and Arm regions. The presence or absence of differences in the mass spectrum between environments is consistent with that in the box plot of M_{mol} (see Section 2.5.1). The γ and M_u in *bar-end* are similar to those in M51 spiral arms.

Since the γ in *bar-end* is larger than those in *bar* and *arm*, *bar-end* would be an environment where the massive GMCs forms more than in *bar* and *arm*. The similarity of the feature between *bar-end* and M51 spiral arms suggests the mechanism which regulate the formation and destruction of GMCs is similar to that in M51 spiral arms. Although the mass spectra in *bar* and *arm* is similar, the GMC destruction mechanism would be different because the star formation activity is apparently different (Section 1.2.2). The stellar feedback process may be predominant in *arm*, but the dynamical effect (e.g. cloud-cloud collision and large-scale shear motion) may be important process in *bar*.

2.8 Discussion: Examination of Gravitationally Unbound GMCs Scenario

Here, we examine the physical mechanisms that suppress the star formation activity of GMCs in the bar regions of NGC 1300. Based on the K-S tests, there is no significant variation in the physical

properties (σ_v , R , M_{mol} , M_{vir} , Σ_{mol} , α_{vir} , and c) of the GMCs between *bar* and *arm* (Table 2.3). Comparing to the GMCs between *bar* and *bar-end*, and *arm* and *bar-end*, (marginally) significant difference is only seen in the distribution of M_{mol} . Therefore, it appears that systematic differences in the GMC properties are not the cause for the SFE differences with environments.

Next we focus on *Scenario 1* that the presence of gravitationally unbound GMCs make the star formation activity low in the bar regions (Section 1.2.2). Sorai et al. (2012) made $^{12}\text{CO}(1-0)$ map of Maffei 2 at an angular resolution of 200 pc, and pointed out a possibility that clouds in the bar regions are gravitationally unbound, which causes the low star formation activity. Nimori et al. (2013) performed a two-dimensional hydrodynamical simulation and also found the unbound clouds in bars. In NGC 1300, the number fraction of GMC with $\alpha_{\text{vir}} > 2$ in *bar* (60 %) is larger than that in *arm* and *bar-end* (30 %), which may partly contribute to decreasing the SFE in the bar region. However, there is no significant difference in α_{vir} based on the K-S test (Table 2.3). This result suggests that the lack of massive star formation in the strong bar of NGC 1300 can not be explained by a systematic difference of α_{vir} (*Scenario 1*).

Hirota et al. (2018) found the α_{vir} of the GMCs in the bar of M83 (median is ~ 1.6) is larger than that in the arm (~ 1.2). This result seems to be inconsistent with our results. However, a direct comparison with our results is not straightforward because the algorithm for identifying GMCs they used was different from ours. It is necessary to compare the GMC properties between M83 and NGC 1300 under the same data quality and methodology. This comparison is important but beyond our scope of this chapter, which remains as a future subject.

Although the galactic environments seem not to affect the physical properties of GMCs in NGC 1300, there is a possibility that the interaction of GMCs is affected; That is, the CCC speed would depend on the galactic environments. CCCs, which induces clump formation by shock compressions, has been suggested as the mechanism of massive star formation (e.g. Habe & Ohta 1992; Fukui et al. 2014). Recent studies suggest that the efficiency of massive star formation strongly depends on the CCC speed. Takahira et al. (2014, 2018) performed hydrodynamical simulations of CCCs. They found that massive clumps ($\sim 100 M_{\odot}$) finally form in the case of slower CCCs ($\sim 5 \text{ km s}^{-1}$). However, in faster CCCs ($> 10 \text{ km s}^{-1}$), clouds are highly compressed, but the duration of the collision is not long enough for the clump mass to grow via gas accretion and no massive clump is formed. Based on a high resolution ($\sim$ a few pc) 3D hydrodynamical simulations aiming at modeling a barred galaxy M83, Fujimoto et al. (2014b,a) found that collision speed among clouds in bar regions is faster than in arm regions and proposed this difference makes SFE variations (*Scenario 3*; Section 1.2.2).

CO observations toward NGC 1300 with a single-dish telescope of Nobeyama 45-m show the higher velocity dispersion in bar regions than in arm regions at a kpc-scale resolution (Maeda et al. 2018). This result suggests the relative velocity among the clouds in the bar regions is larger than that in the arm regions and is qualitatively consistent with the fast CCC scenario in the bar region. Other CO observations toward barred galaxies with a single-dish telescope show the same tendency (e.g. Regan et al. 1999; Morokuma-Matsui et al. 2015; Muraoka et al. 2016; Yajima et al. 2019). Egusa et al. (2018) found that a probability distribution function of velocity dispersion in the bar of M83 is systematically larger than in the arm (see also Sun et al. 2018). Querejeta et al. (2019) found a significant anti-correlation between the SFE and velocity dispersion of the dense gas at a 100 pc scale in M51. The velocity dispersion of the dense gas is thought to be largely reflecting velocity dispersion among different clumps. According to these results, the difference in SFE between the arm and bar regions would be due to the difference in CCC speed rather than the difference in the physical properties of the GMCs.

Fujimoto et al. (2020, Appendix A) presented a hydrodynamical simulation of a strongly barred galaxy, using a stellar potential model of NGC 1300. They found that there is no significant

environmental dependence of cloud properties including the virial parameter, which is consistent with our result presented in this chapter. Further, they show that the collision speed in the bar is significantly faster than the other region due to the elongated global gas motion by the stellar bar. The fraction of colliding clouds with collision speed more than 20 km s^{-1} in bar regions ($\sim 40\%$) is significantly larger than those in other regions ($< 10\%$). They conclude that the physical mechanism that causes the lack of active star-forming regions in the bar of strongly barred galaxies is the high-speed CCCs.

The CCC occurs only a few times within 1 Myr in the bar and arm region and the effects of collision do not last for long time; the excited internal gas motion induced by the collision decays quickly within at most a few Myr, which is thought to be shorter than cloud lifetimes (10 – 40 Myr; e.g. Kawamura et al. 2009; Meidt et al. 2015; Chevance et al. 2020a; Fujimoto et al. 2019). Therefore, in a snapshot of the galaxy, there are a few or less GMCs affected by the collision in the bar and arm regions. Thus the GMC properties observed would not be affected by this effect.

In Chapter 4, we attempt to measure the CCC speed using the GMC catalog we created in this chapter and directly compare the simulation of Fujimoto et al. (2020, Appendix A) to investigate *Scenario 3* observationally.

2.9 Conclusions of This Chapter

We made $^{12}\text{CO}(1-0)$ observations toward the strongly barred galaxy NGC 1300 at a high angular resolution about 40 pc with ALMA. We detected CO emissions from the western arm to the bar region. Using the CPROPS algorithm, we identified 233 GMCs (34, 119, and 49 in *bar*, *arm*, and *bar-end*, respectively) with $\text{S/N} > 4$. We measured R , σ_v , and L_{CO} of these GMCs and then derived M_{mol} , M_{vir} , Σ_{mol} , α_{vir} , and c of them. We focus on a mass completed sample with $M_{\text{mol}} > 2.0 \times 10^5 M_{\odot}$ for the investigation of T_{peak} , σ_v , and M_{mol} and a resolved sample with $M_{\text{mol}} > 5.0 \times 10^5 M_{\odot}$ and $R > 15 \text{ pc}$ for the investigation of R , M_{vir} , Σ_{mol} , α_{vir} , and c . We compare the GMCs properties among the environments. The main results are as follows:

1. Based on the two-sided K-S tests, there is a significant environmental variation in the T_{peak} ; the highest value in *bar-end* followed by *arm* and *bar*. However, there is hardly any significant variations in GMC physical properties (σ_v , R , M_{mol} , M_{vir} , Σ_{mol} , α_{vir} , and c ; Figure 2.5); (marginally) significant difference is only seen in the distribution of M_{mol} between *bar* and *bar-end*, and *arm* and *bar-end* (Table 2.3). The properties of GMCs in NGC 1300 are roughly comparable to those in M51 spiral arms. In particular, the properties in *bar-end* are very similar.
2. We find no obvious $R - \sigma_v$ relation although the majority of the data points lies around the Galactic fit (Figure 2.7). For the relation between M_{vir} and M_{mol} , there is a moderate correlation in *arm* and *bar-end*, while there is no apparent correlation in *bar* (Figure 2.8). We find the α_{vir} decreases with increasing M_{mol} , which suggests the high mass GMCs tend to be strongly bound as seen in M51. There is a moderate correlation between R and M_{mol} in each environment (Figure 2.9). Further, we find the P_{int}/k is roughly constant across the different environments in NGC 1300 (Figure 2.10).
3. No clear difference is found in the shape of GMC mass spectra between in *bar* and *arm*. The slope of the spectrum in the *bar-end* is slightly flatter than those in *arm* and *bar*, and massive GMCs are seen only in the *bar-end* (Figure 2.11). The similarity of the feature between *bar-end* and M51 spiral arms suggests the mechanism regulating formation and destruction of GMCs is similar to that in M51 spiral arms.

4. It appears that systematic differences in the physical properties of the GMCs are not the cause for the low SFE in the bar region of NGC 1300. In particular, the star formation suppression can not explained by the scenario that the presence of gravitationally unbound ($\alpha_{\text{vir}} > 2$) GMCs in the bar regions (*Scenario 1*). Other mechanisms such as high-speed CCCs may control the SFE of GMCs in NGC 1300 (Section 2.8).

Chapter 3

Diffuse Molecular Gases in NGC 1300

Part of this Chapter was published as Maeda et al. 2020, MNRAS, 495, 3840

3.1 Scope of This Chapter

In this chapter, we investigate *Scenario 2* that a large amount of diffuse molecular gases may exist in the bar regions. Diffuse molecular gases in the Milky Way are well studied through emission lines of CO isotopes and absorption lines (e.g. Snow & McCall 2006; Sheffer et al. 2008; Liszt & Pety 2012; Roman-Duval et al. 2016). Because observations of such lines toward nearby galaxies are difficult, we use the recovery fraction of the CO flux (f_{re}), which is the ratio of CO flux obtained from interferometers to total CO flux obtained from single-dishes, as an alternative measure of the amount of the diffuse molecular gases. Interferometers provide higher spatial resolution with a disadvantage that not all spatial scales can be recovered. The shortest baselines determine the largest spatial scale which the interferometers can recover. Therefore, the recovery fraction shows the percentage of the molecular gases that is more compact than the largest scale. Recovery fraction was measured in some galaxies and the presence of diffuse molecular gases is suggested (e.g. M51; Pety et al. 2013, NGC 4736 and NGC 5055; Caldú-Primo et al. 2015). However, the difference in the recovery fraction with environments and the relation between the recovery fraction and SFE have not been adequately studied.

Instead of f_{re} , we present the diffuse gas fraction, f_{dif} , defined as $1 - f_{\text{re}}$ in NGC 1300 using ALMA $^{12}\text{CO}(1-0)$ observations in Chapter 2, which has no sensitivity on extended molecular gases due to lack of ACA (7-m + TP) data, and the total CO flux observations with the 45-m single-dish telescope of NRO. We derive the SFR from archival $\text{H}\alpha$, FUV and IR data, which are the massive star formation tracers, then investigate the relation between f_{dif} and SFE. Further, using the archival data of $^{12}\text{CO}(2-1)$ observations with ACA, we investigate the relation among the f_{dif} , SFE, and the emission line ratio of the $^{12}\text{CO}(2-1)$ to $^{12}\text{CO}(1-0)$ ($R_{21/10}$), which can be a measure to know the physical condition of molecular gases (e.g. Koda et al. 2012).

This chapter is structured as follows: In Section 3.2, we describe our $^{12}\text{CO}(1-0)$ observations with the NRO 45-m (Section 3.2.1) and with ALMA (Section 3.2.2). We also summarize archival $^{12}\text{CO}(2-1)$, $\text{H}\alpha$, FUV and IR data used in our analysis (Section 3.2.3). Then, Section 3.3 presents the resultant molecular gas surface density and SFR. Results of stacking analysis also are presented in Section 3.3.3. The f_{dif} and SFE in NGC 1300, which are main results of the paper, are presented in Section 3.4. In Section 3.5, we discuss the cause for the star formation suppression. Our conclusions are presented in Section 3.6. Appendix C shows the supplementary results of our analysis.

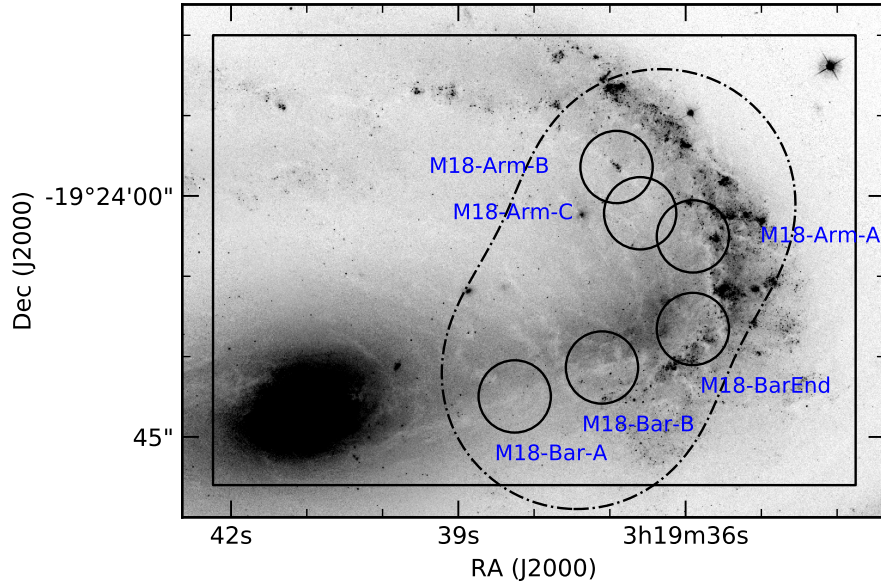


Figure 3.1: V-band image of NGC 1300 taken with F555W filter on ACS of HST. We obtained this image from HLA. The black rectangle represents the mapping area observed with the NRO 45-m (NRO FoV). The black dash-dotted line represents the FoV observed with ALMA 12-m array (ALMA FoV). The black solid circles represent the observed positions with the previous single-pointing observations with the NRO 45-m telescope (Maeda et al. 2018). The diameter of the circles show the beam size of 13.5 arcsec of the NRO 45-m.

3.2 Observations and Data Reduction

In this section, we describe making procedure of fits images we use in this paper; $^{12}\text{CO}(1-0)$ emission line obtained from the NRO 45-m (Section 3.2.1), $^{12}\text{CO}(1-0)$ and $^{12}\text{CO}(2-1)$ emission lines from ALMA (Section 3.2.2 and 3.2.3), $\text{H}\alpha$ emission from HST (Section 3.2.3), FUV from GALEX, and $22\mu\text{m}$ from WISE (Section 3.2.3). The spatial resolution and pixel size of all images we use for analysis are convolved and regridded to those of the $^{12}\text{CO}(1-0)$ image obtained from the NRO 45-m, which have the poorest beam size of 16.7 arcsec and the pixel size of $6.0 \text{ arcsec} \times 6.0 \text{ arcsec}$. In this paper, "pixel" refers to the region of $6.0 \text{ arcsec} \times 6.0 \text{ arcsec}$, unless otherwise noted.

3.2.1 $\text{CO}(1-0)$ emission from the NRO 45-m observations

Observations and data reduction

We carried out simultaneous observations of $^{12}\text{CO}(1-0)$ (rest frequency: 115.271202 GHz) and $^{13}\text{CO}(1-0)$ (110.201353 GHz) emission lines toward NGC 1300 on 2019 February 16, 17, 18, and 20 with the NRO 45-m, employing the on-the-fly (OTF) mapping mode. The observed area is $120 \text{ arcsec} \times 84 \text{ arcsec}$, corresponding to $12.0 \text{ kpc} \times 8.4 \text{ kpc}$, as shown in a black rectangle in Figure 3.1 (hereafter, we call this region NRO FoV). This region covers from the center to the western arm of NGC 1300, which also covers the regions observed with ALMA 12-m array (Section 3.2.2).

We used the multi-beam receiver, FOur-beam REceiver System on the 45-m Telescope (FOREST; Minamidani et al. 2016). FOREST has four beams, which are arranged on the corners of a 50 arcsec square. Each beam is a dual-polarization sideband-separating SIS mixer receiver. The beam size

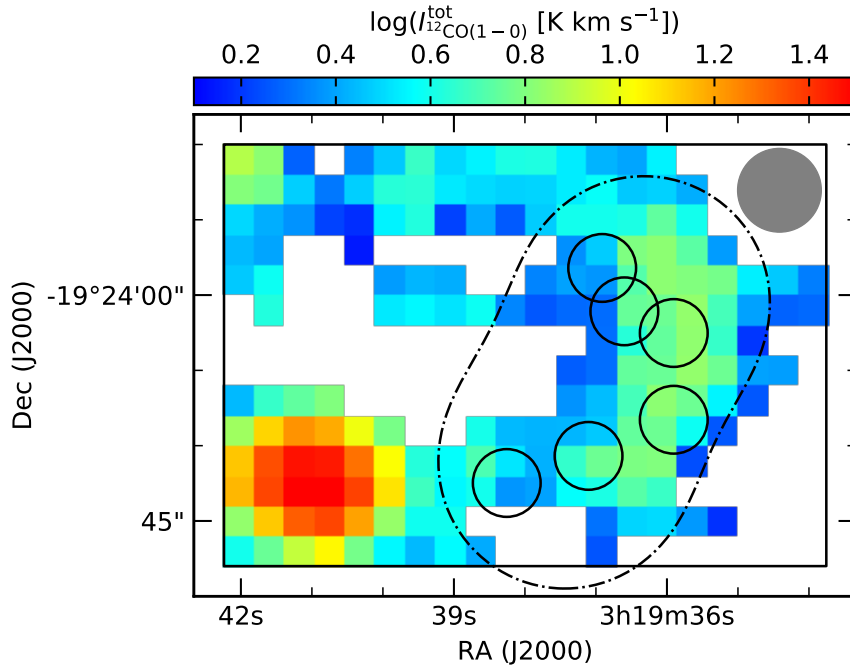


Figure 3.2: Velocity-integrated intensities map of $^{12}\text{CO}(1-0)$ line with the NRO 45-m (i.e. moment zero map). In white pixels, we did not detect any significant emissions. The grey circle represents the effective angular resolution of 16.7 arcsec. Other lines are the same as Figure 3.1.

of each beam is ~ 14 arcsec at 115 GHz. The Intermediate Frequency (IF) bandwidth of 8 GHz enables us to simultaneously observe $^{12}\text{CO}(1-0)$ and $^{13}\text{CO}(1-0)$. The backend is an FX-type correlator system, SAM45, which consists of 16 arrays with 4096 spectral channels each. Two correlators are assigned for each beam and polarization. The bandwidth and resolution were set to 1 GHz and 488.28 kHz, respectively, corresponding to 2600 km s^{-1} and 1.3 km s^{-1} at 115 GHz. Although $\text{C}^{18}\text{O}(1-0)$ (109.782173 GHz) emission line is also within the bandwidth, we do not focus on the line because its emission is expected to be extremely weak (e.g. Sorai et al. 2019).

We performed the OTF mapping along the long side (X scan) and the short side (Y scan) of the black rectangle in Figure 3.1. The separation between the scan rows was set to 5.0 arcsec, and scan speeds were $8.8 \text{ arcsec s}^{-1}$ for X scan and $7.2 \text{ arcsec s}^{-1}$ for Y scan, respectively. The pointing accuracy was checked almost every hour to keep within 3 arcsec by observing SiO maser source, *o* Cet (22° from NGC 1300), using a 43 GHz band receiver. The line intensity was calibrated by the chopper wheel method. The system temperature (T_{sys}) was 300–500 K at 115 GHz, which is slightly high due to the low elevation of $20^\circ - 30^\circ$. The total on-source time was about 15 hrs.

The observed data were analyzed using the software package NOSTAR (Sawada et al. 2008), which comprises tools for OTF data analysis developed by NRO. First, we divided each scan into five spectra and flagged spectra with poor baselines or/and spurious lines by eye. Then, a baseline (second-order polynomial function with small curvature) was subtracted, and the data were regridded to 6.0 arcsec per pixel with an effective angular resolution of approximately 16.7 arcsec, corresponding to 1.67 kpc. We smoothed the spectrum by binning to 20 km s^{-1} . Because the image rejection ratios (side band ratio) in the adopted frequency range were almost larger than 10 dB, no correction was made. We converted the antenna temperature (T_{A}^*) into the main beam brightness temperature (T_{mb}) using the main beam efficiency of 35 ± 3 percent, which is observatory-provided value for 2018-19 observing season. The resultant rms noise is 13.9 mK and 7.7 mK for $^{12}\text{CO}(1-0)$

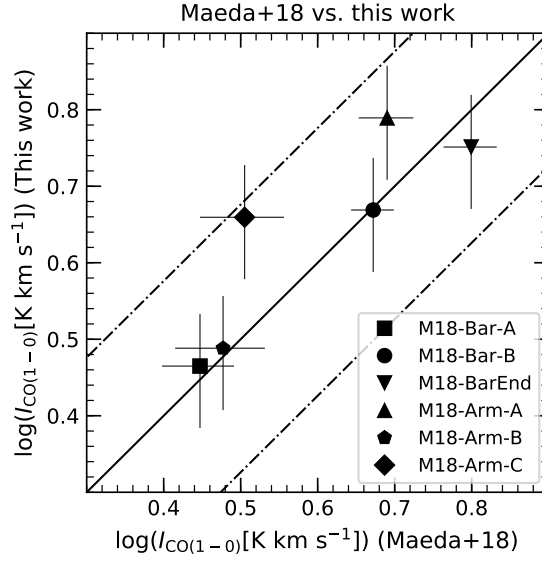


Figure 3.3: Comparison between $^{12}\text{CO}(1-0)$ line intensity obtained from this work and those by Maeda et al. (2018). The legends represent the name of the observed regions, which are shown as black circles in Figure 3.1, defined in Maeda et al. (2018). The solid line and dash-dotted lines represent the 1:1 correlation and factor of 1.5 differences, respectively.

and $^{13}\text{CO}(1-0)$, respectively, at 20 km s^{-1} bin.

CO emissions

Using the data cube obtained, we identified the significant CO emission. First, we identified the channel bins in which signals are above $3\sigma_{\text{rms}}$ in the spectrum of each pixel. Here, σ_{rms} is the rms noise of the spectrum. Then, we expanded these channel bins to include all adjacent bins in which signals are above σ_{rms} . The velocity-integrated intensity, $I_{^{12}\text{CO}(1-0)}^{\text{tot}}$, of each pixel is defined as sum of the identified channel bins. Figure 3.2 shows the $^{12}\text{CO}(1-0)$ map (i.e. moment zero map). We show the pixels where significant $^{12}\text{CO}(1-0)$ emission was detected. We detected the $^{12}\text{CO}(1-0)$ emission from the center to arm including the bar and bar-end regions. $I_{^{12}\text{CO}(1-0)}^{\text{tot}}$ is $10 \sim 15 \text{ K km s}^{-1}$ in center and $3.0 \sim 6.0 \text{ K km s}^{-1}$ between the bar and arm. However, we did not detect any significant $^{13}\text{CO}(1-0)$ emission lines.

We estimate the uncertainty of $I_{^{12}\text{CO}(1-0)}^{\text{tot}}$ as $\sigma_{I_{^{12}\text{CO}(1-0)}^{\text{tot}}} = \sqrt{N}\sigma_{\text{rms}}\Delta V$, where N is the number of channels (bins) used in the integration and ΔV is the channel width of 20 km s^{-1} . The typical uncertainty is 17 percent. An upper limit of the $I_{^{12}\text{CO}(1-0)}^{\text{tot}}$ where we did not detect any significant emission is estimated as $3\sigma_{I_{^{12}\text{CO}(1-0)}^{\text{tot}}}$ by assuming $N = 2.5$, which corresponds to the mean FWHM of the $^{12}\text{CO}(1-0)$ emission lines observed by Maeda et al. (2018).

Comparison with Maeda et al. (2018)

To see the accuracy of the $I_{^{12}\text{CO}(1-0)}^{\text{tot}}$ measurements, we compared the $^{12}\text{CO}(1-0)$ line intensities obtained from this work with those by Maeda et al. (2018), which presented the single-pointing observations of several regions with the NRO 45-m. The black circles in Figure 3.1 show the observed positions of Maeda et al. (2018) with the beam size (HPBW) of 13.5 arcsec of the NRO

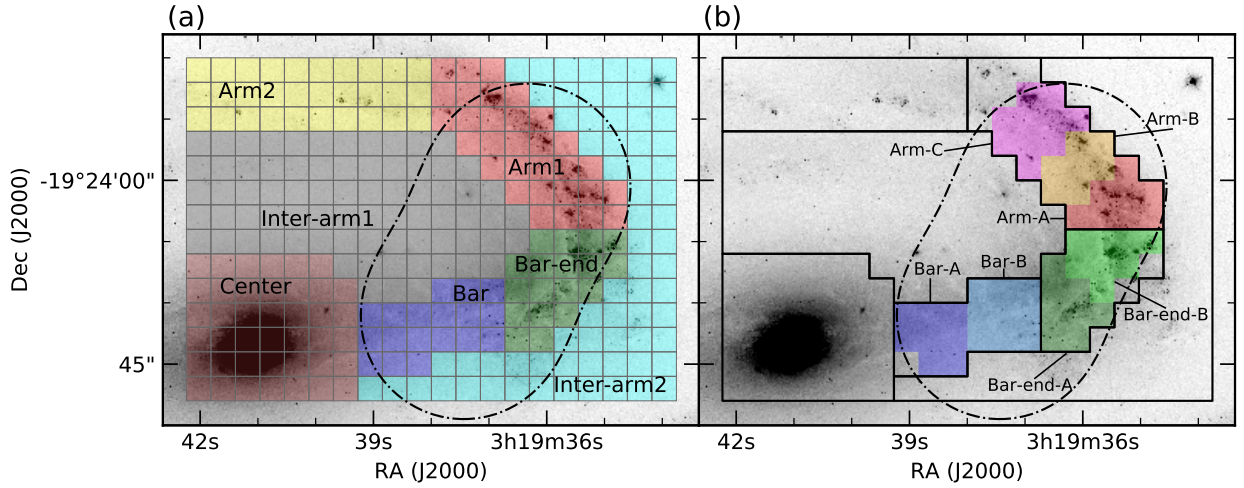


Figure 3.4: (a) Definition of the environmental mask for NRO FoV indicated with color. The *center*, *bar*, *bar-end*, *arm1*, *arm2*, *inter-arm1*, and *inter-arm2* are indicated with brown, blue, green, red, yellow, grey and cyan, respectively. The grey lines show the 6.0 arcsec $\times$ 6.0 arcsec grid. (b) Definition of the environmental mask for ALMA FoV indicated with color. The *bar-A*, *bar-B*, *bar-end-A*, *bar-end-B*, *arm-A*, *arm-B*, and *arm-C* are indicated with blue, lightblue, green, lightgreen, red, orange and magenta, respectively. The black solid lines represent definition of the environmental mask for NRO FoV as panel (a).

45-m. Using the moment zero map of Figure 3.2, we measured the CO(1 – 0) line intensity in the circle assuming the axially symmetric Gaussian beam pattern and 17 percent uncertainty of the line intensity, which is derived in Section 3.2.1. Figure 3.3 shows the one-to-one relation of the $^{12}\text{CO}(1 - 0)$ line intensity. The solid line and dash-dotted lines represent the 1:1 correlation and factor of 1.5 differences, respectively. For the M18-Bar-A, M18-Bar-B, M18-Bar-End and M18-Arm-B regions, we find that the line intensity obtained from this work is mostly the same as those by Maeda et al. (2018). The line intensity in the M18-Arm-A and M18-Arm-C is different from Maeda et al. (2018) by a factor of 1.3 and 1.5, respectively. This result indicates that the $I_{^{12}\text{CO}(1-0)}^{\text{tot}}$ measurements described in Section 3.2.1 are generally accurate but may contain systematic errors up to a factor of 1.5.

Definition of environments

In this study, we measure the physical parameters (Σ_{mol} , f_{dif} , $R_{21/10}$, SFR, and SFE) for each 6.0 arcsec $\times$ 6.0 arcsec region, which is the pixel size of the $^{12}\text{CO}(1 - 0)$ data cube obtained from the NRO 45-m observations. The 6.0 arcsec grid in NRO FoV is shown in Figure 3.4(a) and we separated these pixels into seven environments: *center*, *bar*, *bar-end*, *arm1*, *arm2*, *inter-arm1*, and *inter-arm2*, according to color regions in Figure 3.4(a). Considering the spread of $^{12}\text{CO}(1 - 0)$ emission in Figure 3.2, we defined *center* as a brown region. The blue region is defined as *bar*, which covers the dark lane and associated spurs that are connected almost perpendicularly to the dark lane. The green region that covers the intersection region of the bar and the arm is defined as *bar-end*. The arm region is separated into *arm1* and *arm2* shown as red and yellow regions, respectively. While the bright HII regions are seen in *arm1*, there are several HII regions in *arm2*. The remaining region is separated into *inter-arm1* and *inter-arm2* shown as grey and cyan region, respectively. The environmental mask definition for the NRO FoV are only used to make the H α image in Section 3.2.3 and to investigate the Kennicutt–Schmidt law and the relation between the SFE and $R_{21/10}$ in Appendix C.

Because the main purpose of this paper is to figure out the relation between the f_{dif} and SFE, we mainly use the pixels within the FoV of ALMA $^{12}\text{CO}(1-0)$ observations shown as the black dash-dotted line in Figure 3.1 (hereafter, we call ALMA FoV). In order to compare the relation between the f_{dif} and SFE among galactic environments in details, we separated the pixels in *bar*, *bar-end* and *arm1* within ALMA FoV into *bar-A*(blue) and *bar-B*(light-blue), *bar-end-A*(green) and *bar-end-B*(light-green), and *arm-A*(red), *arm-B*(orange), and *arm-C*(magenta), respectively, according to Figure 3.4(b).

3.2.2 CO(1 – 0) emission from ALMA observations

The details of the observations of $^{12}\text{CO}(1-0)$ line with ALMA and data reduction of them are described in Section 2.2. We convolved the original data cube to the common beam size of 16.7 arcsec. To identify the significant CO emission, we first identify the 3D (position-position-velocity) regions with a signal-to-noise ratio (S/N) ≥ 4 in at least two adjacent velocity channels. We expand this mask to include all adjacent pixels with S/N ≥ 2 in 3D space. Finally, we regridded this data cube to 6.0 arcsec grid. Figure 3.5 shows the map of the velocity-integrated $^{12}\text{CO}(1-0)$ intensities ($I_{^{12}\text{CO}(1-0)}^{\text{ALMA}}$). As the uncertainty of $I_{^{12}\text{CO}(1-0)}^{\text{ALMA}}$ in each pixel, we consider the absolute flux calibration accuracy of ± 5 percent in Band 3 (ALMA Technical Handbook).

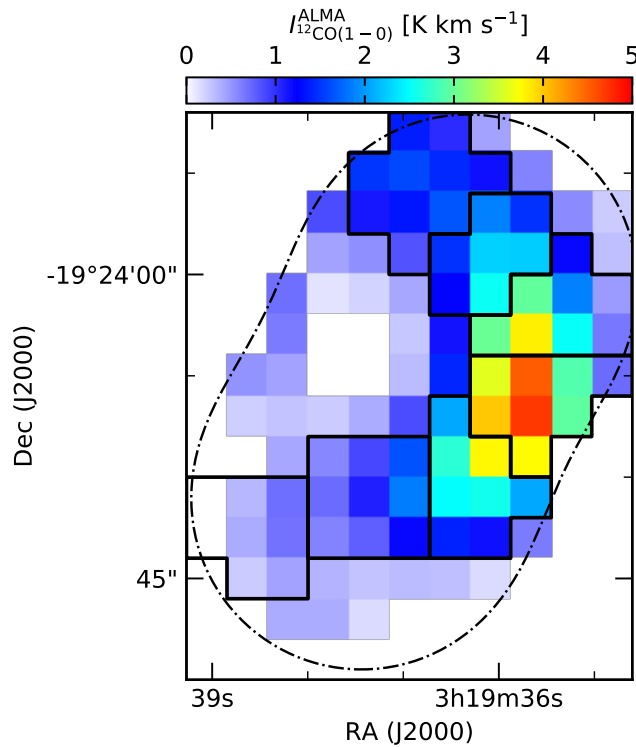


Figure 3.5: Velocity-integrated intensities map of $^{12}\text{CO}(1-0)$ line with ALMA convolved to the common beam size of 16.7 arcsec. The black solid lines represent definition of the environmental mask for ALMA FoV as Figure 3.4(b).

Our ALMA observations did not recover the total $^{12}\text{CO}(1-0)$ flux due to the lack of ACA (7-m+TP) measurements. Here, we check the relationship between the spatial scale of the gas distribution and missing flux, we simulated ALMA observation of a mock Gaussian component. We created a fits image of a circular Gaussian component with a total flux of 1.0 Jy and given

FWHM. The FWHM was set from 100 pc to 2200 pc in 100 pc interval. In order to extract the effect originated from the uv-distribution, we simulated the observation under the same configuration and noise-free condition by using the task of `simobserve` in `CASA`. After reconstructing the image, we measured the flux of the component and recovery fraction. Figure 3.6 shows the recovery fraction of the Gaussian component as a function of the FWHM. We find that the recovery fraction of the Gaussian component with $\text{FWHM} \leq 300$ pc is ~ 1.0 and that with $\text{FWHM} > 300$ pc is under 1.0. For the large Gaussian component with the $\text{FWHM} \geq 700$ pc, more than half of the flux is missed. Thus, a molecular gas structure homogeneously extended to over ~ 700 pc is mostly resolved out in this $^{12}\text{CO}(1-0)$ ALMA observations. If FWHM is larger than the MRS of ALMA observation (2.14 kpc), flux recovers less than 10 percent.

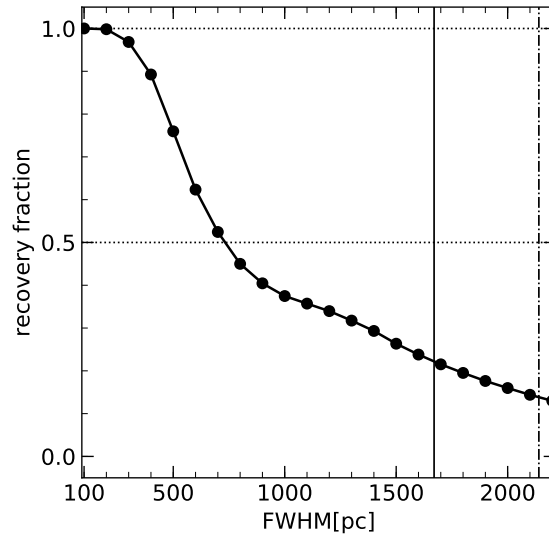


Figure 3.6: Recovery fraction of the Gaussian component as a function of the FWHM. We simulated ALMA observation of the mock Gaussian component with a given FWHM under the same configuration of the $^{12}\text{CO}(1-0)$ ALMA observations and noise-free condition. The horizontal dashed lines indicate the recovery fraction of 1.0 and 0.5. The vertical solid line indicates 1670 pc and the dash-dotted line indicates 2140 pc, corresponding to the beam size of the NRO 45-m telescope and, MRS of the $^{12}\text{CO}(1-0)$ ALMA observations, respectively.

3.2.3 Archival data

CO(2 – 1) emission from ALMA observations

We made a map of $^{12}\text{CO}(2-1)$ (rest frequency: 230.538000 GHz) emission using the archival data which was observed with ACA (7-m + TP) under project 2015.1.00925.S as proposed by B. Guillermo et al. Thanks to the TP data, the total $^{12}\text{CO}(2-1)$ flux was detected. We calibrated raw visibility data using `CASA` and the observatory-provided calibration script. We imaged the interferometric map using the CLEAN algorithm in `CASA` by adopting Briggs weighting with robust = 0.5. The resulting image is feathered with the total power image to recover the extended emission. The spatial resolution is $7.6 \text{ arcsec} \times 4.1 \text{ arcsec}$, corresponding to $760 \text{ pc} \times 410 \text{ pc}$. The rms noise of the data cube is $11.0 \text{ mJy beam}^{-1}$ per 10.0 km s^{-1} bin. Then, we convolved this data cube to the common beam size of 16.7 arcsec and identified the significant $^{12}\text{CO}(2-1)$ emission as the same procedure described in Section 3.2.2. Finally, we regridded this data cube to 6.0 arcsec grid. Figure 3.7 shows the map of the velocity-integrated $^{12}\text{CO}(2-1)$ intensities ($I_{^{12}\text{CO}(2-1)}^{\text{tot}}$). As the

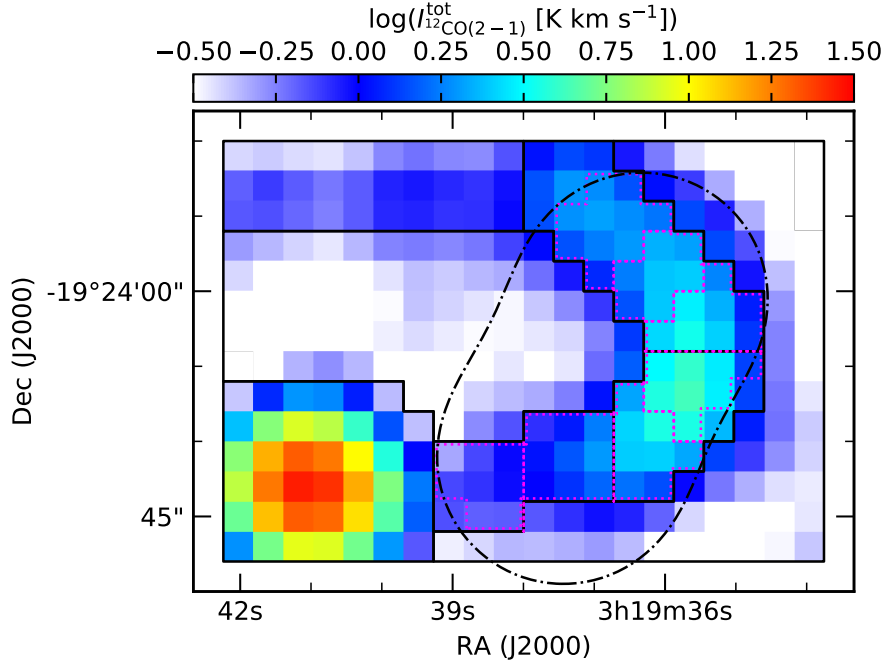


Figure 3.7: Velocity-integrated intensities map of $^{12}\text{CO}(2-1)$ line with ALMA convolved to the common beam size of 16.7 arcsec. The black solid lines and magenta dotted lines represent definition of the environmental mask for NRO FoV and ALMA FoV as Figure 3.4(a) and (b), respectively.

uncertainty of $I_{^{12}\text{CO}(1-0)}^{\text{ALMA}}$ in each pixel, we consider the absolute flux calibration accuracy of ± 10 percent in Band 6 (ALMA Technical Handbook).

H α emission from HST archive data

To measure SFR in NGC 1300, we made an H α image using the archival images observed with the ACS on the HST (proposal ID = 10342, PI = K. Noll) which can be taken from the HLA. The images were taken with a broadband $F555W$ filter (close to standard V band) and a narrowband H α filter, $F658N$. The properties of these filters are summarized in Table 3.1. The observations were carried out in 2004 September and the total exposures time was 1360 s and 2720 s for $F555W$ and $F658N$, respectively. The fits images we used were corrected for bias, dark current, flat-fielding, and rejection of cosmic rays using the standard pipeline calibration for ACS. The spatial sampling was $0.04 \text{ arcsec pixel}^{-1}$. Pixel values of the images were in electrons s^{-1} and we converted this value to the flux density, unit of $\text{erg cm}^{-2} \text{s}^{-1} \text{\AA}^{-1}$, by using the calibration parameter, PHOTFLAM, listed in Table 3.1. The background was determined as a mode value, which is derived based on binning of the flux density (bin size of $1.0 \times 10^{-23} \text{ erg cm}^{-2} \text{s}^{-1} \text{\AA}^{-1}$), in empty corners of the image (i.e. region without emission from the galaxy).

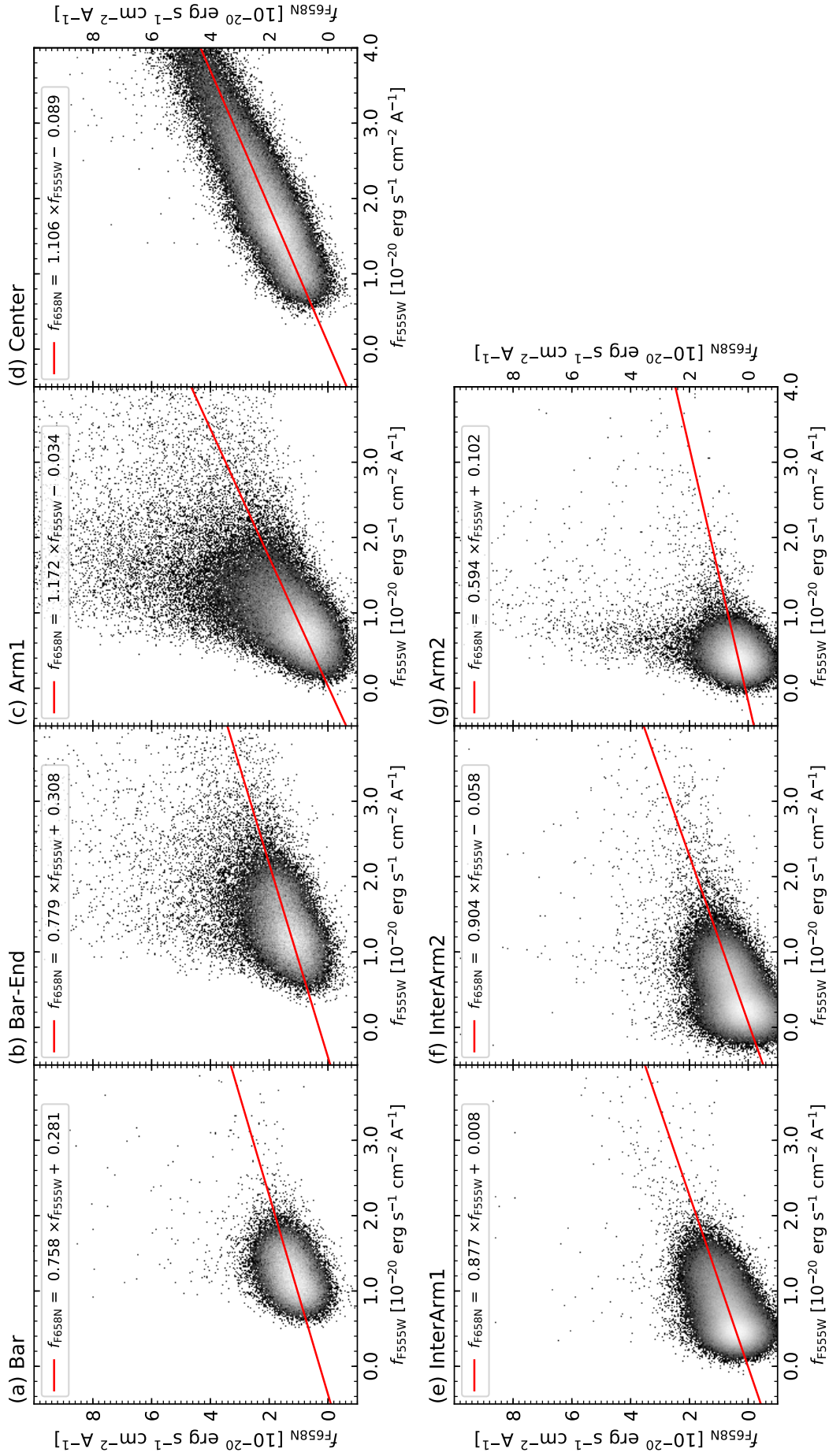


Figure 3.8: (a) The flux densities of the pixels in the F_{658N} image against those of the same pixel in the F_{555W} image in *bar-end*. The red solid line shows the best-fit straight line to the data points by using robust least-squares regression (see text). The best fit values are shown in top. (b)-(g) Same as panel (a) but for *center*, *bar*, *arm1*, *arm2*, *inter-arm1*, and *inter-arm2*, respectively.

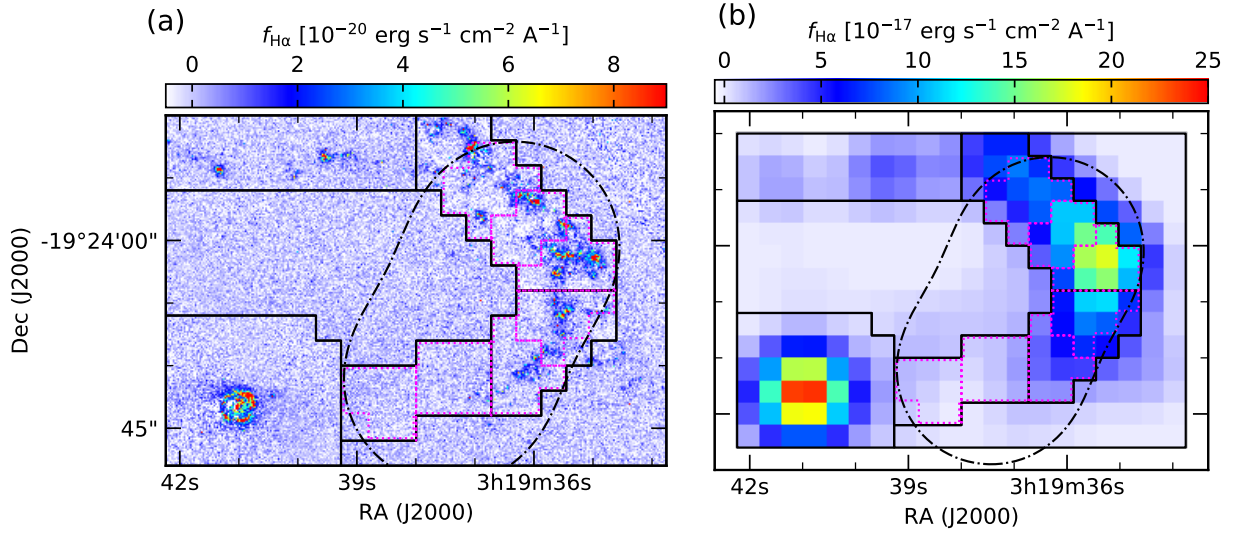


Figure 3.9: (a) Continuum-subtracted $H\alpha$ image made from HST images (see text). Pixel size is 0.04 arcsec. (b) Continuum-subtracted $H\alpha$ image convolved to the common beam size of 16.7 arcsec and regridded to 6.0 arcsec. All lines are the same as Figure 3.7.

Table 3.1: Filter properties

Filter	λ_{pivot}^a (Å)	W_{eff}^b (Å)	PHOTFLAM (erg cm ⁻² s ⁻¹ Å ⁻¹ for 1 e ⁻ s ⁻¹)
F555W	5384.48	1099.65	$1.941069775 \times 10^{-19}$
F658N	6584.06	74.75	$1.965832575 \times 10^{-18}$

^a The pivot wavelength of the filter.

^b The effective width defined by $\int T(\lambda) d\lambda / \text{Max}(T(\lambda))$.

The *F658N* image includes $H\alpha$ emission line and stellar continuum. We thus subtracted the underlying stellar continuum in the *F658N* image adopting a method developed by Bunker et al. (2008) and used by Knapen et al. (2004) and Gutiérrez et al. (2011). The method is as follows: First, we plot the flux density of each pixel in the $H\alpha$ +continuum image versus the flux density of the same pixel in the continuum image. Pixels which do not contain emission line delineate a straight zone in the diagram. Pixels which contain emission line locate outside of this straight zone. Scatter along this straight zone is originated from combination of the observation noise, color variations due to different stellar populations, differential extinction effects, and so on. The slope of this straight zone gives the constant of proportionality for the continuum subtraction. Therefore, we can produce the continuum-subtracted $H\alpha$ image by subtracting the continuum image multiplied by this constant from the original $H\alpha$ image. In this study, we use the *F555W* image as a continuum image assuming that the flux density in the *F658N* image (f_{F658N}) is proportional to the flux density in the *F555W* image (f_{F555W}) in regions without $H\alpha$ emission.

Considering that the stellar population (i.e. color) is different with environments, we determined the constant in each environment defined as Figure 3.4(a). Figure 3.8 shows f_{F658N} of each pixel versus f_{F555W} of the same pixel in each environment. In each panel, a straight zone is seen. Then

we fit the straight zone to a line as

$$f_{F658N} = a \times f_{F555W} + b, \quad (3.2.1)$$

where we added an intercept of b because fitting does not work well with one parameter of a . If ordinary least squares fitting is used, the fitting will fail because the pixels containing $H\alpha$ emission, which become outliers, hinder the calculation. Therefore, we fit the straight zone using robust least-squares regression in order to minimize the influence of the outliers. We use Tukey's biweight to down-weight outliers:

$$w(d) = \begin{cases} \left[1 - \left(\frac{d}{W} \right)^2 \right]^2 & (|d| \leq W) \\ 0 & (|d| > W), \end{cases} \quad (3.2.2)$$

where d is the distance between the point and the regression line, and W is a user selected value that is most often in the range of 4-6. We applied $W = 4.0$, but changing W between 4 and 6 does not influence on the fitting result. We start with an estimate of the regression line with $w(d) = 1.0$ (e.g. ordinary standard least squares). Then, we compute the Tukey's weight based on the estimated regression line. Next, we perform weighted least squares with the weight to get a new estimate of the regression line. This is repeated until a and b are converged. The best fit lines are shown as red solid lines in Figure 3.8. The slope of the best fit line depends on the environments as we expected: The a ranges from 0.6 to 1.2.

Finally, we measure the flux density of the $H\alpha$ ($f_{H\alpha}$) as

$$f_{H\alpha} = f_{F658N} - (a \times f_{F555W} + b). \quad (3.2.3)$$

Figure 3.9(a) shows the continuum-subtracted $H\alpha$ image. Figure 3.9(b) is the image convolved to the common beam size of 16.7 arcsec and regridded to 6.0 arcsec. In order to estimate the uncertainty of $f_{H\alpha}$, we randomly extracted 10^4 pixels from each environment and performed the fitting described above 10 times. The half of the difference when the $H\alpha$ luminosity is maximum and minimum in the 10 iterations is adopted as the uncertainty, leading typically 10 percent uncertainty of $f_{H\alpha}$ in the 6.0 arcsec grid.

Because the narrowband $F658N$ filter covers the $[N_{II}]$ doublet, $\lambda\lambda 6548, 6584$, emission lines, $f_{H\alpha}$ is contaminated. Flux density ratios of $F_{[N_{II}]\lambda 6548}/F_{[N_{II}]\lambda 6584}$ and $F_{[N_{II}]\lambda 6584}/F_{H\alpha}$ are 0.33 and 0.30, respectively, in the normal HII regions (Osterbrock 1989). Considering the transmission corrections, we estimate the $[N_{II}]$ contamination of 21 percent to $f_{H\alpha}$. In the estimation of the SFR from the $H\alpha$ emission in Section 3.3.2, this contamination is corrected by multiplying the correction factor of $C_{[N_{II}]} = 0.79$. It is also possible that the $f_{H\alpha}$ is contaminated from the $[O_{III}]\lambda 5007$, which is the strongest emission line in the broadband $F555W$ filter. The flux density ratio of $F_{[O_{III}]\lambda 5007}/F_{H\alpha}$ ranges from 0.1 to 0.6 in the normal HII regions (e.g. M51; Bresolin et al. 2004). Assuming that the a is typically 1.0, we estimate that the $[O_{III}]$ contamination is up to 3 percent. Since this value is small, we need not be worried about the $[O_{III}]$ contamination.

FUV + 22 μ m

To measure SFR, we also use GALEX FUV (Gil de Paz et al. 2007) and WISE 22 μ m (Wright et al. 2010) archival data as an alternative to using $H\alpha$ image. We converted the unit of the original FUV fits image, count pixel second (CPS), into MJy sr $^{-1}$. Because the angular resolution and pixel size of the original FUV fits image are 4.3 arcsec and 1.5 arcsec, respectively, this image was convolved

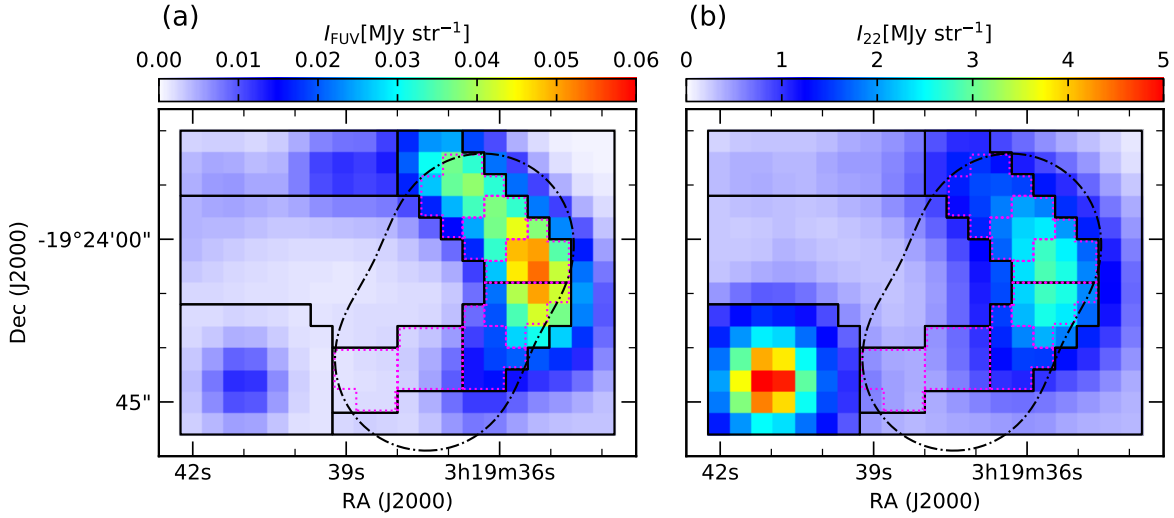


Figure 3.10: (a) FUV image obtained from GALEX, but convolved to 16.7 arcsec and regridded to 6.0 arcsec. The black solid lines and magenta dotted lines represent definition of the environmental mask for NRO FoV and ALMA FoV as Figure 3.4(a) and (b), respectively. The black dash-dotted line represents the FoV observed with ALMA 12-m array. (b) Same as panel (a), but for $22\mu\text{m}$ obtained from WISE.

to the common beam size of 16.7 arcsec and regridded into 6.0 arcsec shown as Figure 3.10(a). For the original WISE $22\mu\text{m}$ image, we first subtracted the background level, which is determined as the mode value at the blank sky. Then, we converted the unit of digital number into MJy sr^{-1} . Since the effective angular resolution of the $22\mu\text{m}$ atlas image is 16.8 arcsec (Cutri et al. 2012)¹ which is almost the same as that of our $^{12}\text{CO}(1-0)$ data obtained from the NRO 45-m, we did not convolve the $22\mu\text{m}$ image. Figure 3.10(b) shows the $22\mu\text{m}$ image regridded into 6.0 arcsec.

3.3 Conversion to Physical Parameters

Since the purpose of this study is investigating the differences in the f_{dif} with environments and the relations between f_{dif} and other parameters, we focus on the physical parameters in the environments defined for the ALMA FoV (Section 3.2.1) in the rest of this paper. The physical parameters in other regions including the center are described in Appendix C.

3.3.1 Molecular gas surface density

Molecular gas surface density ($\Sigma_{\text{mol}}^{\text{tot}}$) is derived from the velocity-integrated intensities ($I_{^{12}\text{CO}(1-0)}^{\text{tot}}$) as

$$\left(\frac{\Sigma_{\text{mol}}^{\text{tot}}}{\text{M}_{\odot} \text{pc}^{-2}} \right) = \left(\frac{\alpha_{\text{CO}}}{\text{M}_{\odot} (\text{K km s}^{-1} \text{pc}^2)^{-1}} \right) \left(\frac{I_{^{12}\text{CO}(1-0)}^{\text{tot}}}{\text{K km s}^{-1}} \right) \cos i, \quad (3.3.1)$$

where α_{CO} is CO-to- H_2 conversion factor and $\cos i$ shows the effect of the inclination of the galaxy. Here, we adopt the standard α_{CO} of $4.4 \text{ M}_{\odot} (\text{K km s}^{-1} \text{pc}^2)^{-1}$ including a factor of 1.36 to account for the presence of helium. Among the bar, arm and bar-end regions, Σ_{mol} is comparable and about $10 - 15 \text{ K km s}^{-1}$. As described in Maeda et al. (2018), this result indicates that the molecular gases

¹Cutri, R. M., et al. 2012, Explanatory Supplement to the WISE All-Sky Data Release Products

do exist in the strong bars with no clear HII regions. The range of $10 - 15 \text{ M}_\odot \text{ pc}^{-2}$ is consistent with those in the disk of nearby non-barred spiral galaxies (e.g. Bigiel et al. 2008). Compared bar regions of other barred galaxies, the Σ_{mol} in the bar regions of NGC 1300 is lower; Half of Σ_{mol} in NGC 1530 ($\sim 24 \text{ M}_\odot \text{ pc}^{-2}$; Reynaud & Downes 1998) and NGC 5383 ($\sim 30 \text{ M}_\odot \text{ pc}^{-2}$; Maeda et al. 2018). Less than 4 times Σ_{mol} of NGC 3627 ($\sim 60 \text{ M}_\odot \text{ pc}^{-2}$; Regan et al. 1999; Kuno et al. 2007), NGC 2903 ($\sim 50 \text{ M}_\odot \text{ pc}^{-2}$; Muraoka et al. 2016) and NGC 4303 ($\sim 86 \text{ M}_\odot \text{ pc}^{-2}$; Yajima et al. 2019). Here the α_{CO} is unified to $4.4 \text{ M}_\odot (\text{K km s}^{-1} \text{ pc}^2)^{-1}$.

Sorai et al. (2012) suggested that α_{CO} in the bar regions may be 0.5 – 0.8 times smaller than that in the arm regions in Maffei 2 using large velocity gradient analysis. Morokuma-Matsui et al. (2015) suggested the existence of non-optically-thick components of $^{12}\text{CO}(1-0)$ in the bar regions may make the α_{CO} by a factor of a few smaller than in the arm regions in NGC 3627. A similar result is reported by Watanabe et al. (2011). Therefore, there is a possibility that the Σ_{mol} in the bar regions of NGC 1300 may be overestimated by a factor of a few. However, this issue is beyond our scope and remains as future work.

3.3.2 Star formation rate

SFR from $\text{H}\alpha$

We calculated the surface density of SFR from the continuum-subtracted $\text{H}\alpha$ image (Figure 3.9(b)) by

$$\left(\frac{\Sigma_{\text{SFR}}^{\text{H}\alpha}}{\text{M}_\odot \text{ yr}^{-1} \text{ kpc}^{-2}} \right) = 5.3 \times 10^{-42} \left(\frac{L_{\text{H}\alpha}}{\text{erg s}^{-1}} \right) \frac{\cos i}{S}, \quad (3.3.2)$$

where 5.3×10^{-42} is the conversion factor from $\text{H}\alpha$ luminosity ($L_{\text{H}\alpha}$) to the SFR obtained by Calzetti et al. (2007), i is the inclination of NGC 1300 and S is the covered area for each pixel of $600 \text{ pc} \times 600 \text{ pc}$. The $L_{\text{H}\alpha}$ is derived as

$$L_{\text{H}\alpha} = 4\pi f_{\text{H}\alpha} W_{\text{eff}} D^2 C_{[\text{NII}]} 10^{0.4A_V}, \quad (3.3.3)$$

where $f_{\text{H}\alpha}$ is the $\text{H}\alpha$ flux density derived from the continuum-subtracted $\text{H}\alpha$ image, W_{eff} is the effective width of the *F658N* filter listed in Table 3.1, D is the distance to NGC 1300, $C_{[\text{NII}]}$ is the correction factor of 0.79 which is needed to remove the $[\text{NII}]$ emission described in Section 3.2.3, and A_V is a correction for the dust extinction. The dust extinction can vary in star-forming regions, and it is difficult to determine the optical depth. Here, we assumed an extinction of $A_V = 1.0$ mag, which is a typical value for integrated galaxy disks obtained by Leroy et al. (2012). They investigate SFRs in 30 disk galaxies from $\text{H}\alpha$, IR, and FUV images, and found that $\text{H}\alpha$ emission contributes ~ 40 percent of the total SFR over the range, $\Sigma_{\text{SFR}} = 10^{-1} - 10^{-3} \text{ M}_\odot \text{ yr}^{-1} \text{ kpc}^{-2}$, corresponding to ~ 1.0 mag of extinction. Figure 3.11(a) shows the spatial distribution of $\Sigma_{\text{SFR}}^{\text{H}\alpha}$. While the $\Sigma_{\text{SFR}}^{\text{H}\alpha}$ is $10^{-2.7} - 10^{-1.9} \text{ M}_\odot \text{ yr}^{-1} \text{ kpc}^{-2}$ in arm and bar-end regions, $\Sigma_{\text{SFR}}^{\text{H}\alpha}$ is mostly lower than $10^{-3} \text{ M}_\odot \text{ yr}^{-1} \text{ kpc}^{-2}$ in bar (and inter-arm) regions. The uncertainty of $\Sigma_{\text{SFR}}^{\text{H}\alpha}$ is typically 10 percent propagated from the determination of $f_{\text{H}\alpha}$ described in Section 3.2.3.

SFR from FUV and 22 μ m

The surface density of SFR can be calculated from a linear combination of GALEX FUV and WISE 22 μ m intensities by Casasola et al. (2017) as

$$\left(\frac{\Sigma_{\text{SFR}}^{\text{IR}}}{\text{M}_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}} \right) = \left[8.1 \times 10^{-2} \left(\frac{I_{\text{FUV}}}{\text{MJy str}^{-1}} \right) + 3.2 \times 10^{-3} \left(\frac{I_{22\mu\text{m}}}{\text{MJy str}^{-1}} \right) \right] \cos i, \quad (3.3.4)$$

where I_{FUV} and $I_{22\mu\text{m}}$ are the FUV and 22 μ m intensities, respectively. Note that the equation (3.3.4) is the relation presented by Leroy et al. (2008) by replacing 24 μ m intensity with the 22 μ m one.

To estimate the SFR from IR emission, contamination from the older stellar population need to be considered. Qualitatively, the dust emission from old stars represents a second-order correction, but still important in nearby disk galaxy (Law et al. 2011; Leroy et al. 2012). We remove the 22 μ m emission not associated with recent star formation using following equation:

$$\left(\frac{I_{22\mu\text{m}}^{\text{old}}}{\text{MJy str}^{-1}} \right) = 1.2 \times 10^{-2} \left(\frac{\Sigma_{\text{gas}}}{\text{M}_{\odot} \text{ pc}^{-2}} \right), \quad (3.3.5)$$

where Σ_{gas} is the gas surface density combines H I and H₂. This equation is presented by Leroy et al. (2012) and we replaced 24 μ m intensity with the 22 μ m one. Comparing the H I image (England 1989b) and H₂ map we obtained, we assume $\Sigma_{\text{H}_2}/(\Sigma_{\text{H I}} + \Sigma_{\text{H}_2}) = 0.7$. The derived $I_{22\mu\text{m}}^{\text{old}}$ is typically 0.1 ~ 0.3 MJy str⁻¹ and contribution from IR emissions originated from old stars to $\Sigma_{\text{SFR}}^{\text{IR}}$ is 5 – 10 percent in *arm-A*, *arm-B*, *arm-C* and *bar-end-B* and 15 – 25 percent in *bar-end-A*, *bar-A*, and *bar-B*. Old stars may still produce some FUV emission, which also contaminates SFR estimates. However, such contamination appears to be only 3 percent of the total SFR where $\Sigma_{\text{SFR}} > 10^{-3} \text{ M}_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$ (Leroy et al. 2012). Thus, we neglected this contamination in this study.

Figure 3.11(b) shows the spatial distribution of $\Sigma_{\text{SFR}}^{\text{IR}}$. $\Sigma_{\text{SFR}}^{\text{IR}}$ is $10^{-2.5} - 10^{-2.1} \text{ M}_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$ in arm and bar-end regions and $< 10^{-2.7} \text{ M}_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$ in bar regions. The uncertainty of $\Sigma_{\text{SFR}}^{\text{IR}}$ is typically 16 percent, which includes the uncertainty of contamination from the older stellar population and calibration uncertainties of I_{FUV} and $I_{22\mu\text{m}}$; The FUV zero-point calibration is estimated to be 0.15 mag, which yields the uncertainty of ~ 15 percent (Gil de Paz et al. 2007). The photometric accuracy of the WISE calibrators is 5.7percent for the 22 μ m band (Jarrett et al. 2011).

For our calibration of $\Sigma_{\text{SFR}}^{\text{H}\alpha}$ and $\Sigma_{\text{SFR}}^{\text{IR}}$, we adopt the initial mass function (IMF) from Calzetti et al. (2007). To convert the Σ_{SFR} to those shown by Kennicutt (1998a) adopted the truncated Salpeter (1955) IMF, a factor of 1.59 should be multiplied.

SFR Comparison

In order to check the accuracy of the Σ_{SFR} measurements, we compared $\Sigma_{\text{SFR}}^{\text{H}\alpha}$ and $\Sigma_{\text{SFR}}^{\text{IR}}$ in Figure 3.11(c). The small symbols represent individual 6.0 arcsec pixels. The mean value of the Σ_{SFR} in each environment is shown as a large symbol and listed in Table 3.2. In *arm-A*, *arm-B*, and *arm-C* regions, $\Sigma_{\text{SFR}}^{\text{H}\alpha}$ is systematically larger than $\Sigma_{\text{SFR}}^{\text{IR}}$ by a factor up to 1.4. While in *bar-end-A* and *bar-end-B* regions, $\Sigma_{\text{SFR}}^{\text{H}\alpha}$ is systematically smaller than $\Sigma_{\text{SFR}}^{\text{IR}}$ by a factor of 0.8 – 0.9. The cause for these differences is unknown, but there are some possibilities: differences of dust extinction among environments, uncertainties in estimations of the 22 μ m emission not associated with recent star formation, and so on. In any case, the magnitude of systematic differences rarely exceeds a factor of two (0.3 dex) above $\Sigma_{\text{SFR}} = 10^{-3.0} \text{ M}_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$.

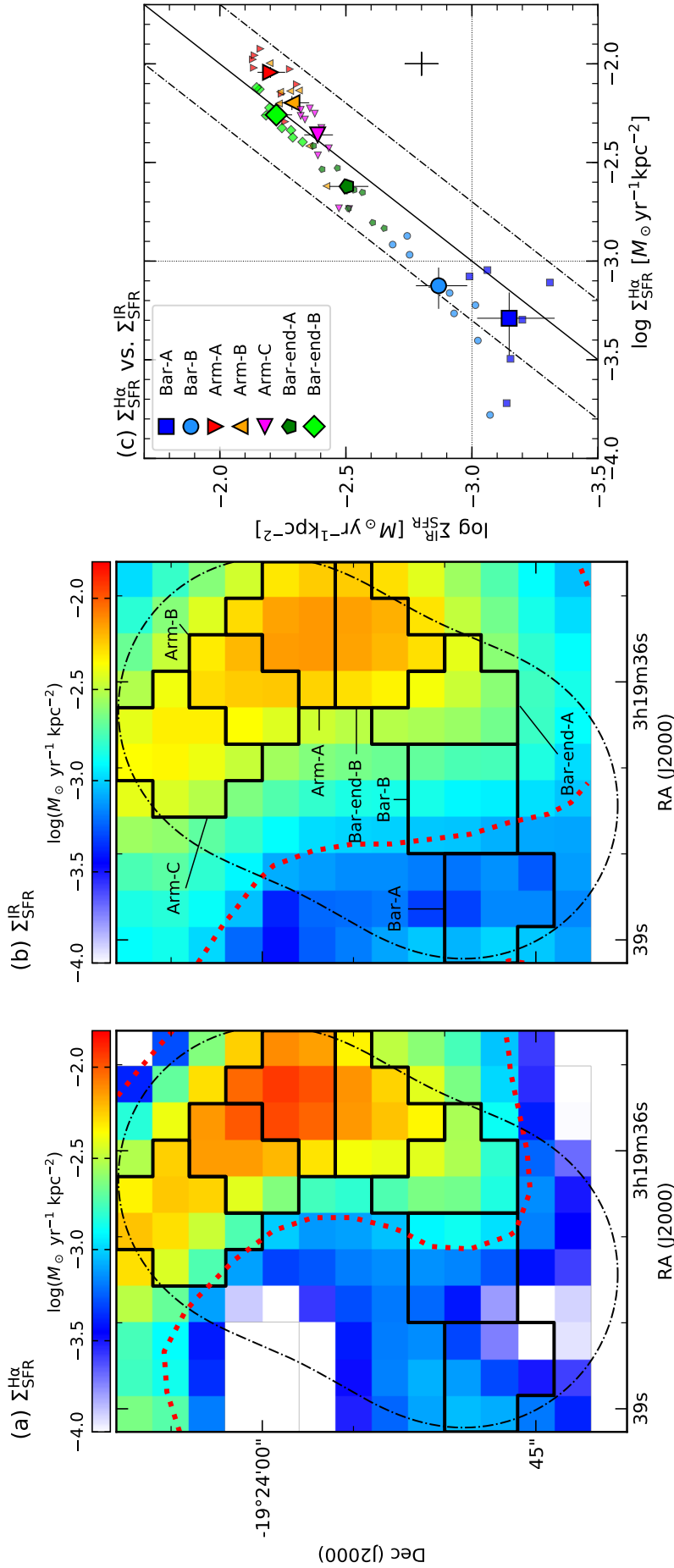


Figure 3.11: (a) Spatial distribution of SFR derived from H α image in ALMA FoV. The red dotted line represents $10^{-3} M_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$. Other lines are the same as Figure 3.5. (b) Same as panel (a), but for SFR derived from FUV and $22\mu\text{m}$ images. (c) Comparison between surface densities of SFR derived from H α image and those from FUV and $22\mu\text{m}$ images in ALMA FoV. Small and large symbols represent the value in individual 6.0 arcsec pixels and the mean value in each environment, respectively. The typical uncertainty for each 6.0 arcsec pixel is shown as a black cross. The dotted lines represent $10^{-3} M_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$. The solid line and dash-dotted lines represent the 1:1 correlation and factor of 2.0 differences, respectively.

Table 3.2: Mean values of physical parameters for ALMA FoV.

	Bar-A	Bar-B	Arm-A	Arm-B	Arm-C	Bar-end-A	Bar-end-B
$\Sigma_{\text{SFR}}^{\text{H}\alpha}$	0.5 ± 0.2	0.8 ± 0.2	9.1 ± 0.6	6.3 ± 0.5	4.4 ± 0.4	2.4 ± 0.2	5.5 ± 0.3
$\Sigma_{\text{SFR}}^{\text{IR}}$	0.7 ± 0.2	1.4 ± 0.3	6.3 ± 0.8	5.2 ± 0.8	4.1 ± 0.5	3.1 ± 0.6	6.0 ± 0.8
$I_{12\text{CO}(1-0)}^{\text{tot}}$	4.4 ± 0.5	4.1 ± 0.3	4.6 ± 0.4	5.3 ± 0.4	3.0 ± 0.3	4.9 ± 0.3	4.7 ± 0.3
$I_{12\text{CO}(1-0)}^{\text{ALMA}}$	0.40 ± 0.02	1.05 ± 0.01	2.08 ± 0.02	1.89 ± 0.03	1.32 ± 0.03	2.29 ± 0.02	3.40 ± 0.02
$I_{12\text{CO}(2-1)}^{\text{tot}}$	0.7 ± 0.1	1.4 ± 0.1	2.3 ± 0.2	2.2 ± 0.2	1.7 ± 0.2	2.4 ± 0.2	3.4 ± 0.3
$\Sigma_{\text{mol}}^{\text{tot}}$	12.3 ± 1.3	11.4 ± 0.9	12.9 ± 1.1	15.0 ± 1.1	8.6 ± 0.8	13.9 ± 0.9	13.3 ± 1.0
f_{dif}	0.91 ± 0.10	0.74 ± 0.07	0.55 ± 0.05	0.65 ± 0.06	0.57 ± 0.06	0.53 ± 0.05	0.28 ± 0.02
$\text{SFE}^{\text{H}\alpha}$	0.06 ± 0.02	0.09 ± 0.02	0.96 ± 0.10	0.58 ± 0.06	0.69 ± 0.09	0.23 ± 0.03	0.57 ± 0.05
SFE^{IR}	0.08 ± 0.03	0.16 ± 0.04	0.66 ± 0.10	0.47 ± 0.08	0.65 ± 0.10	0.31 ± 0.06	0.61 ± 0.09
$R_{21/10}$	0.17 ± 0.02	0.34 ± 0.04	0.51 ± 0.07	0.41 ± 0.05	0.55 ± 0.07	0.49 ± 0.06	0.72 ± 0.09
$R_{13/12}$	< 0.09	< 0.09	< 0.12	< 0.07	< 0.25	< 0.08	< 0.08

Below $\Sigma_{\text{SFR}}^{\text{H}\alpha} = 10^{-3.0} \text{ M}_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$, or in *bar-A*, *bar-B*, the both values differ by more than a factor of two in some pixels; $\Sigma_{\text{SFR}}^{\text{IR}}$ is larger than $\Sigma_{\text{SFR}}^{\text{H}\alpha}$ by a factor up to 5.0. Such large difference below $\Sigma_{\text{SFR}} = 10^{-3.0} \text{ M}_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$ is also reported by Leroy et al. (2012). They claim the cause for the difference is that the measured H α surface brightness of $\Sigma_{\text{SFR}} \leq 10^{-3.0} \text{ M}_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$ is most likely not originated from massive star formation and $\Sigma_{\text{SFR}}^{\text{IR}}$ strongly depends on the method to remove IR cirrus. Because of the absence of HII regions, the $\Sigma_{\text{SFR}}^{\text{H}\alpha}$ in *bar-A* seems to be dominated by the noise and the smear of the H α emission in the center region by the convolution. $\Sigma_{\text{SFR}}^{\text{H}\alpha}$ can be underestimated because ionising photons can escape HII regions, but some extragalactic studies suggest that this effect might be small when averaging at extragalactic scales (e.g. Murphy et al. 2011; Querejeta et al. 2019). In summary, the accuracy of the Σ_{SFR} above $10^{-3.0} \text{ M}_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$ seems to be high, but below $10^{-3.0} \text{ M}_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$, the measured Σ_{SFR} may not indicate the exact amount of massive star formation and should be considered to be an upper limit.

3.3.3 Stacking Analysis

Since the rms noise level of $^{12}\text{CO}(1-0)$ spectra obtained from the NRO 45-m is high, spatial distribution of f_{dif} and $R_{21/10}$ seem to be slightly noisy. In this section, in order to improve the S/N of the $^{12}\text{CO}(1-0)$ emission, we performed the stacking analysis of CO spectra with velocity axis alignment devised by Schruba et al. (2011, 2012). This method is commonly adopted for the CO spectra in nearby galaxies (e.g. Morokuma-Matsui et al. 2015; Muraoka et al. 2016; Yajima et al. 2019). The procedure is as follow: First, the velocity field of NGC 1300 is estimated from $^{12}\text{CO}(2-1)$ data obtained from ALMA. We calculated the intensity-weighted mean velocity ($\bar{v}_{\text{CO}(2-1)}$) of each pixel. Then, the $^{12}\text{CO}(1-0)$ spectra are shifted along the velocity axis based on the $\bar{v}_{\text{CO}(2-1)}$. Finally, we made an average $^{12}\text{CO}(1-0)$ spectrum in each environment. For $^{13}\text{CO}(1-0)$ spectra and $^{12}\text{CO}(1-0)$ spectra obtained from ALMA, we adopted this method. Figure 3.12 shows the stacked CO spectra. Black line represents the stacked $^{12}\text{CO}(1-0)$ spectra. The rms noise level is improved ($8 \sim 14 \text{ mK}$ at 10.0 km s^{-1}). Red and blue line represent the stacked $^{12}\text{CO}(2-1)$ and $^{13}\text{CO}(1-0)$ spectra, respectively. In Table 3.2, we listed the velocity integrated intensity of each stacked spectrum. Although the rms noise level of $^{13}\text{CO}(1-0)$ spectra is improved ($5 \sim 8 \text{ mK}$ at 10.0 km s^{-1}), we did not detect the significant $^{13}\text{CO}(1-0)$ emission line in any environments.

For $^{12}\text{CO}(1-0)$ data obtained from ALMA, the mean value of the pixels in each environment is adopted as a stacked value. This is because significant negative structures ("bowls") in the data and this structures may influence on the stacking analysis of the spectra with velocity axis alignment. These negative bowls are expected to be present in interferometric data because our data are missing the shortest uv spacings.

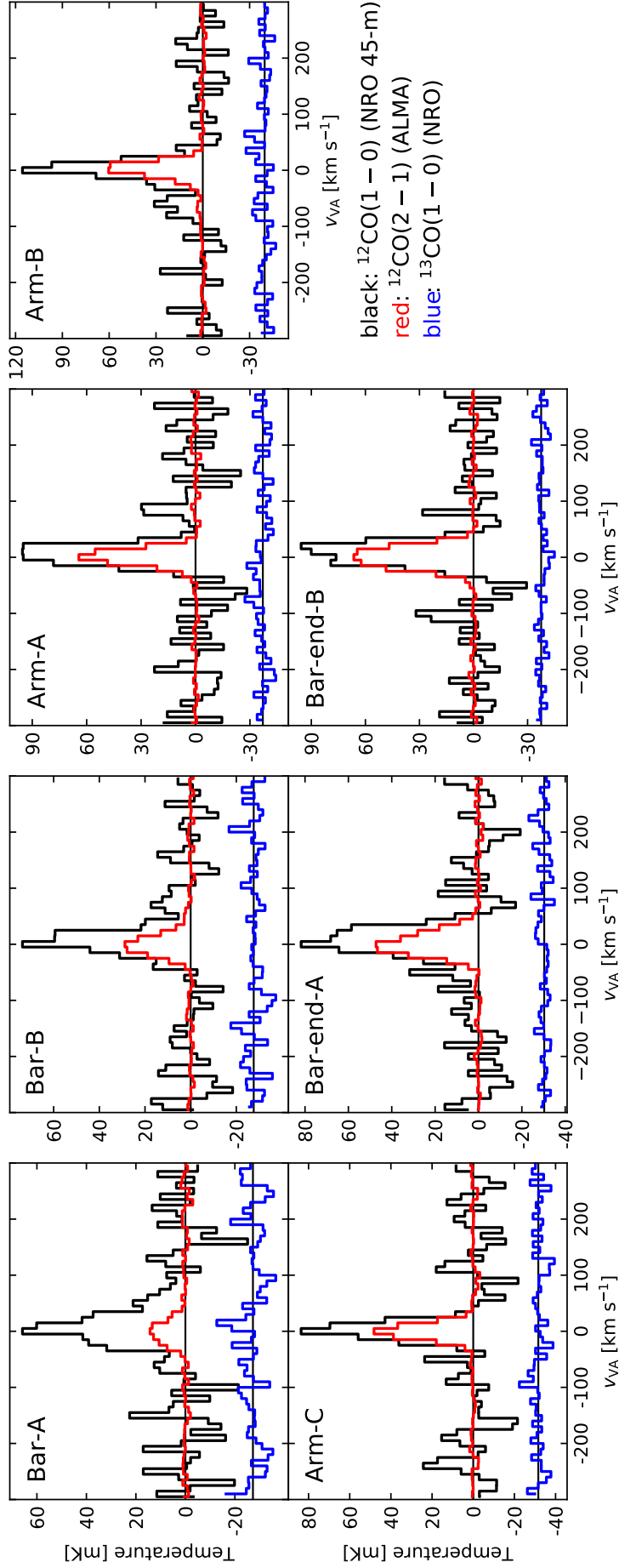


Figure 3.12: Stacked CO spectra for each environment in NGC 1300. The black, red, and blue lines indicate $^{12}\text{CO}(1-0)$ emission obtained from the NRO 45-m, $^{12}\text{CO}(2-1)$ emission obtained from ALMA, and $^{13}\text{CO}(1-0)$ emission obtained from the NRO 45-m, respectively. The channel width is 10.0 km s^{-1} . For visualization purpose, base line of $^{13}\text{CO}(1-0)$ spectra is shifted.

3.4 Star Formation Efficiency and Recovery Fraction

3.4.1 Star formation efficiency

As described in Section 3.1, star formation activity is quite different among the environments in NGC 1300. In this section, we examine the difference quantitatively through the SFE. SFE is calculated using the surface density of SFR and that of molecular hydrogen ($\Sigma_{\text{H}_2}^{\text{tot}}$) as follows:

$$\left(\frac{\text{SFE}}{\text{Gyr}^{-1}} \right) = 10^3 \left(\frac{\Sigma_{\text{SFR}}}{\text{M}_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}} \right) \left(\frac{\Sigma_{\text{H}_2}^{\text{tot}}}{\text{M}_{\odot} \text{ pc}^{-2}} \right)^{-1}, \quad (3.4.1)$$

where $\Sigma_{\text{H}_2}^{\text{tot}}$ is $\Sigma_{\text{mol}}^{\text{tot}}/1.36$ to remove the helium. The SFE obtained from $\Sigma_{\text{SFR}}^{\text{H}\alpha}$ and $\Sigma_{\text{SFR}}^{\text{IR}}$, which are denoted as $\text{SFE}^{\text{H}\alpha}$ and SFE^{IR} , respectively. Figure 3.13(a) and (b) show the spatial distribution of $\text{SFE}^{\text{H}\alpha}$ and SFE^{IR} , respectively. We display the pixels where both the SFR tracers and $^{12}\text{CO}(1-0)$ emission observed with the NRO 45-m were significantly detected. The mean values obtained from the stacked $^{12}\text{CO}(1-0)$ spectra and mean Σ_{SFR} in each environment are listed in Table 3.2. The difference of the SFE with the environments is clearly seen: In bar regions, although the uncertainty of Σ_{SFR} is large (Section 3.3.2), SFE is very low (0.06 – 0.16) Gyr^{-1} . In *bar-end-A* near the bar region, SFE is low (0.23 – 0.31) Gyr^{-1} in comparison to other arm and bar-end regions. The SFE is the highest in *arm-A* (0.66 – 0.96) Gyr^{-1} , followed in *bar-end-B*, *arm-B*, *arm-C* (0.47 – 0.69) Gyr^{-1} . In summary, SFEs in the bar regions are more than $\sim 5 - 10$ times lower than those in the arm regions. In spatial distribution of SFE, gradient in SFE from leading to trailing side is also seen in the arm and bar-end regions. This gradient is originated from the offsets between SFR tracers ($\text{H}\alpha$) and CO emission, which are often seen in spiral galaxies (e.g. Schinnerer et al. 2013, 2017; Kreckel et al. 2018).

The differences of the SFE with environments are also clearly seen in the molecular red Kennicutt-Schmidt diagram, or $\Sigma_{\text{H}_2}^{\text{tot}}$ vs. Σ_{SFR} , as shown in Figure 3.14(a) and (b). Large symbols show the mean values in the environments, which are listed in Table 3.2. The grey scale represents the result by Bigiel et al. (2008), which derived K-S relations at an angular resolution of 750 pc in a sample of 18 nearby non-barred spiral galaxies. SFRs were measured from a combination of FUV and $24\mu\text{m}$ IR fluxes and H_2 gases were measured from $^{12}\text{CO}(2-1)$ assuming the line ratio of $R_{21/10} = 0.8$. Open squares represent the K-S relation in NGC 4303 at an angular resolution of 1.4 kpc by Yajima et al. (2019). They also used FUV and $24\mu\text{m}$ IR fluxes, but measured H_2 gases from $^{12}\text{CO}(1-0)$. Black dash-dotted lines show the constant SFE of 1.0 and 0.10 Gyr^{-1} .

In Figure 3.14(a) and (b), it is clearly shown that the SFEs in the bar regions are much lower than those in the arm regions despite the Σ_{H_2} is comparable. This result supports that the star formation in the bar regions is suppressed compared to the arm regions. We also find that the SFE in *bar-end-A* is slightly suppressed compared to the *arm-A*, *arm-B*, *arm-C* and *bar-end-B* where the SFEs are the same as the result by Bigiel et al. (2008). Although the $\Sigma_{\text{H}_2}^{\text{tot}}$ in NGC 4303 is 7 – 8 times higher than those in NGC 1300, the SFEs in arm and bar-end regions in NGC 4303 are comparable to those in the arm regions in NGC 1300. As seen in these panels, in intermediate-type barred galaxies like NGC 4303, the SFE in the bar regions is about 1.5 – 2.0 times smaller than that in the arm region (see also Momose et al. 2010; Hirota et al. 2014). Our result indicates that the star formation in the bar regions of the strongly barred galaxies is further suppressed than in the intermediate-type barred galaxies.

As described in Section 3.3.1, the CO-to- H_2 conversion factor may be about 2 times smaller than $\alpha_{\text{CO}} = 4.4 \text{ M}_{\odot} (\text{K km s}^{-1} \text{ pc}^2)^{-1}$ in the bar regions. If so, SFEs in the bar regions are much lower than those in the arm regions. Therefore, we conclude that the star formation activity is remarkably suppressed in the bar regions of strongly barred galaxy, NGC 1300.

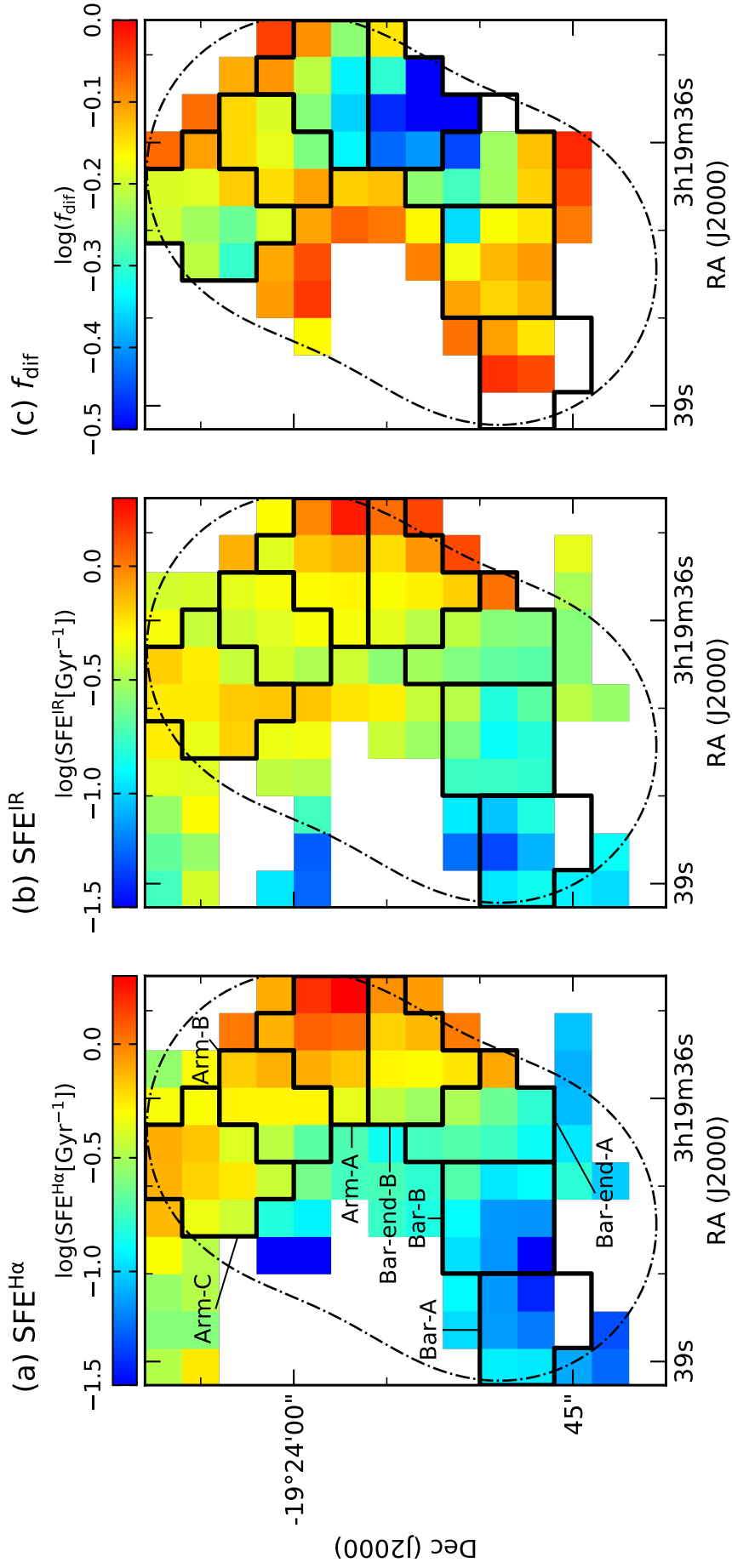


Figure 3.13: (a) Spatial distribution of the SFE obtained from $\text{H}\alpha$ image. All lines are the same as Figure 3.5. (b) Same as panel (a), but for the SFE obtained from FUV and $22\mu\text{m}$ image. (c) Same as panel (a), but for the diffuse molecular gas fraction.

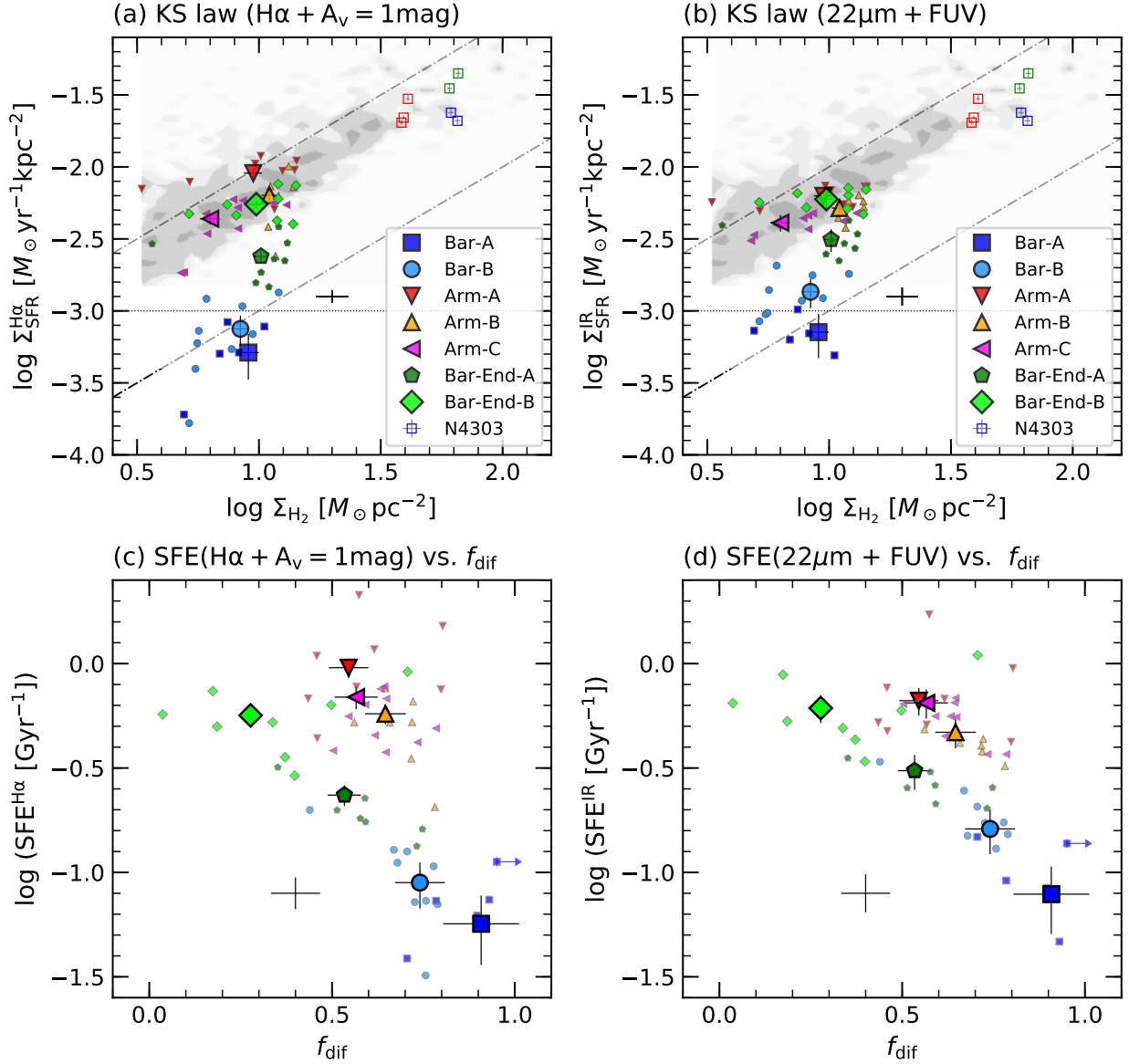


Figure 3.14: (a) Molecular Kennicutt-Schmidt relation of NGC 1300. SFR is derived from the H α emission. The small and large symbols represent the value in individual 6.0 arcsec pixels and the mean value in each environment, respectively. The typical uncertainty for each 6.0 arcsec pixel is shown as a black cross. The grey scale represents the result by Bigiel et al. (2008). The open squares represents the result in NGC 4303 by Yajima et al. (2019) (blue: bar, red: arm, and green: bar-end). The grey dash-dotted lines show the constant SFE of 1.0 and 0.1 Gyr $^{-1}$. The horizontal dotted line represents $\Sigma_{\text{SFR}} = 10^{-3} \text{ M}_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$. (b) Same as panel (a), but SFR is derived from FUV and IR. (c) Correlation of diffuse molecular gas fraction, f_{dif} with SFE. SFR is derived from the H α emission. (d) Same as panel (c), but SFR is derived from FUV and IR.

3.4.2 Diffuse molecular gas fraction

We measure the diffuse molecular gas fraction, f_{dif} , in NGC 1300 as

$$f_{\text{dif}} = 1 - f_{\text{re}} = 1 - \frac{I_{12\text{CO}(1-0)}^{\text{ALMA}}}{I_{12\text{CO}(1-0)}^{\text{tot}}}, \quad (3.4.2)$$

where f_{re} is the recovery fraction, i.e. the ratio of CO flux obtained from interferometer of ALMA 12-m array to total CO flux obtained from the NRO 45-m. As shown in Figure 3.6, a molecular gas structure homogeneously extended to over ~ 700 pc is mostly resolved out in our $^{12}\text{CO}(1-0)$ data obtained from ALMA. Therefore, the f_{dif} (f_{re}) indicates the ratio of molecular gas on a scale of 700 pc or more (less). Figure 3.13(c) shows the spatial distribution of the f_{dif} . We display the pixels where both the $I_{^{12}\text{CO}(1-0)}^{\text{tot}}$ and $I_{^{12}\text{CO}(1-0)}^{\text{ALMA}}$ were significantly detected. The mean values of f_{dif} obtained from the stacked $^{12}\text{CO}(1-0)$ spectra and mean $I_{^{12}\text{CO}(1-0)}^{\text{ALMA}}$ in each environment are listed in Table 3.2. The difference of the f_{dif} with the environments is seen, and we find that f_{dif} in the bar region is large. Thus significant fraction of the molecular gas is diffuse as compared with arm and bar-end regions: In *bar-A* and *bar-B*, the f_{dif} is the highest (0.74 – 0.91), which indicates most of the molecular gas in the bar region exists as diffuse gas with FWHM $\gtrsim 700$ pc. In *bar-end-A*, *arm-A*, *arm-B* and *arm-C*, the f_{dif} ranges 0.53 – 0.65. In *bar-end-A*, the f_{dif} is the lowest (0.28), which implies that the compact molecular gas components like GMCs are concentrated.

3.4.3 SFE vs. diffuse molecular gas fraction

Does the presence of a large amount of diffuse molecular gases really make the SFE low in the bar regions? If this scenario is true, the SFE is expected to decrease as f_{dif} increases. Thus we investigate the relation between SFE and f_{dif} as shown in Figure 3.14(c) and (d). Large symbols show the mean values in the environments, which are listed in Table 3.2. We find that the SFE decreases with increasing f_{dif} for the large symbols: In the bar regions, f_{dif} and SFE are 0.74 – 0.91 and (0.06 – 0.16) Gyr^{-1} , respectively, and f_{dif} and SFE are higher and lower than those in the arm and bar-end regions ($f_{\text{dif}} = 0.28 - 0.65$ and $\text{SFE} = 0.23 - 0.96 \text{ Gyr}^{-1}$). A tighter relationship is seen when using the FUV and $22\mu\text{m}$ as an SFR tracer rather than using $\text{H}\alpha$ emission. This decreasing trend would support the idea that a large amount of diffuse molecular gases makes the SFE low. In bar regions, a significant diffuse molecular component would be not directly related to the star formation activity.

The arm regions show ~ 3 (~ 2) times higher $\text{SFE}^{\text{H}\alpha}$ (SFE^{IR}) at a fixed f_{dif} as compared with the bar-end regions. This suggests that the difference of SFE can not be explained only by the difference of f_{dif} , implying the existence of other mechanisms which control the SFE. This difference might reflect a difference in the process of feedback by massive stars. In the bar-end regions, because the distance between the GMCs is smaller than in the arm regions (see Figure 12 in Fujimoto et al. 2020), the stellar feedback would work well, and subsequent star formation may be unlikely to occur. It is interesting to investigate the variations in the effect of stellar feedback with environments, but it is beyond our scope in this paper and remains as a future study.

3.5 Discussion

3.5.1 Trends with $R_{21/10}$

As described in Section 3.4.3, SFE decreases toward high f_{dif} in NGC 1300, which suggests that a large amount of diffuse molecular gases makes SFE low in the bar region. In this section, to further investigate the physical condition of molecular gases, we measure the $^{12}\text{CO}(2-1)/^{12}\text{CO}(1-0)$ line ratio, $R_{21/10}$, in NGC 1300 and examine the relation between $R_{21/10}$ and other physical parameters. $R_{21/10}$ has been known for the measure to know the physical condition of molecular gases. Systematic variation of $R_{21/10}$ have reported in molecular clouds in the Milky Way (e.g. Sakamoto et al. 1994, 1995) and in galaxy of M51 (Koda et al. 2012) and M83 (Koda et al. 2020). The systematic

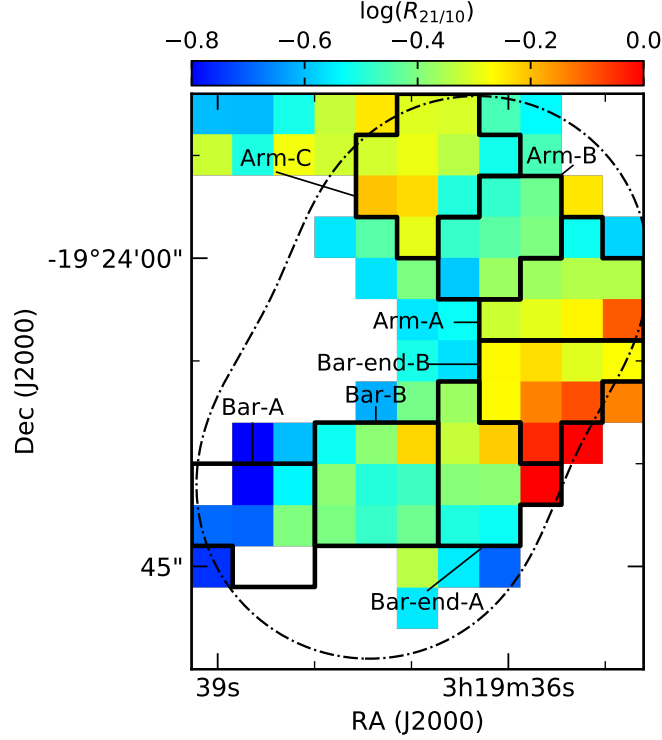


Figure 3.15: Spatial distribution of $R_{21/10}$. All lines are the same as Figure 3.5.

variations of $R_{21/10}$ can be interpreted as changes of H_2 gas density and/or temperature (Koda et al. 2012).

We derived $R_{21/10}$ from total $^{12}CO(1-0)$ flux obtained from the NRO 45-m (Section 3.2.1) and total $^{12}CO(2-1)$ flux obtained from ALMA archival data (Section 3.2.3) as

$$R_{21/10} = \frac{I_{^{12}CO(2-1)}^{\text{tot}}}{I_{^{12}CO(1-0)}^{\text{tot}}}. \quad (3.5.1)$$

Figure 3.15 shows the resultant spatial distribution of $R_{21/10}$ in NGC 1300. We display the pixels where both the $I_{^{12}CO(1-0)}^{\text{tot}}$ and $I_{^{12}CO(2-1)}^{\text{tot}}$ were significantly detected. The uncertainties of $R_{21/10}$ are mainly propagated from the $I_{^{12}CO(1-0)}^{\text{tot}}$. We find that systematic variation of $R_{21/10}$: In *bar-end-B*, the $R_{21/10}$ is the highest (~ 0.7), followed by *bar-end-A*, *arm-A*, *arm-B* and *arm-C* ($\sim 0.4 - 0.6$). In *bar-A* and *bar-B*, the $R_{21/10}$ is the lowest ($0.2 - 0.4$). This tendency is the opposite of f_{dif} (Section 3.4.2).

Figure 3.16(a) and (b) show the correlations between $R_{21/10}$ with SFE. Large symbols show the mean values in the environments, which are listed in Table 3.2. We find that the SFE decreases with decreasing $R_{21/10}$ for the large symbols. This clear correlation have been reported in M51 (Koda et al. 2012). We find that a tight correlation of $R_{21/10}$ and f_{dif} as shown in Figure 3.16(c). The lower $R_{21/10}$ and higher f_{dif} are seen in the bar regions where SFE is also low, while higher $R_{21/10}$ and lower f_{dif} are seen in active star forming regions, or arm and bar-end regions.

According to the non-LTE analysis by Koda et al. (2012), the higher $R_{21/10}$ in the star-forming regions implies that the gas may be warmer and/or denser. Thus, high $R_{21/10}$ and low f_{dif} in the star-forming regions (i.e. arm and bar-end) in NGC 1300 are interpreted as follows; most of the

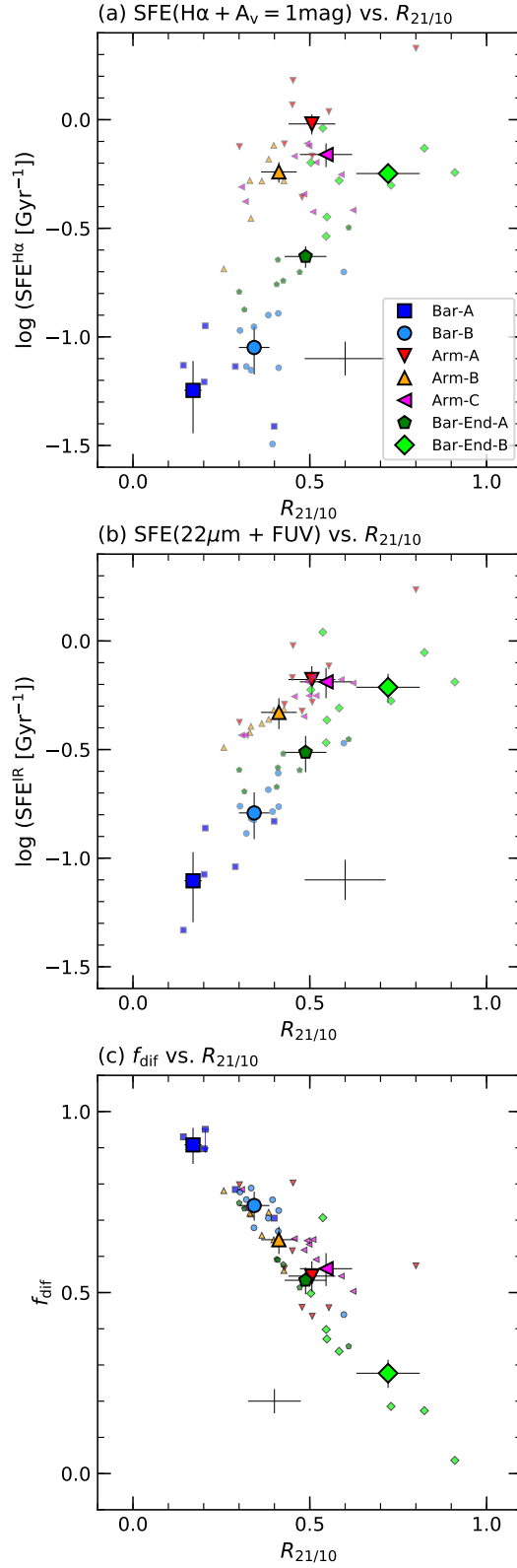


Figure 3.16: (a) Correlation of $R_{21/10}$ with SFE. SFR is derived from the $\text{H}\alpha$ emission. The small and large symbols represent the value in individual 6.0 arcsec pixels and the mean value in each environment, respectively. The typical uncertainty for each 6.0 arcsec pixel is shown as a black cross. (b) Same as panel (a), but SFR is derived from FUV and IR. (c) Correlation of $R_{21/10}$ with f_{dif} .

molecular gas is composed of molecular clouds there, resulting in a higher density of the molecular gas. In these regions, OB stars are associated with in the molecular clouds, which heat the molecular gas (i.e. stellar feedback). On the other hand, in the bar regions, the gas density may be low because diffuse gas would dominate shown as high f_{dif} . Because there is no massive star formation, stellar feedback would not work there and gas temperature may be low. As a result of these, $R_{21/10}$ is considered to be low in the bar regions.

The $^{13}\text{CO}(1-0)/^{12}\text{CO}(1-0)$ line ratio, $R_{13/12}$, is also a tool to investigate the physical condition of molecular gases. It is reported that $R_{13/12}$ in the bar regions is lower than that in the arm regions (e.g. Watanabe et al. 2011; Morokuma-Matsui et al. 2015; Yajima et al. 2019). Watanabe et al. (2011) find the low $R_{13/12}$ in the bar regions, which indicates the presence of diffuse gas as a result of the strong streaming motion. Further, combination of $R_{21/10}$ and $R_{13/12}$ can be used to limit the gas density and temperature (e.g. Muraoka et al. 2016). Due to the non-detection of $^{13}\text{CO}(1-0)$ in NGC 1300 with the NRO 45-m, however, we cannot examine the variation of $R_{13/12}$ with environments, which remains for the next study. In table 3.2, we show the upper limit of $R_{13/12}$ using stacked spectra. Here, we estimate the 3σ upper limit of $I_{^{13}\text{CO}(1-0)}$ as $3\sigma_{\text{rms}}^{13}\sqrt{\text{FWHM}_{^{12}\text{CO}(1-0)}\Delta V}$, where σ_{rms}^{13} is the rms noise level of stacked $^{13}\text{CO}(1-0)$ spectrum, $\text{FWHM}_{^{12}\text{CO}(1-0)}$ is the velocity width of the $^{12}\text{CO}(1-0)$ spectrum, and ΔV is the channel width of 10 km s^{-1} .

3.5.2 Can the low SFE in the bar region be explained by only the difference of the fraction of diffuse molecular gas?

As described in Section 3.4.1, SFE in the bar regions is clearly suppressed in the strongly barred galaxy of NGC 1300. Our analysis shows the SFE decreases toward high f_{dif} and low $R_{21/10}$. These correlations support the idea that the diffuse gas contributes significantly to the $\Sigma_{\text{H}_2}^{\text{tot}}$ used in the SFE calculation, which makes the SFE apparently low in the bar regions (*Scenario 3*). If the environmental dependence of SFEs comes only from the difference of the fraction of diffuse gas, we expect that SFEs will be constant if we recalculate them excluding the diffuse molecular gas in the estimates of total gas mass. To check this, we examine the following SFE defined as

$$\left(\frac{\text{SFE}_{\text{GMC}}}{\text{Gyr}^{-1}}\right) = 10^3 \left(\frac{\Sigma_{\text{SFR}}^{\text{H}\alpha}}{\text{M}_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}}\right) \left(\frac{\Sigma_{\text{GMC}}}{\text{M}_{\odot} \text{ pc}^{-2}}\right)^{-1}, \quad (3.5.2)$$

where $\Sigma_{\text{SFR}}^{\text{H}\alpha}$ is the total SFR surface density derived from H α emission by assuming $A_V = 1.0 \text{ mag}$ and Σ_{GMC} is the surface density of the molecular gas organized inside GMCs in each environment. Here, the $\Sigma_{\text{SFR}}^{\text{H}\alpha}$ is derived from the original (not deconvolved and regridded) H α image. We first measured the total SFR in the environment, and then divided it by the area of the environment. Because of the absence of HII regions, the upper limit of the $\Sigma_{\text{SFR}}^{\text{H}\alpha}$ in *bar-A* is calculated using the SFR of an HII region with a size of 50 pc whose H α flux in each pixel is 3 times of the noise level. The Σ_{GMC} is derived using the GMC catalog (Chapter 2 and Appendix D). We first measured the total mass of the GMCs in the environments, and then divided it by the area of the environment. Note that Σ_{GMC} is not a gas surface density of individual GMC.

Figure 3.17(a) shows the Kennicutt-Schmidt diagram using $\Sigma_{\text{SFR}}^{\text{H}\alpha}$ and Σ_{GMC} . We present the same diagram, but using the total SFR and total mass of the GMCs in Figure 3.17(b) to avoid the uncertainty of the area. The SFE_{GMC} in each environment is listed in Table 3.3. The significant variations of SFE_{GMC} with environments are still seen: the SFE_{GMC} in the arm regions is the highest ($\sim 1.6 \text{ Gyr}^{-1}$), followed by the bar-end ($\sim 0.5 \text{ Gyr}^{-1}$) and the bar regions (0.17 Gyr^{-1} in *bar-B* and $< 0.04 \text{ Gyr}^{-1}$ in *bar-A*). These results can easily be expected from the fact that the GMCs exists in the bar regions where the prominent HII region does not exist. It is unveiled that the SFE excluding

diffuse components is significantly suppressed in the bar regions, which suggests the presence of other causes, in addition to a large amount of the diffuse molecular gases. The fact that the SFE_{GMC} is different by a factor of 3 between the arm and bar-end regions also may reflect differences of the star formation process of GMCs (see Section 3.4.3).

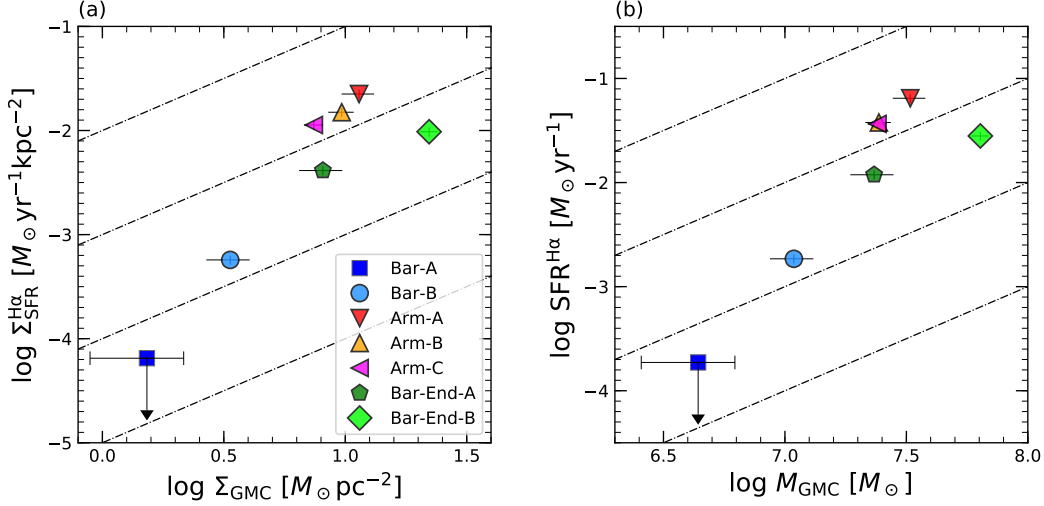


Figure 3.17: (a) The SFEs of molecular gas excluding diffuse components (i.e. molecular gas organized inside GMCs) in NGC 1300: SFR surface density derived from H α vs. molecular gas surface density derived from the GMC catalog (Chapter 2 and Appendix D) in each environment (see text). The black dash–dotted lines show the constant SFE of 10^1 , 10^0 , 10^{-1} , and 10^{-2} Gyr $^{-1}$. (b) Same as panel (a), but used total SFR and total molecular gas mass.

Table 3.3: SFE of the molecular gas excluding diffuse components.

	Bar-A	Bar-B	Arm1-A	Arm1-B	Arm1-C	Bar-end-A	Bar-end-B
SFE_{GMC} (Gyr $^{-1}$)	< 0.04	0.17 ± 0.04	1.97 ± 0.36	1.55 ± 0.24	1.52 ± 0.20	0.51 ± 0.11	0.44 ± 0.06

Why is the SFE excluding the diffuse molecular gas suppressed in the bar region of NGC 1300? The cause is discussed in detail in Section 2.8. Thus we briefly discuss here. There are two possibilities for the cause. One is that GMCs in the bar regions may be gravitationally unbound (*Scenario 1*; e.g. Sorai et al. 2012; Meidt et al. 2013; Nimori et al. 2013). However, this scenario is unlikely to be a main process of the star formation suppression of the GMCs in NGC 1300; there is no significant variations in virial parameters of the GMCs among the bar, arm and bar-end regions using the GMCs catalog in NGC 1300 (Chapter 2). A hydrodynamical simulation modeled NGC 1300 by Fujimoto et al. (2020, Appendix A) showed qualitatively similar result. These results suggest that the star formation suppression in the bar can not be explained by a systematic difference of virial parameter.

Another possibility is that the fast CCCs may occur in the bar regions (*Scenario 3*). It is thought that a fast CCC in the bars shortens a gas accretion phase of the cloud cores formed, leading to suppression of core growth and massive star formation (Fujimoto et al. 2014a; Takahira et al. 2014, 2018). Fujimoto et al. (2020) showed that the collision speed in the bar regions is significantly faster than the other regions (Figure A.8). This result suggests the high-speed CCC is the physical

mechanism which causes the lack of massive star formation. Summarizing the discussion above, the low values of the SFE in the bar regions of NGC 1300 appear to be caused not only by the presence of a large amount of diffuse molecular gases but also other mechanisms such as high-speed CCCs among GMCs.

Why does a large amount of diffuse molecular gases exist in the bar regions? The answer is unclear. If molecular clouds form from surrounding diffuse gases, one possibility is that efficiency of conversion from diffuse gases to molecular clouds is lower in the bar region. For example, a strong shock and/or shear along the bar may prevent forming GMCs from diffuse gases (e.g. Tubbs 1982; Athanassoula 1992; Reynaud & Downes 1998). Some observations reported the diffuse molecular gases constitute a thick disc (e.g. Garcia-Burillo et al. 1992; Sofue & Nakai 1993; Pety et al. 2013). Pety et al. (2013) estimated between 2 and 20 percent of the total molecular gas mass to be at galactic heights larger than 400 pc. Some simulations of the disk galaxies suggest that the cold molecular gas from the disk to the halo is caused by the feedback of massive star formation (e.g. Wada 2008; Dobbs et al. 2011). However, it would be unlikely that the large amount of diffuse molecular gases forms the thick molecular gas disk in the bar regions of NGC 1300 because of the absence of the massive star formation.

3.6 Conclusions of This Chapter

In order to understand the cause for the low SFE in the bar regions, we test the scenario that the diffuse gas greatly contributes to the Σ_{H_2} . We measured the diffuse molecular gas fraction (f_{dif}) in the strongly barred galaxy NGC 1300, which is one of the suitable laboratories because the absence of the star formation is clearly seen in the bar regions. The f_{dif} is measured using $^{12}\text{CO}(1-0)$ observations data obtained with the single-dish NRO 45-m and with the ALMA 12-m array, which has no sensitivity on diffuse (extended) molecular gases due to the lack of ACA. Using SFR derived from archival $\text{H}\alpha$, FUV and IR data, we investigated the correlations f_{dif} with SFE in NGC 1300. The main results are as follows:

1. The $\Sigma_{\text{mol}}^{\text{tot}}$ in bar, arm, and bar-end regions of NGC 1300 ranges from 10 to 15 K km s^{-1} , which indicates that the molecular gases do exist in the strong bars with no clear HII regions (Figure 3.2). The $\Sigma_{\text{mol}}^{\text{tot}}$ in the bar regions is lower than those in other nearby barred galaxies (Section 3.3.1).
2. We derived SFR from $\text{H}\alpha$ emission assuming $A_V = 1.0$ mag and hybrid tracers (FUV + IR). The magnitude of systematic differences in both SFRs rarely exceeds a factor of two. While the Σ_{SFR} is $10^{-2.7} - 10^{-2.1} \text{ M}_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$ in arm and bar-end regions, Σ_{SFR} is mostly lower than $10^{-3} \text{ M}_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$ in bar regions (Section 3.3.1 and Figure 3.11).
3. SFEs in the bar regions are 5 – 10 times lower than those in the arm and bar-end regions despite the Σ_{H_2} is comparable between the both regions in NGC 1300: $(0.06 - 0.16) \text{ Gyr}^{-1}$ in the bar regions and $(0.47 - 0.96) \text{ Gyr}^{-1}$ in the arm and bar-end regions. Our result indicates that the star formation in the bar regions of the strongly barred galaxies is further suppressed than in the intermediate-type barred galaxies (Section 3.4.1, Figure 3.13(a) and (b), and Figure 3.14(a) and (b)).
4. We found difference of the f_{dif} among the environments: the f_{dif} is $0.74 - 0.91$ in the bar regions and $0.28 - 0.65$ in the arm and bar-end regions. This indicates most of the molecular gas in the bar region exists as the diffuse gas with $\text{FWHM} \gtrsim 700 \text{ pc}$ (Section 3.4.2 and Figure 3.13(c)).

5. We found the SFE decreases toward high f_{dif} , which suggests that the presence of a large amount of the diffuse molecular gases makes the SFE low in appearance (Section 3.4.3 and Figure 3.14(c) and (d)).
6. We found a tight negative correlation between the line ratio of $R_{21/10}$ and the f_{dif} . This result supports the idea that a large amount of diffuse molecular gases makes the star formation low and suggests low gas density and/or temperature in the bar regions. (Section 3.5.1 and Figure 3.16).
7. The SFEs of molecular gas excluding diffuse components (i.e. molecular gas organized inside GMCs) in the bar regions are significantly lower than those in the arm and bar-end regions, which suggests the presence of other causes for the suppression besides the large amount of the diffuse molecular gases. Based on the studies on GMC properties in NGC 1300 (Chapter 2 and Fujimoto et al. 2020; Appendix A), the low SFE may be caused not only by a large amount of diffuse molecular gases (*Scenario 2*) but also other mechanisms such as high-speed cloud–cloud collisions among GMCs (*Scenario 3*; Section 3.5.2).

Chapter 4

Environmental dependence of cloud-cloud collision speed in NGC 1300

Part of this Chapter was submitted to Monthly Notices of the Royal Astronomical Society

4.1 Introduction and Scope of This Chapter

In order to understand the diversity of galactic-scale SFE, it is essential to understand how the galactic environments set conditions for star formation within the GMCs. One of the key parameters to control the star formation activity is a CCC speed. The concept of CCCs had been previously proposed before (e.g. Stone 1970a,b; Loren 1976; Gilden 1984; Scoville et al. 1986), and the CCC models as a triggering mechanism of massive star formation were proposed (e.g. Habe & Ohta 1992; Fukui et al. 2014); CCCs induce clump formation by shock compressions at the collision interface. Tan (2000) proposed a model in which the majority of star formation in disk galaxies is induced by CCCs. After that, the role of CCCs in the star formation activity of the galaxies and the impact of the galactic structure on the CCCs have been investigated by three-dimensional hydrodynamical simulations of disk galaxies (e.g. Tasker & Tan 2009; Fujimoto et al. 2014b; Dobbs et al. 2015; Renaud et al. 2015).

Recent simulation results of CCCs suggest that star formation activity strongly depends on the relative speed of the two colliding clouds. Takahira et al. (2014, 2018) performed sub-parsec scale simulations of CCCs of two clouds with different CCC speeds of $3\text{--}30\text{ km s}^{-1}$ and found a faster CCC can shorten the gas accretion phase of the cloud cores formed, leading to suppression of core growth and massive star formation. A high-resolution ($\sim$ a few pc) three-dimensional hydrodynamical simulation of an intermediate-type barred galaxy performed by Fujimoto et al. (2014b) found that CCC speed in the bar regions is larger than in the arm regions. Based on this simulation, Fujimoto et al. (2014a) suggested that the observed low SFE in the bar in nearby galaxies can be explained quantitatively by fast CCCs with assumptions that collisions between 10 and 40 km s^{-1} are effective to form stars while CCCs with $< 10\text{ km s}^{-1}$ and $> 40\text{ km s}^{-1}$ are inefficient. Although the range of CCC speed used in their assumption is somewhat rough (in fact, Takahira et al. 2014, 2018 showed that the efficiency of massive core formation is anticorrelated with the CCC speed in the range of $> 10\text{ km s}^{-1}$), they demonstrated that differences in CCC speed among the environments would be responsible for the observed differences in SFE. According to these results, to understand the diversity of galactic-scale SFE, the connection between the environment, the CCC speed, and the star formation activity should be investigated observationally.

In the Milky Way, the number of CCC samples has been increasing recently (more than 80;

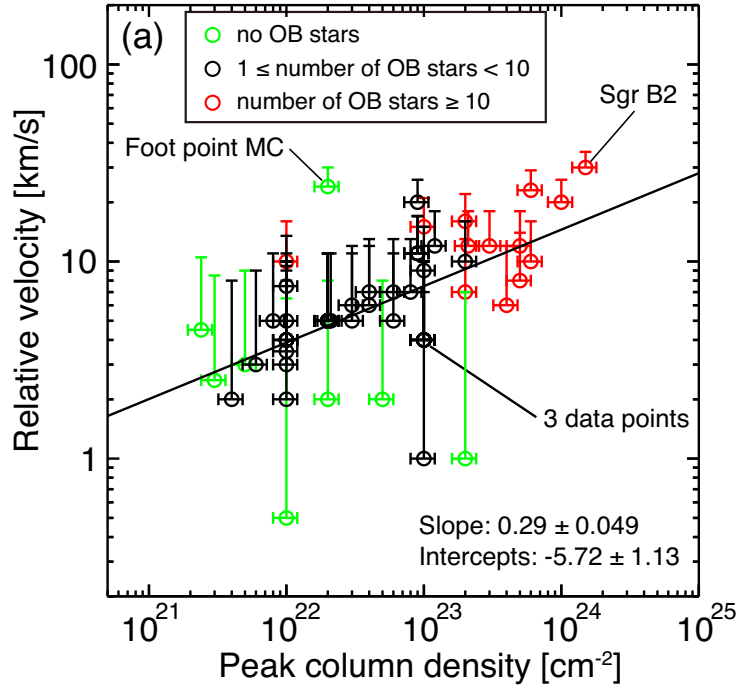


Figure 4.1: Scatter plot of the peak column density and relative velocity of colliding clouds of the Galactic sources. The black, red, and light green symbols, respectively, indicate CCCs associated with clusters having less than 10 O- and early B-type stars, more than 10 O- and early B-type stars, and without any O- or early B-type stars. The black line indicates the best-fitting result of black and red symbols using a least-squares method. Figure taken from Enokiya et al. (2019).

see Fukui et al. 2020), and the dependence of the peak column density of colliding clouds and relative velocity of them on the number of OB stars is revealing (Figure 4.1; Enokiya et al. 2019); OB stars tend to reside in colliding molecular clouds with higher peak column density and large relative velocity. On the other hand, a high-speed CCC without OB stars is observed in the central region of the Milky Way, which supports the conclusion by Takahira et al. (2014). However, CCC speed-environment connection in nearby galaxies is still unclear. Recent measurements of Oort parameters in disk galaxies suggest that SFRs at a few hundred-parsec scales are driven by CCCs (Aouad et al. 2020). Although direct observations of extragalactic CCCs have been made (e.g. LMC; Fukui et al. 2015, Saigo et al. 2017, M33; Sano et al. 2020; Tokuda et al. 2020; Muraoka et al. 2020, Antennae galaxies; Finn et al. 2019), the sample is still not large enough to investigate the connection, and the CCC in the bar regions of nearby galaxies has not been observed within our knowledge.

In this chapter, we investigate the CCC speed and its possible effect on the SFE in NGC 1300 using $^{12}\text{CO}(1-0)$ observations at a high angular resolution of ~ 40 pc with ALMA, which detected more than 200 GMCs (Chapter 2). Direct observation of CCC in NGC 1300 is desired, but it is difficult with the current angular resolution of our (and archive) data. Therefore, we attempt to estimate the CCC speed of GMCs by predicting the motion of the GMCs based on the mean velocity field of the molecular gas and cataloged line-of-sight velocity of the GMCs. Besides this method, we measure velocity deviation between the GMC and its surrounding GMCs, which is a model-independent observable and a good indicator of the qualitative trends of the CCC speed. We have two main goals: first, we examine the differences of the estimated CCC speed and the velocity deviation between the environments (i.e. bar, arm, bar-end; Figure 2.3). The second goal

is to compare the results with the simulation by Fujimoto et al. (2020, F20; Appendix A), which presented a hydrodynamical simulation of a strongly barred galaxy using a stellar potential model of NGC 1300. The simulation shows that the CCC speed in the bar regions is significantly faster than those in the arm and bar-end regions. They concluded that high-speed CCCs would be one of the physical mechanisms that make the star formation activity extremely low in the strong bar.

It is worth emphasizing here that unveiling the cause for the massive star formation suppression is also very important to understand the star formation process in high redshift galaxies. In the high redshift universe, merging is frequent and is considered to be a very important process for the formation and evolution of galaxies. Cloud collisions must be mainly responsible for the star formation in such galaxies at high(est) redshifts, but we do not know well the actual physical mechanism and process to produce stars by cloud collision. Therefore, understanding conditions of the CCC speed for star formation is important to obtain a better understanding of galaxy evolution.

This chapter is organized as follows: In Section 4.2, we estimate the CCC speeds using the catalog and a modeled mean velocity field of the molecular gas. Then we investigate their differences among the environments and compare the observation with the simulation. Section 4.3 shows the results of the velocity deviation and comparison with the simulation. In Section 4.4, we comprehensively discuss the physical mechanisms controlling galaxy-scale SFE diversity, including other ideas besides the scenario based on CCC speed differences.

4.2 Estimated CCC Speed

In this section, we attempt to estimate the CCC speeds. GMCs are considered to be moving along the global gas velocity field. Therefore, in Section 4.2.1, we first obtain the global velocity field model of the molecular gases based on the CO(2 – 1) 1st-moment map of NGC 1300 using an open tool, DISKFIT (Spekkens & Sellwood 2007; Sellwood & Sánchez 2010). Then, in Section 4.2.2, we estimate GMC motion and the CCC speeds using the model and the catalog. Section 4.2.3 shows the estimated CCC speed and the differences among the environments. In Section 4.2.4, we compare the observations with the simulation by F20.

4.2.1 Velocity Field Model

1st-moment map of CO(2 – 1) emission

We made a $^{12}\text{CO}(2 - 1)$ (rest frequency: 230.538000 GHz) cube using the archival data which was observed with 12-m array and ACA (7-m + Total Power) under project 2018.1.01651.S (PI = A. Leroy) and 2015.1.00925.S (PI = B. Guillermo), respectively. We calibrated raw visibility data using CASA and the observatory-provided calibration script. We imaged the interferometric cube using the CLEAN algorithm in CASA. We adopted a taper in the uv -plane to set the angular resolution of 4.0 arcsec, corresponding to 400 pc. Finally, using the CASA task `feather`, the interferometric cube was combined with the cube obtained with the Total Power. The rms noise of the data cube is $2.73 \text{ mJy beam}^{-1}$ per 5.0 km s^{-1} bin.

Figure 4.2(a) shows the 1st-moment map of the CO(2 – 1) in NGC 1300. To make the image, we identified significant CO emissions using CPROPS as follows; we first identified 3D (position-position-velocity) regions with a signal-to-noise ratio (S/N) ≥ 4 in at least two adjacent velocity channels. Then, we expanded this mask to include all adjacent pixels with $S/N \geq 1.5$ in the 3D space. Using the masked cube, we made the 1-st moment map by the `immoments` task in CASA.

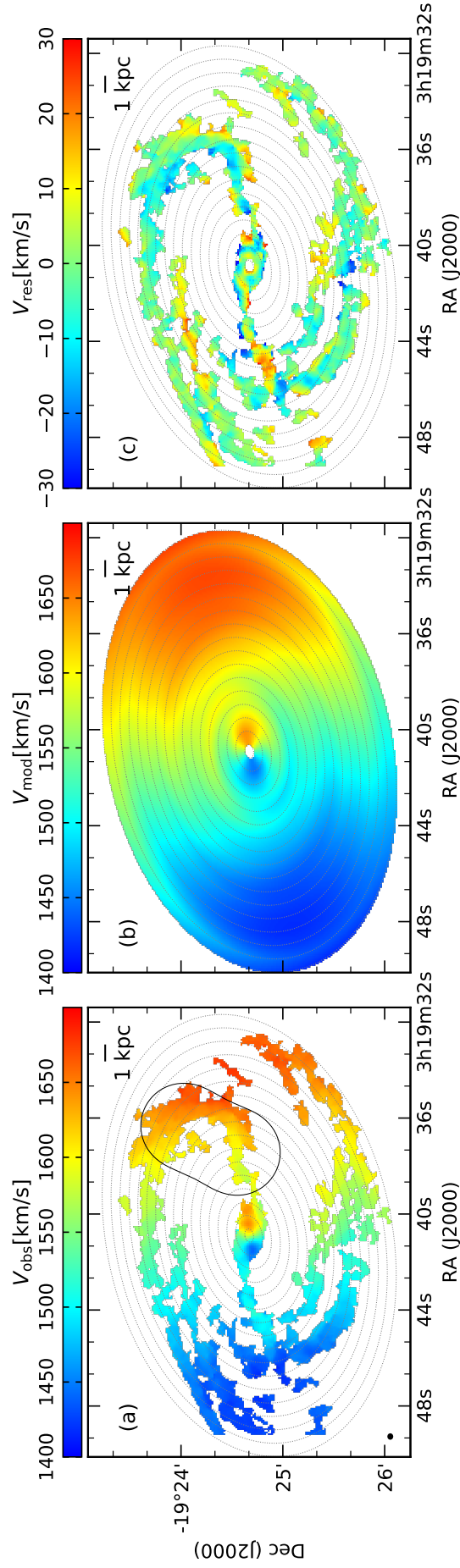


Figure 4.2: Kinematic models of NGC 1300 velocity field. (a) Observed velocity field obtained from CO(2 – 1) observations with ALMA. The black line represents the FoV of CO(1 – 0) observations with ALMA. The black circle of the left bottom corner represents the beam-size of 4.0 arcsec. (b) Best-fitted modeled velocity field obtained from DISKFIT. (c) Residual map. We project the model and fit to the observed data, using linear interpolation to predict data values between rings. The radii of the rings set from 0.4 kpc to 13.2 kpc in a 0.8-kpc interval shown as gray dotted lines.

Fitting with DISKFIT

To determine the velocity field of galaxies, a number of techniques already exist. Tilted-ring technique, which is introduced by Rogstad et al. (1974) to describe the H I gas disk of M83, is now widely used. This technique determines position angle, ϕ'_d , and inclination, i , as a function of galactocentric radius, and works well for smooth extended H I gas with the warp and radial inflow in the outer region of the galaxies (e.g. Schmidt et al. 2016). However, molecular gas is more compact and organized in a centrally thin disk, so the CO emissions are unlikely to trace such a wrap disk. Further, it is pointed out that ϕ'_d and i can be biased by applying the tilted-ring technique to kinematic tracer such as the CO emission in which non-circular motions are seen (e.g. Lang et al. 2020). Therefore, ϕ'_d and i are held constant with radius in this study.

Assuming that molecular gases move in a 2D plane, the line-of-sight velocity in the sky plane, $V_{\text{obs}}(\alpha, \delta)$, is the sum of the projected tangential, V_t , and radial, V_r , velocities in the disk plane:

$$V_{\text{obs}}(\alpha, \delta) = V_{\text{sys}} + \sin i [V_t(r, \theta) \cos \theta + V_r(r, \theta) \sin \theta], \quad (4.2.1)$$

where (r, θ) is polar coordinate in the disk plane, V_{sys} is the systemic velocity, i is the inclination.

This equation can be expressed as a Fourier series by

$$V_{\text{obs}} = V_{\text{sys}} + \sin i \left[\bar{V}_t(r) \cos \theta + \sum_{m=1}^{\infty} V_{m,t} \cos \theta \cos(m\theta + \theta_{m,t}) + \bar{V}_r(r) \sin \theta + \sum_{m=1}^{\infty} V_{m,r} \sin \theta \cos(m\theta + \theta_{m,r}) \right], \quad (4.2.2)$$

where the coefficients $V_{m,t}$ and $V_{m,r}$, and phases $\theta_{m,t}$ and $\theta_{m,r}$ are functions of r . The terms of $\bar{V}_t(r)$ and $\bar{V}_r(r)$ are the mean tangential and radial motion of the gas, respectively. To estimate the global gas velocity, we used a purely axisymmetric kinematic model with coefficients of $m > 0$ terms set to be zero, but retaining the $\bar{V}_r(r)$ term:

$$V_{\text{obs}}(\alpha, \delta) = V_{\text{sys}} + \sin i [\bar{V}_t(r) \cos \theta + \bar{V}_r(r) \sin \theta]. \quad (4.2.3)$$

We performed fit to the line-of-sight velocity field (1st moment map) of CO(2 – 1) with the Equation (4.2.3) using DISKFIT (Spekkens & Sellwood 2007; Sellwood & Sánchez 2010). In addition to the axisymmetric kinematic model expressed in Equation (4.2.3), non-axisymmetric kinematic models are implemented in DISKFIT. A bisymmetric model expresses the non-circular motion driven by barlike distortion using the $m = 2$ term in the Fourier expansion of V_t and V_r . However, it is known that application of this model fails when the galactic bar is almost parallel to the major axis of the disk due to the degeneracy of the velocity components (Sellwood & Sánchez 2010; Randriamampandry et al. 2015, 2018). Since the PA of the bar in NGC 1300 is close to that of the line of node (see Table 1.1), it is inappropriate to use the bisymmetric mode. Thus, we use the axisymmetric model of Equation (4.2.3).

DISKFIT consists of a set of model values for $\bar{V}_t$ and $\bar{V}_r$ around circular rings in the disk plane that project to ellipses on the sky plane with a common center, (x_c, y_c) . Then, DISKFIT projects the model values and fit to the observed data, using linear interpolation to predict data values between rings. The radii of the rings set from 0.4 kpc to 13.2 kpc in a 0.8-kpc interval ($= 2 \times$ beam size) shown as gray dotted lines in Figure 4.2. DISKFIT estimates the velocities ($\bar{V}_t, \bar{V}_r$) and the other parameters ($V_{\text{sys}}, \phi'_d, i, x_c, y_c$) using a χ^2 minimization technique. The values in Table 1.1 were applied as their initial guesses. To estimate the uncertainty on the parameters, DISKFIT performs a bootstrap method and we made 100 times iterations.

Figure 4.2(b) and (c) show the best-fitted model image and residual image, respectively. The best fitted disk parameters of ϕ'_d and i are $281^\circ.8 \pm 0^\circ.5$ and $50^\circ.4 \pm 0^\circ.3$, respectively, and are almost the same as the initial guesses derived by England (1989b). There are a few observations that

Table 4.1: Fitted velocity components for NGC 1300

r (kpc)	$\bar{V}_t$ (km s ⁻¹)	$\bar{V}_r$ (km s ⁻¹)
0.4	-119.5 ± 2.9	0.0 ± 3.1
1.2	-127.1 ± 2.9	5.3 ± 3.9
2.0	-86.5 ± 4.0	-18.3 ± 6.1
2.8	-51.2 ± 9.9	-0.3 ± 18.2
3.6	-58.8 ± 3.7	43.7 ± 13.2
4.4	-48.9 ± 2.8	30.3 ± 6.4
5.2	-77.0 ± 2.1	20.1 ± 4.4
6.0	-95.0 ± 1.9	18.3 ± 2.5
6.8	-113.5 ± 1.8	29.2 ± 2.2
7.6	-136.4 ± 1.5	27.4 ± 1.7
8.4	-150.0 ± 1.6	11.8 ± 1.9
9.2	-154.6 ± 1.5	14.4 ± 1.7
10.0	-164.0 ± 1.7	9.8 ± 1.7
10.8	-165.9 ± 1.7	6.3 ± 2.5
11.6	-157.6 ± 1.8	19.7 ± 2.8
12.4	-140.1 ± 2.7	39.2 ± 4.0
13.2	-164.9 ± 8.9	34.5 ± 10.0

report different values from the result by England (1989b) (e.g., $\phi'_d = 267^\circ$ and $i = 35^\circ$; Lindblad et al. 1997, $\phi'_d = 278^\circ.1$ and $i = 31^\circ.8$; Lang et al. 2020), but using these values as the initial

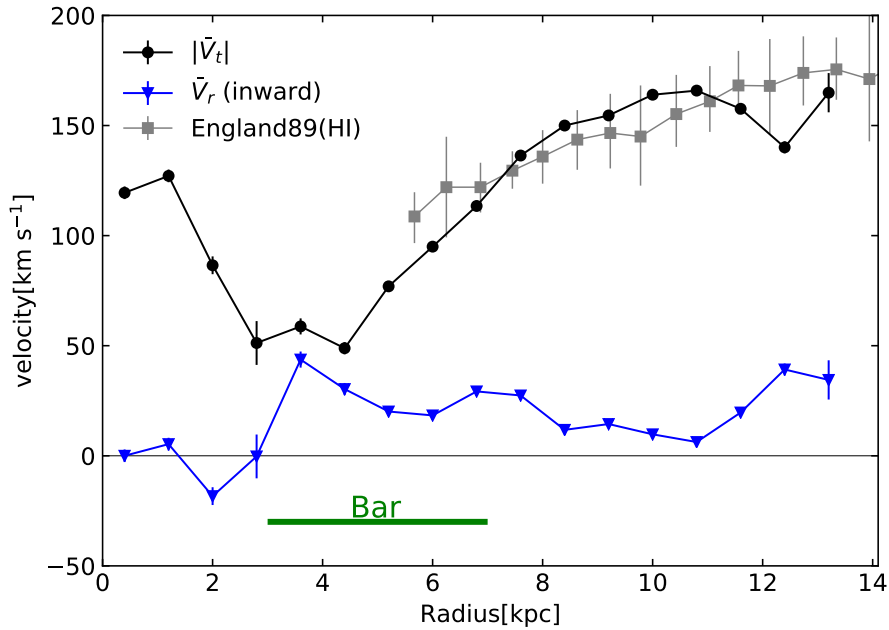


Figure 4.3: Fitted velocity components for NGC 1300. $\bar{V}_t(r)$ and $\bar{V}_r(r)$ are shown by the black circles and blue triangles, respectively. Gray squares show the angle-averaged rotation curve obtained from H I observations by England (1989b).

guesses does not change the best-fitted values. The best-fitted V_{sys} is $1544.7 \pm 0.2 \text{ km s}^{-1}$. The best-fitted $\bar{V}_t$ and $\bar{V}_r$ are shown in Table 4.1. Here, DISKFIT defines the positive direction of $\bar{V}_t$ and $\bar{V}_r$ as counterclockwise and central direction, respectively.

Figure 4.3 shows the fitted tangential velocities (i.e. rotation curve) and radial velocities. In the bar region ($3 \text{ kpc} < r < 7 \text{ kpc}$), the radial velocity is large ($20 - 40 \text{ km s}^{-1}$). This would be due to the elongated gas motion by the bar potential (F20). In the arm region ($7 \text{ kpc} < r < 10 \text{ kpc}$), the gas motion is generally circular motion. Our best fit rotation curve is consistent with that derived by H I observations (England 1989b, Figure 4.3).

4.2.2 Estimation of the cloud-cloud collision speed

To estimate the CCC speed, we first estimate the motion of the GMCs in the disk plane using the mean velocity field of the molecular gas obtained in the previous subsection. Figure 4.4 is a schematic illustration showing the relationship between the velocity vector of a GMC, $\mathbf{V}_{\text{GMC}}$, and the mean velocity field. The $\mathbf{V}_{\text{model}}$ is the velocity field obtained using DISKFIT at that position. The ϕ_{GMC} and ϕ_{model} are angles of the projected major axis (i.e. x axis) to $\mathbf{V}_{\text{GMC}}$ and $\mathbf{V}_{\text{model}}$, respectively. We decompose the difference vector between $\mathbf{V}_{\text{GMC}}$ and $\mathbf{V}_{\text{model}}$ into the sum of two perpendicular vector components with one parallel to $\mathbf{V}_{\text{model}}$, $\mathbf{V}_{\parallel}$, and one perpendicular to $\mathbf{V}_{\text{model}}$, $\mathbf{V}_{\perp}$;

$$\mathbf{V}_{\text{GMC}} = \mathbf{V}_{\text{model}} + \mathbf{V}_{\parallel} + \mathbf{V}_{\perp}. \quad (4.2.4)$$

The observed line-of-sight velocity of the GMC, $V_{\text{GMC}}^{\text{obs}}$, is expressed as follows;

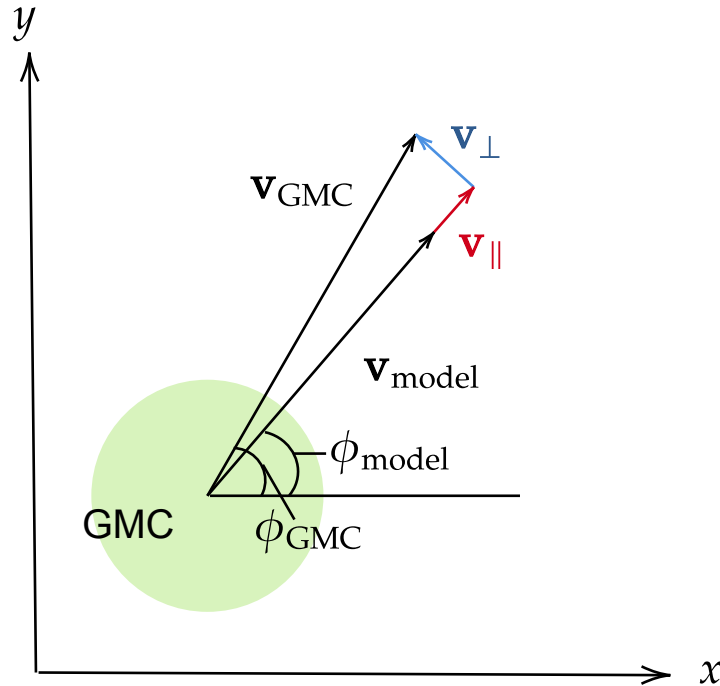


Figure 4.4: Schematic illustration showing the relationship between the velocity vector of a GMC, $\mathbf{V}_{\text{GMC}}$, and the mean velocity field in the disk plane. The $\mathbf{V}_{\text{model}}$ is the velocity field obtained by the method described in the text at that position. The ϕ_{GMC} and ϕ_{model} are angles of the projected major axis to $\mathbf{V}_{\text{GMC}}$ and $\mathbf{V}_{\text{model}}$, respectively. Difference vector between $\mathbf{V}_{\text{GMC}}$ and $\mathbf{V}_{\text{model}}$ is decomposed into the sum of two perpendicular vector components with one parallel to $\mathbf{V}_{\text{model}}$, $\mathbf{V}_{\parallel}$, and one perpendicular to $\mathbf{V}_{\text{model}}$, $\mathbf{V}_{\perp}$.

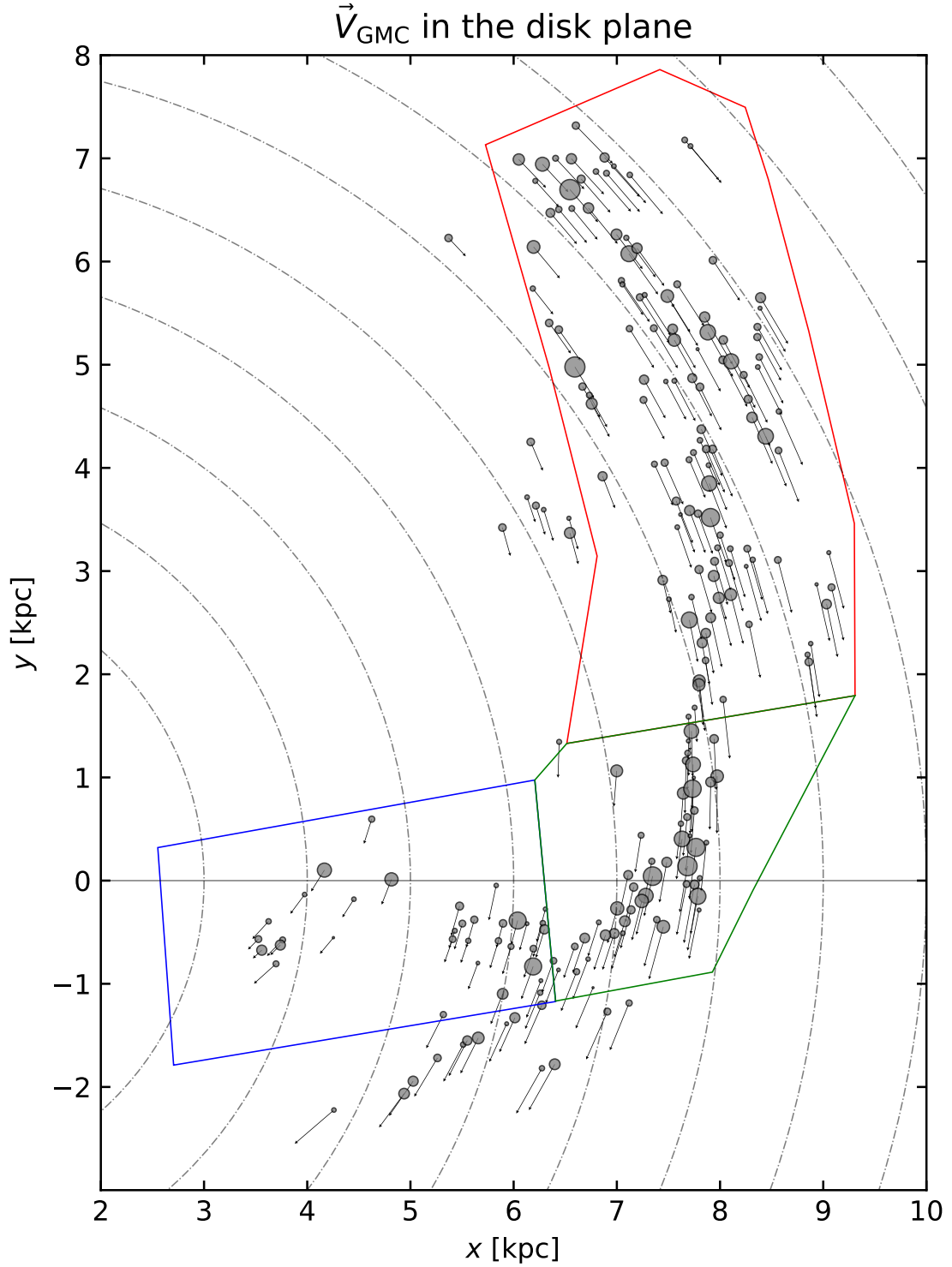


Figure 4.5: Derived $\vec{V}_{\text{GMC}}$ in the disk plane based on the observed line-of-sight velocity of the GMCs and the modeled velocity field. The color solid lines indicate the definition of the environmental mask (see Figure 2.3). Horizontal line shows the projected major axis. Dash-dotted lines shows concentric circles around the galactic center with 1 kpc interval.

$$V_{\text{GMC}}^{\text{obs}} = V_{\text{sys}} + \sin i [|V_{\text{model}}| \sin \phi_{\text{model}} + |V_{\parallel}| \sin \phi_{\text{model}} + |V_{\perp}| \cos \phi_{\text{model}}]. \quad (4.2.5)$$

Using the GMC catalog by Maeda et al. (2020a) and the modeled mean velocity field, we calculated $|V_{\parallel}|$ and then, derived V_{GMC} . Here, we assume the direction of the GMC motion is parallel to the global velocity field i.e. $V_{\perp} = \mathbf{0}$ ($V_{\text{GMC}} \parallel V_{\text{model}}$. See Section 4.4.1 for more details.).

Figure 4.5 shows the distribution of V_{GMC} in the disk plane of NGC 1300. The galactic center is set to be $(x_c, y_c) = (0, 0)$. The motion of GMCs in *bar* deviates from the circular motion. This would be due to the elongated elliptical gas motion shifted by the bar potential. Such deviation can be seen in *bar-end*. On the other hand, GMCs in *arm* are close to the circular orbit around the galactic centre. Similar motions are seen in the simulation modeled NGC 1300 (Figure A.10).

Next step is to estimate the CCC speed. We denote the velocity vectors of two GMCs located at (x_i, y_i) and (x_j, y_j) at the current time ($t = 0$) as $\mathbf{V}_{\text{GMC}}^i = (v_{x,i}, v_{y,i})$ and $\mathbf{V}_{\text{GMC}}^j = (v_{x,j}, v_{y,j})$, respectively. To estimate the collision velocity, we impose some assumptions: (1) All GMCs are spherical shape. (2) GMCs are in constant linear motion. (3) The interactions among clouds such as gravity and viscosity are negligible. Thus, the distance between the two GMCs at time of t , $D_{i,j}(t)$, becomes

$$D_{i,j}(t) = \{ [(x_i + v_{x,i}t) - (x_j + v_{x,j}t)]^2 + [(y_i + v_{y,i}t) - (y_j + v_{y,j}t)]^2 \}^{1/2}. \quad (4.2.6)$$

To identify the potentially colliding pairs, we first extracted the pairs (i, j) which are within a distance of 300 pc and move towards each other; $D_{i,j}(0) \leq 300$ pc and $\frac{dD_{i,j}}{dt}|_{t=0} < 0$. Here, we set a cut-off distance of 300 pc to include 75 percent of the distances to the nearest GMC in *bar*, where the GMCs are most sparsely distributed (see also Figure 4.8(a)). Next, we extract the pairs such that there exists a t that satisfies $D_{i,j}(t) \leq R_i + R_j$ in the range of $0 \leq t < 10$ Myr, where R_i and R_j are cataloged radii. If there are other GMCs between the two GMCs (ID = i, j), we exclude the pair. Finally, we determine the relative speed as the estimated CCC speed;

$$v_{\text{col}} = \left| \mathbf{V}_{\text{GMC}}^i - \mathbf{V}_{\text{GMC}}^j \right|. \quad (4.2.7)$$

It should be noted that the assumptions of (2) and (3) lead to neglect of the impact of collisionless encounters (scattering by other GMCs) in this study. Therefore, there is a possibility that the paths of the pairs expected to collide with each other in the near future may change by the collisionless encounters.

We limited the range of t within 10 Myr because the assumption of straight motion for GMCs is a reasonable approximation of the circular motion within this range. In other words, the moving distance is small enough for around the galaxy; the ωt is less than 0.2 rad, which corresponds to the fraction of the orbital time of $\sim 1/30$, within 10 Myr. Here, ω is the angular velocity of $\bar{V}_t/r \sim 0.02$ rad Myr $^{-1}$, where $\bar{V}_t$ and r in *arm* are ~ 150 km s $^{-1}$ and $r \sim 9$ kpc. Note that the timescale of 10 Myr ($\sim 1/30$ of the orbital time) is comparable or shorter than the collision timescales obtained from observations and galaxy simulations; ~ 7 Myr in the W43 GMC complex in the Milky Way's bar-end region (Kohno et al. 2020), ~ 25 Myr ($\sim 1/5$; Tasker & Tan 2009), $8 - 10$ Myr ($\sim 1/15$) in a simulation with spiral arms and 28 Myr ($\sim 1/5$) with no imposed spiral arms (Dobbs et al. 2015), and 71 Myr ($\sim 1/3$), 57 Myr ($\sim 1/5$), and 72 Myr ($\sim 1/4$) in *bar*, *bar-end*, and *arm*, respectively, in a simulation of a strongly barred galaxy (F20).

4.2 Estimated CCC Speed

Table 4.2: Estimated CCC speed in the different environments of NGC 1300

Region	n_{cloud}^*	$n_{\text{ccc}}^\dagger$	$v_{\text{col}}^\S$ (km s^{-1})	$n_{>20\text{km/s}}^\ddagger$ ($\text{Gyr}^{-1} \text{ kpc}^{-2}$)	$f_{\text{ccc}}^\star$ (Gyr^{-1})
Bar	34	8	$20.5^{+4.8}_{-5.7}$	51.6 ± 6.5 (50.0)	24.8 ± 2.5 (23.5)
Arm	119	12	$11.2^{+3.5}_{-3.6}$	14.4 ± 2.8 (12.9)	10.7 ± 0.5 (10.2)
Bar-end	49	12	$16.0^{+11.3}_{-5.9}$	88.4 ± 0.7 (88.5)	24.3 ± 0.6 (24.5)

* Number of GMCs.

† Number of collisions.

§ Estimated CCC speed based on the best-fitted model, which is noted as M_{D25}^{D75} , where M , $D25$, and $D75$ are the median, the distance to the 25th percentile from the median, and the distance to the 75th percentile from the median of the number distribution, respectively.

‡ Number density of high-speed CCC with $v_{\text{col}} > 20 \text{ km s}^{-1}$ per unit time and area. The uncertainty is calculated based on the 100 times iterations. The value in parentheses is derived using best-fitted model.

* Collision frequency. Notation is the same as $n_{>20\text{km/s}}$.

4.2.3 Results

We find a tendency for the estimated CCC speed, v_{col} , to depend on the environment. Figure 4.6 shows the normalized cumulative distribution function of the estimated CCC speed. The GMCs in the samples are expected to collide each other within 10 Myr from the current time. As shown in Table 4.2, the v_{col} in *bar* and *bar-end* are higher than that in *arm*: $14.8 - 25.3 \text{ km s}^{-1}$ in *bar*, $10.1 - 25.3 \text{ km s}^{-1}$ in *bar-end*, and $7.6 - 14.7 \text{ km s}^{-1}$ in *arm*, respectively. This result does not change by using the fitting results of the 100 times bootstrap iterations (Section 4.2.1); median value of the v_{col} is $19.9 \pm 2.3 \text{ km s}^{-1}$, $16.1 \pm 0.2 \text{ km s}^{-1}$, and $11.1 \pm 0.2 \text{ km s}^{-1}$ in *bar*, *bar-end*, and *arm*, respectively.

We statistically checked the environmental variation of the v_{col} distribution using the two-sided Kolmogorov-Smirnov (K-S) test (see Section 2.5.1). The p -value showing significant difference was not detected; > 0.1 . Although this result indicates that there would be no statistically significant difference among the environments, it is possible that the p -value may be high due to the small number of samples. Generally, when comparing two samples (the number of samples of N_1 and N_2), the effective number of sample $N_e = N_1 N_2 / (N_1 + N_2)$ is preferably more than 8 in order to obtain the accurate p -value according to the approximation by Stephens (1970). However, in this study, N_e is 4.8, 4.8, and 6.0 when comparing *bar* and *arm*, *bar* and *bar-end*, and *arm* and *bar-end*, respectively. Therefore, it is premature to draw a statistical conclusion about the environmental dependence on v_{col} and further observations are desirable (e.g. observations of the GMC across the whole NGC 1300.).

Figure 4.7 shows the scatter plot between the estimated CCC speed and the molecular gas mass of the most massive GMC in each pair. Large symbols show the median values in the environments. Comparing *bar* and *arm*, molecular gas mass is comparable but the v_{col} in *bar* tends to be higher than that in *arm*. On the other hand, comparing *bar* and *bar-end*, v_{col} is roughly comparable but the molecular gas mass in *bar-end* tends to be higher than that in *bar*. In Sections 4.4.2 and 4.4.3, we

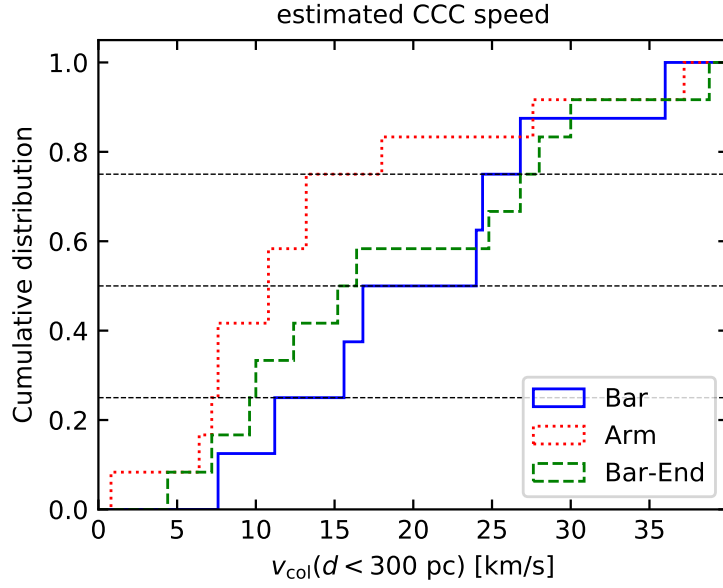


Figure 4.6: Normalized cumulative distribution function of the CCC speed. The samples are the potentially colliding pairs we identified (see text). The vertical lines show the cumulative distribution function of 0.25, 0.50, and 0.75, respectively.

further discuss the connection among star formation activity, CCC speed, and molecular gas mass of the colliding GMCs.

Next, we focus on high-speed CCCs with $v_{\text{col}} > 20 \text{ km s}^{-1}$. Such a high-speed CCC can shorten the gas accretion phase of the cloud cores formed, leading to massive star formation suppression (Takahira et al. 2014, 2018). As shown in Table 4.2, we find that the number density of high speed CCC with $v_{\text{col}} > 20 \text{ km s}^{-1}$ per unit time and area, $n_{>20\text{km/s}}$, is significantly higher in *bar* ($\sim 52 \text{ Gyr}^{-1} \text{ kpc}^{-2}$) and *bar-end* ($\sim 88 \text{ Gyr}^{-1} \text{ kpc}^{-2}$) than in *arm* ($\sim 14 \text{ Gyr}^{-1} \text{ kpc}^{-2}$). High number density in both *bar* and *bar-end*, where the star formation activity is significantly different, suggests that whether or not star formation is induced by CCC depends not only on the CCC speed, but also on other parameters. Takahira et al. (2018) pointed out that the core mass growth also depends on the mass (size) of the colliding clouds. This point is discussed in more detail in Section 4.4.2.

Lastly, we investigated collision frequency defined as,

$$f_{\text{ccc}} = \frac{n_{\text{ccc}}}{n_{\text{cloud}} \Delta t}, \quad (4.2.8)$$

where n_{ccc} is the number of collisions, n_{cloud} is the number of clouds in each environment (Table 4.2), and Δt is the tracking time of 10 Myr. The collision frequency is estimated to be $10 - 25 \text{ Gyr}^{-1}$ (Table 4.2). We find that the collision frequencies in *bar* and *bar-end* are about two times higher than that in *arm*. The lack of star formation activity despite the high collision frequency in *bar* suggests that the star formation activity is not controlled only by the collision frequency.

We checked the dependence on the cut-off distance. If the cut-off distance is varied from 200 pc to 400 pc, the number of samples in each environment increases or decreases by a few, and the results remain almost the same. In the case of 200 pc, v_{col} in *bar*, *bar-end*, and *arm* are $20.0^{+4.6}_{-7.4} \text{ km s}^{-1}$, $15.4^{+10.6}_{-5.4} \text{ km s}^{-1}$, and $11.2^{+3.5}_{-3.6} \text{ km s}^{-1}$, respectively. In the case of 400 pc, v_{col} in *bar*, *bar-end*, and *arm* are $20.5^{+4.8}_{-5.7} \text{ km s}^{-1}$, $16.7^{+11.7}_{-6.5} \text{ km s}^{-1}$, and $11.2^{+3.5}_{-3.6} \text{ km s}^{-1}$, respectively. However, if we take the cut-off distance as 150 pc or less, we can hardly see the environmental dependence in the CCC

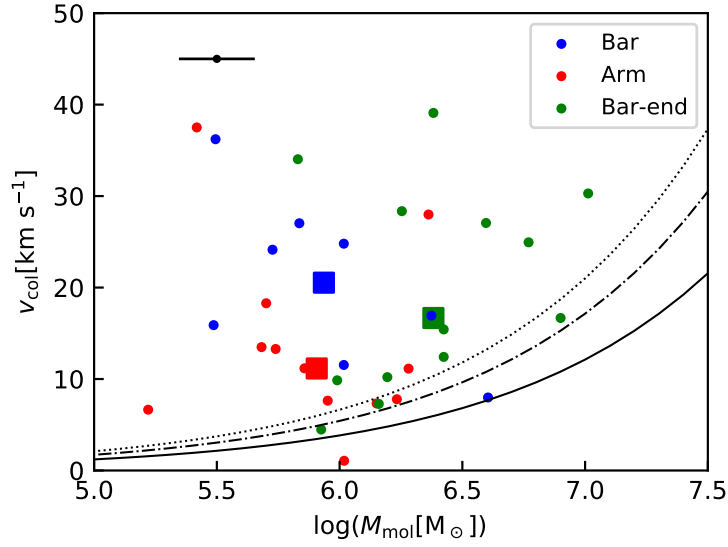


Figure 4.7: Scatter plot of the CCC speed versus the mass of the most massive GMC in each collision. The v_{col} was derived using the best-fitted velocity-field model. The large symbols show the median values. The black bar in the upper left shows the typical uncertainty of the molecular gas mass of the GMCs derived by Maeda et al. (2020a). The black lines show a free fall speed as a function of GMC mass (see equation (4.2.9)). We set $R = 50$ pc and $D_{\text{nearest}} = 120$ pc (solid line), $R = 50$ pc and $D_{\text{nearest}} = 150$ pc (dash-dotted line), and $R = 50$ pc and $D_{\text{nearest}} = 200$ pc (dotted line).

speed. This is because the number of pairs halved in the bar region. Since the median value of the distance to the nearest GMC is 150 pc in the bar (see also Figure 4.8(a)), setting the cut-off distance to 150 pc or less would be inappropriate, leading to an unfair decrease in the number of the sample in the bar.

4.2.4 Comparison of estimated CCC speeds with the simulation

Here we compare the CCC speed between our observations and simulation by F20. F20 presented a hydrodynamical simulation of a strongly barred galaxy. The simulation was run using adaptive mesh refinement hydrodynamics code ENZO (Bryan et al. 2014). The minimum cell size is ~ 2 pc. They used a fixed potential model which is taken from observational results of NGC 1300 (England 1989a). There is no star formation or stellar feedback in the simulation.

For the CCC speed in *bar*, the simulation result is generally consistent with the estimated CCC speed. In the simulation, fraction of collided clouds with CCC speed more than 20 km s^{-1} is roughly 40 per cent in *bar*, which is also consistent with our results. In *arm*, the simulation result is median value is $\sim 10 \text{ km s}^{-1}$, which is comparable to our results. However, the results in *bar-end* are different; estimated CCC speed is higher than that in the simulation ($\sim 10 \text{ km s}^{-1}$). This result indicates that the deviation from the circular motion may be larger in *bar-end* than that expected in the simulation.

In Figure 4.7, the black lines show the free-fall speed as a function of the GMC mass. The free-fall speed is defined in equation (13) in F20 as,

$$v_{\text{ff}} = \sqrt{2GM_{\text{mol}} \left(\frac{1}{2R} - \frac{1}{D_{\text{nearest}}} \right)}, \quad (4.2.9)$$

where M_{mol} is the molecular gas mass of the GMC, R is the radius of the GMC, and D_{nearest} is the distance to the nearest GMC. We use $R = 50$ pc, which is the median value in the catalog by Maeda et al. (2020a), and $D_{\text{nearest}} = 120, 150,$ and 200 pc. In the simulation by F20, the *bar-end* and *arm* clouds roughly follow the free-fall line, which supports the idea of a large contribution of gravitational interactions between clouds to driving CCCs. However, most of the observed values in all environments are located above the lines. This suggests that gravitational interactions have only a small contribution to driving collisions. As mentioned in the next section, not the gravitational interaction but the random-like motion of GMCs may contribute to the collisions to some extent.

For the collision frequency, unlike the observations, a significant environmental dependence is not seen in the simulation. The collision frequencies in the simulation in *bar* and *bar-end* ($\sim 15 \text{ Gyr}^{-1}$) are slightly lower than those in the observations. The possible reason for the difference is that the size of the clouds in the simulation is smaller than that of the observed GMCs. Because of differences in the threshold density for cloud identification and the spatial resolution (see Section 4.4.1), the cloud radius is smaller in the simulation (median of ~ 8 pc) than that of observed GMCs (~ 40 pc). Thus, the cross-sections of clouds in the simulation may be smaller and then collision frequencies get lower.

4.3 Velocity Deviation

We investigated the properties of CCC with another approach using GMC catalog as a model-independent method. We examined the distance to the nearest GMC, velocity deviation between the GMC and its surrounding GMCs, and collision frequency of GMCs by assuming that GMCs are in random motions.

Figure 4.8(a) shows the normalized cumulative distribution function of the distance to the nearest GMC. The median value in *bar*, *arm*, and *bar-end* are 142, 120, and 100 pc, respectively; the *bar-end* GMCs have a smaller distance to the nearest GMC. This result indicates that the spatial distribution of the *bar-end* GMCs is more crowded, which would be one of the cause for the high collision frequency. The difference between observations and the simulations by F20 is only a few tens of parsec, but unlike observations, the *bar* clouds have a smaller distance to the nearest cloud than other regions in the simulation. As we explain in later sections, the differences can be attributed to differences in methodology of the cloud identification and in spatial resolution.

Next, we calculated the velocity deviation between the GMC and its surrounding GMCs defined as,

$$\Delta_v(< r) = \sqrt{2} |v_{\text{los}} - \bar{v}_{\text{los}}(< r)| / \sin i, \quad (4.3.1)$$

where the v_{los} is the line-of-sight velocity of the GMC and $\bar{v}_{\text{los}}(< r)$ is the mass-weighted mean line-of-sight velocity of its surrounding GMCs within a radius of r , respectively, and i is the inclination of NGC 1300. We multiplied by the factor of $\sqrt{2}$ by assuming that the GMCs move randomly in a 2D plane. We set a cut-off distance of 300 pc to include 75 percent of the distances to the nearest GMC in the bar region (Figure 4.8(a)). The simulation by F20 shows that the velocity deviation in the bar region is larger than that in the arm and bar-end regions. This tendency is the same as the CCC speed in the simulation, indicating that the velocity deviation can be a good indicator of the qualitative trends of the CCC speed.

Table 4.3 shows the observed $\Delta_v(< 300 \text{ pc})$ in each environment. Figure 4.8(b) shows the cumulative distribution of $\Delta_v(< 300 \text{ pc})$. We find that the Δ_v in *bar* and *bar-end* are larger than that in *arm*; $\Delta_v(< 300 \text{ pc})$ in *bar* and *bar-end* are $6.2 - 20.0 \text{ km s}^{-1}$ and $3.6 - 24.7 \text{ km s}^{-1}$, respectively, followed by $3.3 - 13.6 \text{ km s}^{-1}$ in *arm*. This result suggests that the CCC speeds in *bar* and *bar-end* are higher than that in *arm*, which is consistent with the collision speed derived in Section 4.2.3.

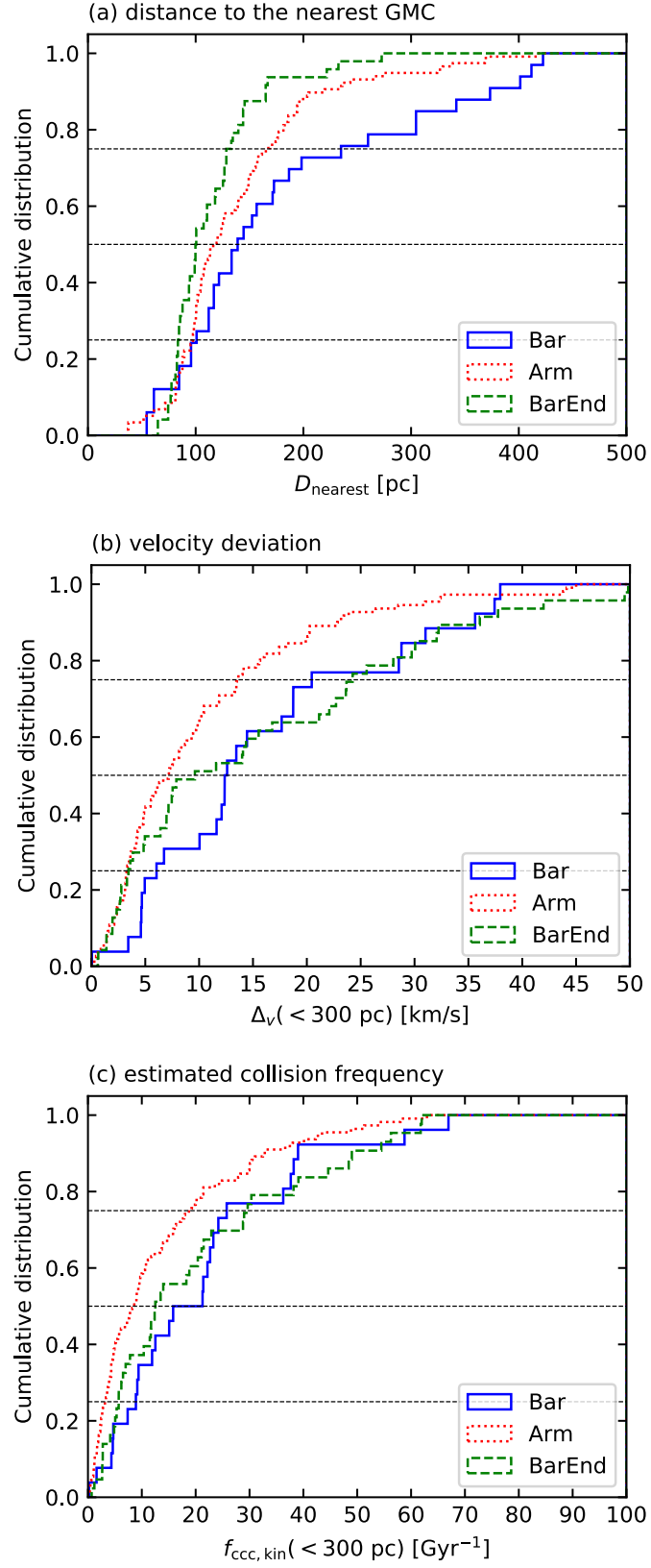


Figure 4.8: Normalized cumulative distribution function of (a) the distance to the nearest GMC, (b) the velocity deviation between the GMC and its surrounding GMCs within a radius of $r < 300 \text{ pc}$ and, (c) the estimated collision frequency of GMCs.

Table 4.3: Velocity deviation ($r = 300$ pc) in the different environments of NGC 1300

Region	# *	Δ_v † (km s ⁻¹)	$f_{\text{ccc,kin}}$ † (Gyr ⁻¹)
Bar	26	12.5 ^{+7.5} _{-6.3}	18.6 ^{+6.8} _{-9.6}
Arm	111	7.2 ^{+6.4} _{-3.9}	8.4 ^{+10.3} _{-5.1}
Bar-end	48	10.6 ^{+14.1} _{-7.0}	16.1 ^{+24.3} _{-10.0}

* Number of the GMC which has the nearest GMC within 300 pc.

† Notation is the same as v_{col} in Table 4.2.

We statistically checked the environmental variation of the $\Delta_v (< 300$ pc) distribution using the two-sided K-S test. Significant differences are seen between *bar* and *arm*, and *bar-end* and *arm*; The p -values are 0.011 and 0.018, respectively. On the other hand, there is no significant difference between *bar* and *bar-end*; p -value is 0.37. We checked the dependence on the cut-off distance. The tendency of environmental dependence does not change even if the cut-off distance is varied from 200 pc to 400 pc; $\Delta_v (< 200$ pc) in *bar*, *bar-end*, and *arm* are 4.7 – 22.8 km s⁻¹, 6.7 – 26.6 km s⁻¹, and 1.0 – 13.4 km s⁻¹, respectively. $\Delta_v (< 400$ pc) in *bar*, *bar-end*, and *arm* are 7.3 – 18.6 km s⁻¹, 6.3 – 25.9 km s⁻¹, and 4.5 – 16.3 km s⁻¹, respectively. Although the trend of environmental dependence is similar, the estimated CCC speed is larger than the velocity deviation. As described in F20, this might be because we use only GMCs which are the potentially colliding pairs to estimate the CCC speed, while we use all GMCs to calculate the velocity deviation including those that have low-velocity deviation and are unlikely to collision soon.

Lastly, we estimated the collision frequency of the GMCs using cloud's kinematics model using the formula applied by F20 defined as,

$$f_{\text{ccc,kin}} = 2RN\Delta_v, \quad (4.3.2)$$

where R is the cataloged radius of the GMC, N is the surface number density of GMCs. Here, five assumptions are imposed: (1) GMCs are spherical shape and which is much smaller than the average distance between them. (2) GMCs are in constant, rapid, and random motion. (3) GMCs undergo random elastic collisions between themselves. (4) Except during collisions, the interactions among GMCs such as gravity and viscosity are negligible. (5) GMCs move in a 2D plane. This model is well known as kinetic theory and is often applied to ideal gases. The N and Δ_v are calculated within a circle whose radius is 300 pc centered at the GMC.

Figure 4.8(c) shows the normalized cumulative distribution function of the estimated collision frequency, $f_{\text{ccc,kin}}$, of GMCs. The $f_{\text{ccc,kin}}$ and f_{ccc} derived in Section 4.2.3 are roughly comparable. It is natural to get this result because we made almost the same assumptions in calculating both frequencies. Compared to the observations and simulation by F20, $f_{\text{ccc,kin}}$ in *bar* is comparable. F20 suggests that a random-like motion of clouds induced by the elongated gas stream due to the bar potential could be the physical mechanism of the high-speed CCC in *bar*.¹ In the simulation,

¹Fujimoto et al. (2014a) suggested another mechanism; massive clouds create strong gravitational interactions and thus increase the CCC speed. However, the mass of the massive clouds exceeds $10^7 M_{\odot}$, which is inconsistent with the observed GMCs. That might be because they performed the GMC formation simulation for over 200 Myr without

the median $f_{\text{ccc,kin}}$ in the *bar-end* and *arm* are $\sim 5 \text{ Gyr}^{-1}$, which is much lower than those in the observations. The reason of this difference is that the observed Δ_v is much larger than that in the simulation ($\sim 2 \text{ km s}^{-1}$). F20 concludes that gravitational interactions between clouds have a larger contribution to collisions in *arm* and *bar-end* regions than random-like motion of GMCs, resulting in low $f_{\text{ccc,kin}}$. However, based on the observed $f_{\text{ccc,kin}}$, random-like motion of GMCs may have some extent contribution to the collisions in *arm* and *bar-end*.

4.4 Discussion

4.4.1 Biases and caveats on our analyses

Biases on GMC motion

In this study, several assumptions are imposed on the GMC motion, and we discuss them here. First, we neglect the vertical GMC distributions in the galactic mid-plane. This assumption would have little effect on the above results. In the simulation by F20, all clouds lie in the small region between $-30 \text{ pc} < z < 30 \text{ pc}$ around the galactic mid-plane. In the Milky Way, the median height of GMC from Galactic plane is $\sim 30 \text{ pc}$ (Solomon et al. 1987). These results indicate we can neglect the effect of the vertical GMC distribution.

Second assumption is that we neglect the vertical velocities of GMC motion. In the simulation by F20, the vertical velocity is much less than 10 km s^{-1} and any difference among the environments is not seen. Therefore, the vertical motion of the GMCs can be neglected.

Third assumption is that V_{GMC} is parallel to V_{model} , i.e. $V_{\perp} = 0$. In other words, we neglected the impact of collisionless encounters (scattering by other GMCs), which increases the radial perturbation of the GMCs and thus increases the collision frequency. Although it is impossible to derive the $V_{\perp}$ with current data, we derived the v_{col} assuming the $V_{\perp}$ to check this assumption. We set the $|V_{\perp}|$ of each GMC randomly selected from a Gaussian distribution with a mean of 0 km s^{-1} and a standard deviation of 7 km s^{-1} , which is comparable to the cloud-cloud velocity dispersion within 3 kpc of the Sun (Stark & Brand 1989). We made 100 times iterations. As a result, the collision frequency in the arm region increased by a factor of 1.5 because the deviation from circular motion became large. The median v_{col} became larger in all regions, especially the largest increase was seen in *arm*; $v_{\text{col}} = 21.9 \text{ km s}^{-1}$, 19.3 km s^{-1} , and 16.6 km s^{-1} in *bar*, *bar-end*, and *arm*, respectively. The tendency of the v_{col} does not change, but the difference in v_{col} among the environments becomes small. This result suggests that our assumption results in an underestimation of the collision frequency and velocity in *arm*. Note that we also assumed that GMCs are in constant linear motion in this check. Therefore, the paths of the pairs expected to collide with each other may change by the further collisionless encounters.

Forth assumption is that we implicitly neglect the impact of feedback on the GMCs. Local stellar feedback (e.g. photoionisation, stellar winds, and supernovae) affects the GMC's formation and evolution (e.g. Dobbs et al. 2011; Tasker et al. 2015; Fujimoto et al. 2016; Grisdale et al. 2018). Recent studies show that feedback mechanisms caused by massive star formation such as photoionisation and stellar winds play a major role in dispersing the GMC before the first supernova explosion (e.g. Kruijssen et al. 2019; Chevance et al. 2020a). Therefore, a GMC associated with HII regions is likely to be affected by the feedback. There may be no effect in the strong bar with no HII regions, but we may have to consider the impact on the GMCs in *arm* and *bar-end* regions where

stellar feedback. In addition, their galaxy model is the intermediate-type barred galaxy M83, not the strongly barred galaxy NGC 1300 we discuss in this paper. That also might be the reason Fujimoto et al. (2014a) did not see the strongly elongated gas stream.

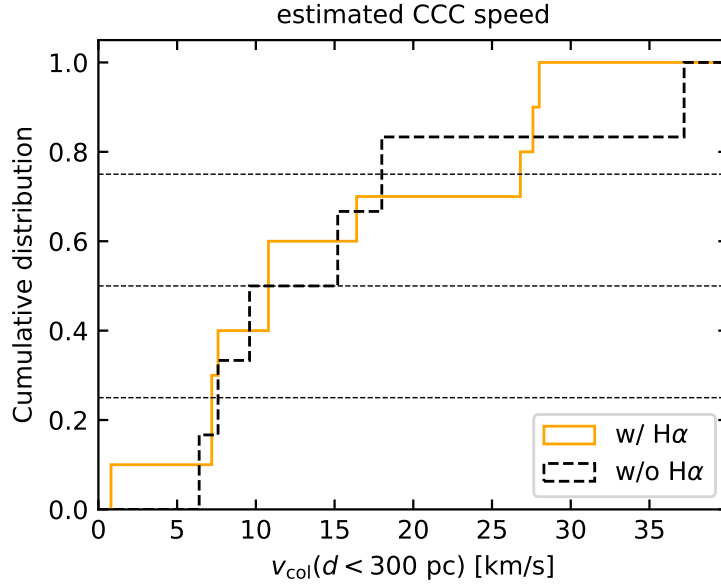


Figure 4.9: Normalized cumulative distribution function of the estimated collision frequency of GMCs with H α and without H α . We use the GMCs in the *arm* and *bar-end*.

the prominent HII regions are seen. Figure 4.9 shows the comparison of the CCC speeds of the pairs with H α and without H α in *arm* and *bar-end* regions. Here, we used a continuum-subtracted H α image of NGC 1300 obtained from HST images (Figure 3.9(a)). We don't see any difference between the both distributions, indicating the effect of the feedback would be small.

It is also necessary to mention the timescale of the GMC dispersal by the stellar feedback. Recent observations show the feedback timescale, which is the time between the emergence of the first ionizing photons due to massive star formation and the eventual dispersal of the GMC, is 1 – 5 Myr (e.g. Hollyhead et al. 2015; Kruijssen et al. 2019; Hygate et al. 2019; Chevance et al. 2020a). This implies that the GMCs associated with HII regions at current time are likely to be dispersed soon. Thus, many of the pairs in *arm* and *bar-end* regions we identified as likely to collide within 10 Myr may disappear before they collide.

Caveats on the comparison between observation and simulation

Above sections, we simply compared the results of the observations and the simulation, but we must note that the data quality and method of molecular cloud identification are different. In the simulation by F20, the cloud mass ranges from $5 \times 10^3 M_\odot$ to $5 \times 10^6 M_\odot$, radius ranges from 5 pc to 15 pc. On the other hand, the mass and size of observed GMCs (Chapter 1) are larger than those in the simulation; cataloged mass and radius range from $6 \times 10^4 M_\odot$ to $1.0 \times 10^7 M_\odot$ and from 8 pc to 100 pc, respectively. This is because the spatial resolution of our ALMA observations is ~ 40 pc, which is much larger than the 2 pc resolution of the simulation, and the mass completeness limit of the observation is estimated to be $2 \times 10^5 M_\odot$. Therefore, our observations miss the low-mass GMCs, would overestimate the radius, and would blend the small GMCs. Further, the method of identification of GMCs are different. In the simulation, cloud is defined as a connected dense region that is enclosed by a contour at a threshold number density of 400 cm^{-3} . This threshold would be higher than that in the observations because the critical density of $^{12}\text{CO}(1-0)$ is lower than 400 cm^{-3} . Therefore, the simulation and observation might be looking at somewhat different objects. It is possible that a gas clump that is split into multiple clouds in the simulation is identified

as a single GMC in the observations. In order to make a more complete comparison, we need to match the spatial resolution between the simulation and observations by convolving the simulation with the beam size of the observations and identify the cloud with the same method. Further, similar to our analysis, the effect of GMC dispersal due to feedback on CCC is neglected in the simulation. Therefore, the simulation should include stellar feedback in the future.

4.4.2 The cause for the different star formation activity between bar and bar-end with the same high CCC speed

Interestingly, the star formation activity in *bar* and *bar-end* regions, where the number density of high-speed CCC is similar, is quite different. The SFE is $0.08 - 0.12 \text{ Gyr}^{-1}$ and $0.45 - 0.53 \text{ Gyr}^{-1}$, respectively (Chapter 3; Maeda et al. 2020b). If the CCC is a triggering mechanism for massive star formation, our results show that star formation is triggered by high-speed CCC in *bar-end*, whereas it is not triggered in *bar*. This difference suggests that there are other parameters besides CCC speed that control the star formation.

One of the candidate parameters is the mass of the colliding molecular clouds. Previous studies proposed the CCCs are responsible for the correlation between the SFE and the mass of the cloud (e.g. Scoville et al. 1986; Ikuta & Sofue 1997; Tan 2000). Takahira et al. (2018) performed sub-parsec scale simulations of CCCs of two molecular clouds with different masses and with various collision speeds and investigated the formation of cores. They show the shape of the cumulative core mass function depends not only on the relative velocity of the clouds but also on the cloud mass (i.e. size). The number of massive cores tends to decrease with increasing collision speed and decreasing mass of the colliding cloud. Therefore, a CCC with a higher relative velocity would require higher masses of the clouds to trigger star formation. Even if the collision velocity is the same, collisions between denser molecular clouds are more likely to trigger massive star formation.

In NGC 1300, the cataloged molecular gas mass of the GMC in *bar-end* is significantly larger than in *bar* (Maeda et al. 2020a). Further, a rough estimation of the average density of the GMC, n_{H_2} , shows that n_{H_2} in *bar-end* ($\sim 70 \text{ cm}^{-3}$) is about two times larger than that in *bar* ($\sim 35 \text{ cm}^{-3}$). Here, n_{H_2} is defined as $M_{\text{mol}}/(\frac{4}{3}\pi R^3)$. In fact, Figure 4.7 shows the molecular gas mass of the most massive GMC in each pair in *bar-end* is larger than that in *bar*. Thus, the difference in the molecular gas mass (density) would be cause for the different star formation activity between *bar* and *bar-end* with the same high CCC speed. Recent CCC observations in the Milky Way are consistent with the conclusion of Takahira et al. (2018). Despite the same higher collision speed with $20 - 30 \text{ km s}^{-1}$, CCCs with and without OB stars have been found; In the Sgr B2 and W 43, which are the famous star-burst regions in the Milky Way, CCCs with higher peak column density ($10^{23} - 10^{24} \text{ cm}^{-2}$) are founded (Hasegawa et al. 1994; Grisdale et al. 2018; Kohno et al. 2020). On the other hand, in the central region of the Milky Way, no OB stars are associated with a CCC with lower peak column density ($2 \times 10^{22} \text{ cm}^{-2}$) in M-3.8+0.9 (Enokiya et al. 2019).

Prominent HII regions in barred galaxies are preferentially located in the bar-end regions. In NGC 1300, we see that the collision frequency of the GMCs is higher in *bar-end* than in *arm* based on the estimation of v_{col} and measurement of Δ_v . This result suggests that active star formation is induced by frequent CCCs. Previous observations and simulations toward the bar-end regions proposed the same scenario (e.g. M83; Kenney & Lord 1991, NGC 3627; Beuther et al. 2017, simulations; Motte et al. 2014; Renaud et al. 2015). They proposed that orbital crowding at the bar-end leads to CCC that can form massive molecular complexes and massive stellar associations. Recent observations by Kohno et al. (2020) show that the high collision frequency in the W 43 GMC complex, which is located in the bar-end region of the Milky Way. They argue that converging gas flow from the arm and the bar causes highly turbulent conditions leading to the high frequency.

4.4.3 The cause of the low SFE in the bar region

As described in Section 1, massive star formation in bars of barred galaxies is suppressed. However, physical mechanisms of the suppression are still unclear. Several explanations have been proposed in observational and theoretical studies. Numerical hydrodynamic simulations of a strongly barred galaxy, NGC 5383, suggested that the molecular clouds are destroyed by shock due to the high velocity of the gases which flow into the bar structure (Tubbs 1982). Some hydrodynamic simulations and observations argued that the existence of a high shear probably suppresses the molecular cloud formation (e.g. Athanassoula 1992; Zurita et al. 2004; Emsellem et al. 2015). Observations toward NGC 1530 suggest a combination of the shock and the shear is the cause of the low star formation activity (Reynaud & Downes 1998). It was proposed that gas in the bar regions is efficiently depleted due to the formation of the bar structure (e.g. Spinoso et al. 2017; James & Percival 2018).

Recent studies proposed other scenarios and physical mechanisms that could suppress the star formation fall into the following three scenarios: (*Scenario 1*) Gravitationally unbound molecular clouds in bar regions (Sorai et al. 2012; Nimori et al. 2013). (*Scenario 2*) A large amount of diffuse molecular gases in bar regions (e.g. Muraoka et al. 2016; Yajima et al. 2019; Torii et al. 2019). (*Scenario 3*) High-speed CCCs in bar regions (Fujimoto et al. 2014a). Here, we discuss these scenarios based on previous observations of NGC 1300 (Chapter 2 and 3; Maeda et al. 2020a,b) and the results of this work.

Maeda et al. (2020b, Chapter 3) tested *Scenario 2*. Molecular gas traced by $^{12}\text{CO}(1-0)$ is supposed to consist of two components: GMCs and the extended diffuse component that is distributed on scales larger than sub-kpc (see e.g. Pety et al. 2013; Caldú-Primo et al. 2015; Querejeta et al. 2020). In the SFE calculation using $\text{CO}(1-0)$ emission, the diffuse molecular gas, which would not directly contribute to the current star formation activity, is included in the Σ_{H_2} . Thus, in other words, the diffuse gas greatly contributes to the Σ_{H_2} in the bar regions and that the SFE becomes low in appearance. To examine the relationship between the SFE and the amount of the diffuse molecular gas, Maeda et al. (2020b) measured the diffuse molecular gas fraction, f_{dif} , in NGC 1300. Here, the f_{dif} is defined as $f_{\text{dif}} = 1 - I_{\text{CO}(1-0)}^{\text{ALMA}} / I_{\text{CO}(1-0)}^{\text{tot}}$, where $I_{\text{CO}(1-0)}^{\text{ALMA}}$ is $\text{CO}(1-0)$ flux obtained from the ALMA 12-m array, which has no sensitivity on diffuse (full width at half-maximum $\gtrsim 700$ pc) molecular gases due to the lack of ACA, and $I_{\text{CO}(1-0)}^{\text{tot}}$ is the total $\text{CO}(1-0)$ flux obtained from the Nobeyama 45-m single-dish telescope. Thus, the diffuse molecular gas is defined as a molecular gas that is spread on a scale of 700 pc. They found the environmental dependence of the f_{dif} and that the SFE decreases with increasing in f_{dif} ; The f_{dif} and SFE are $0.74 - 0.91$ and $(0.06 - 0.16) \text{ Gyr}^{-1}$ in *bar*, and $0.28 - 0.65$ and $(0.23 - 0.96) \text{ Gyr}^{-1}$ in *arm* and *bar-end*. This result supports *Scenario 2*. If the low SFE in the bar comes only from the large diffuse molecular gas fraction, recalculated SFEs using the molecular gas excluding the diffuse components (i.e. molecular gas organized inside GMCs) in the bar should be comparable to that in the arm and bar-end. However, the SFE using the molecular gas in GMCs is still significantly suppressed in the bar regions (see Figure. 3.17), which suggests the presence of other causes for the low SFE, besides a large amount of the diffuse molecular gases. There should be mechanisms that control the star formation process in the GMCs and *Scenario 1* and *3* are the candidates.

Maeda et al. (2020a, Chapter 2) investigated whether *Scenario 1* is responsible for the suppression of SFE excluding the diffuse molecular gas in the bar region. Using a resolved GMC sample with $M_{\text{mol}} > 5.0 \times 10^5 M_{\odot}$ and $R > 15$ pc, they investigated environmental dependence of the distribution of the virial parameter, which is a measure for gravitational binding of molecular clouds (Bertoldi & McKee 1992). There is no clear difference in the virial parameter between the GMCs in *bar* and those in *arm* and *bar-end*. This result suggests that the lack of massive star formation in the strong bar of NGC 1300 cannot be explained by a systematic difference of the virial parameter (i.e. second scenario). Note that the virial parameter of the GMCs with smaller masses ($< 5 \times 10^5 M_{\odot}$) are

unknown and additional observations would be required.

In this chapter, we investigated *Scenario 3* and find that the CCC speeds in *bar* and *bar-end* tend to be higher than that in *arm*. As discussed in Section 4.4.2, not only the CCC speed but also the mass (density) of the colliding GMCs is a key parameter that controls the star formation activity of the GMCs. The lower molecular gas mass (density) would be the cause for the different star formation activity between *bar* and *bar-end* with the same high CCC speed. Compared *arm* and *bar*, the molecular gas mass of the colliding GMCs is comparable in both environments (Figure 4.7). Therefore, the higher CCC speed would be the cause for the difference in the star formation activity between *arm* and *bar* with the same molecular gas mass. From this discussion, the cause for the low SFE of the GMCs in the bar regions of strongly barred galaxies would be the high-speed CCCs between lower mass (density) GMCs.

To summarize the discussion, the leading candidates of causes for the star formation suppression in the bar region in NGC 1300 are the presence of a large amount of diffuse molecular gases, which would not contribute to the star formation and makes the SFE low in appearance, and high-speed CCCs between lower mass (density) GMCs, which shorten the gas accretion phase of the cloud cores formed, leading to suppression of core growth and massive star formation.

4.5 Conclusions of This Chapter

Recent simulations proposed that a CCC speed is different among galactic-scale environments, which is responsible for the observed differences in SFE. In particular, it is proposed that a high-speed CCC can suppress massive star formation in the bar regions. To examine this scenario, we investigated the CCC speed and its possible effect on the SFE in the strongly barred galaxy NGC 1300, which is one of the suitable laboratories because the absence of the massive star formation is clearly seen in the bar regions. We used two methods. One is the estimation of the CCC speed based on the mean velocity field of the molecular gas and catalogued line-of-sight velocity of the GMCs. The other is the measurement of the velocity deviation between the GMC and its surrounding GMCs, which is a model-independent observable and a good indicator of the qualitative trends of the CCC speed. Our main results are as follows:

1. We find environmental dependence in the estimated CCC speed. The speed tends to be higher in *bar* ($\sim 20 \text{ km s}^{-1}$) and *bar-end* ($\sim 16 \text{ km s}^{-1}$) than in *arm* ($\sim 11 \text{ km s}^{-1}$) (Section 4.2.3, Figure 4.6, and Table 4.2).
2. The number density of high-speed CCC with $v_{\text{col}} > 20 \text{ km s}^{-1}$ is higher in *bar* and *bar-end* than in *arm*. High number density of high-speed CCC in both *bar* and *bar-end*, where the star formation activity is significantly different, suggests that the existence of other parameters that control triggered star formation (Section 4.2.3, and Table 4.2).
3. The collision frequency is estimated to be $10 - 25 \text{ Gyr}^{-1}$ for all regions. We find that the collision frequencies in *bar* and *bar-end* are about two times higher than that in *arm*. The lack of star formation activity despite the high collision frequency in *bar* suggests that the star formation activity does not control only by the collision frequency (Section 4.2.3 and Table 4.2).
4. We compare the estimated CCC speed with the simulation by Fujimoto et al. (2020), which presented a hydrodynamical simulation of a strongly barred galaxy, using a stellar potential model of NGC 1300. In *bar* and *arm*, the estimated CCC speed are generally comparable to the simulated CCC speed. However, in *bar-end*, the estimated CCC speed ($\sim 20 \text{ km s}^{-1}$) is

- higher than the simulated CCC ($\sim 10 \text{ km s}^{-1}$), which suggests the deviation from the circular motion may be higher in *bar-end* than that expected in the simulation (Section 4.2.4).
5. We find that the velocity deviation in *bar* and *bar-end* are larger than that in *arm*, which is qualitatively consistent with the estimation of CCC speed (Section 4.3, Figure 4.8, and Table 4.3).
 6. One of the other parameters besides the CCC speed that control the star formation process by the CCC may be the mass (density) of the colliding molecular cloud. The significant difference of molecular gas mass (average density) between *bar* (lower mass and lower density) and *bar-end* (higher mass and higher density) may be cause for the different star formation activity despite the same high CCC speed (Figure 4.7 and Section 4.4.2).
 7. Considering the relationship among the molecular gas mass of GMCs, the CCC speed, and star formation activity, one of the causes for the star formation suppression in the bar of NGC 1300 would be the high-speed CCCs between lower mass (density) GMCs. Further, combining our previous observations of NGC 1300 (Chapter 2 and 3; Maeda et al. 2020a,b), we conclude that the leading candidates of causes for the suppression are the presence of a large amount of diffuse molecular gases (*Scenario 2*) and high-speed CCCs between low mass GMCs (*Scenario 3*; Section 4.4.3).

Chapter 5

Summary and Future Prospects

5.1 Summary

To unveil the impact of the galactic environment on the properties of molecular gas and star formation activity, we focus on the nearest strongly barred galaxy NGC 1300 as an ideal laboratory. This is because significant differences in star formation activity are clearly seen in this galaxy. Compared to the arm regions, the (massive) star formation in the bar regions is remarkably suppressed. Thus, the differences in the physical mechanisms that control star formation are expected to be clearly seen in NGC 1300, which leads to our better understanding of the star formation process in galaxies. We carried out the CO observations using ALMA and Nobeyama 45-m telescope to unveil which of the following three scenarios is the most dominant cause for the star formation suppression in the bar regions; *Scenario 1*: Gravitationally unbound molecular clouds in bar regions. *Scenario 2*: A large amount of diffuse molecular gases in bar regions. *Scenario 3*: High-speed CCCs in bar regions. Our main results are as follows;

Examination of Scenario 1 We made $^{12}\text{CO}(1-0)$ observations toward NGC 1300 at a high angular resolution about 40 pc with ALMA 12-m array. We detected CO emissions from the western arm to the bar region. Using the CPROPS algorithm, we identified 233 GMCs (34, 119, and 49 in the western bar, arm, and bar-end regions, respectively) with $S/N > 4$. We compare the GMCs properties among the environments. Based on the two-sided K-S tests, there is a significant environmental variation in the T_{peak} ; the highest value in the bar-end region followed by the arm and bar regions. However, there is hardly any significant variations in GMC physical properties (σ_v , R , M_{mol} , M_{vir} , Σ_{mol} , α_{vir} , and c); a marginally significant difference is only seen in the distribution of M_{mol} between the bar and bar-end regions, and the arm and bar-end regions. It appears that systematic differences in the physical properties of the GMCs are not the cause for the low SFE in the bar region of NGC 1300. In particular, the star formation suppression can not be explained by the scenario that the presence of gravitationally unbound ($\alpha_{\text{vir}} > 2$) GMCs in the bar regions.

Examination of Scenario 2 We investigated the relationship between the SFE and the diffuse molecular gas fraction (f_{dif}) in NGC 1300. The SFE is measured by using Σ_{SFR} derived from archival $\text{H}\alpha$, FUV and, IR data, and Σ_{mol} derived from $^{12}\text{CO}(1-0)$ observations data obtained with the Nobeyama 45-m telescope. We found that SFEs in the bar regions are 5 – 10 times lower than those in the arm and bar-end regions despite the Σ_{H_2} is comparable between both regions in NGC 1300: $(0.06 - 0.16) \text{ Gyr}^{-1}$ in the bar regions and $(0.47 - 0.96) \text{ Gyr}^{-1}$ in the arm and bar-end regions. Our result indicates that the star formation in the bar regions of the

strongly barred galaxies is further suppressed than in the intermediate-type barred galaxies. The f_{dif} is measured using $^{12}\text{CO}(1-0)$ data obtained with the Nobeyama 45-m telescope and with the ALMA 12-m array, which has no sensitivity on diffuse (extended) molecular gases due to the lack of ACA. We found the difference in the f_{dif} among the environments: The f_{dif} is $0.74-0.91$ in the bar regions and $0.28-0.65$ in the arm and bar-end regions. This indicates most of the molecular gas in the bar region exists as the diffuse gas with $\text{FWHM} \gtrsim 700$ pc. Then, we found the SFE decreases toward high f_{dif} , which suggests that the presence of a large amount of the diffuse molecular gases makes the SFE low in appearance.

Furthermore, we found that the SFEs of molecular gas excluding diffuse components (i.e. molecular gas organized inside GMCs) in the bar regions are significantly lower than those in the arm and bar-end regions, which suggests the presence of other causes for the suppression besides a large amount of the diffuse molecular gases. This suggests that the low SFE appears to be caused not only by a large amount of diffuse molecular gases but also by other mechanisms that control the SFE of GMCs except for *Scenario 1*.

Examination of Scenario 3 We investigated the CCC speed in NGC 1300 and its environmental dependence. We used two methods. One is the estimation of the CCC speed based on the mean velocity field of the molecular gas and the cataloged line-of-sight velocity of the GMCs. The other is the measurement of the velocity deviation between the GMC and its surrounding GMCs, which is a model-independent observable and a good indicator of the qualitative trends of the CCC speed. Using the former method, we found environmental dependence in the estimated CCC speed. The speed tends to be higher in the bar region ($\sim 20 \text{ km s}^{-1}$) and the bar-end region ($\sim 16 \text{ km s}^{-1}$) than in the arm region ($\sim 11 \text{ km s}^{-1}$). The number density of high speed CCC with $v_{\text{col}} > 20 \text{ km s}^{-1}$ is higher in the bar and bar-end regions than in the arm region. The latter method also shows that the velocity deviation in the bar and bar-end regions are larger than that in the arm region, which is qualitatively consistent with the estimation of CCC speed.

The high number density of high-speed CCC in both the bar and bar-end regions, where the star formation activity is significantly different, suggests that the existence of other parameters that control triggered star formation. One of the other parameters besides the CCC speed that control the star formation process by the CCC may be the mass (density) of the colliding molecular cloud. The significant difference of molecular gas mass (average density) between the bar region (lower mass and lower density) and the bar-end region (higher mass and higher density) may be cause for the different star formation activity despite the same high CCC speed; high-speed CCCs between lower mass GMCs would make the star formation suppressed in the bar regions in NGC 1300.

Based on the above results, we conclude that there are two leading candidates of causes for the star formation suppression in the bar region in NGC 1300. One is the presence of a large amount of diffuse molecular gases (*Scenario 2*), and the other is high-speed CCCs between low mass GMCs (*Scenario 3*).

5.2 Future Prospects

CCC survey in nearby galaxies

Our study observationally showed that the CCC speed would depend on the galactic environments. To further understand the massive star formation process triggered by the CCC, it is essential to quantify the conditions under which star formation is induced. As described in Chapter 3, the key parameters are (1) collision speed (v_{col}) and (2) GMC mass (M_{GMC}) or molecular gas density of the GMC (ρ_{GMC}). Therefore, it is required to quantify the ranges in which star formation is induced in the parameter spaces of v_{col} , M_{GMC} , and/or ρ_{GMC} . Vigorous observations of the CCCs over the last decade have revealed the relationship among the magnitude of the star formation, v_{col} , and the column density of the colliding clouds (N_{H}) in the Milky Way (Enokiya et al. 2019, Figure 4.1). For the formation of a single massive star, $10^{22} \text{ cm}^{-2} \leq N_{\text{H}} \leq 10^{23} \text{ cm}^{-2}$ and $2 - 10 \text{ km s}^{-1}$ are required, and in the colliding clouds with $N_{\text{H}} \geq 10^{23} \text{ cm}^{-2}$ and $10 - 20 \text{ km s}^{-1}$ more than 10 massive stars tend to form. However, it is unclear whether the relationship in the Milky Way is universal in other galaxies.

To quantify the conditions under which star formation is induced in nearby galaxies, we have two following plans; The first plan is direct CCC observations toward nearby galaxies, which is the same method used in the study of CCCs in the Milky Way. Thanks to ALMA, we can observe GMCs with a high angular resolution ($\sim$ a few pc) and a high-velocity resolution ($\sim$ a few km s^{-1}). One of the targets is NGC 1300 in which environmental dependence in CCC speed is expected by our study. Two GMCs that are currently colliding are in the same line of sight. Therefore, we will extract such pairs of GMCs from the GMC catalog (Appendix D) and target for the ALMA observations. The CCC simulation by Habe & Ohta (1992) shows that several observational signatures are useful for identifying and characterizing a CCC: (1) the displaced complementary distributions of the two clouds, (2) the bridge feature linking them, and (3) the U-shaped cavity. For a pair of GMCs with such signatures, we determine the difference in line-of-sight velocity as the v_{col} and investigate the relationship among v_{col} , $M_{\text{GMC}}(\rho_{\text{GMC}})$, and the presence or absence of associated HII regions. Then, we will compare the results between NGC 1300 and the Milky Way. To increase the sample size, a similar survey will be conducted for other galaxies. In particular, the barred galaxy of M83 is a good laboratory because it is very close to us ($\sim 4 \text{ Mpc}$). Because the M_{GMC} in M83 is larger than that in NGC 1300 (Hirota et al. 2018), CCC can be investigated with a different range of parameters than NGC 1300.

The second plan is applying the CCC speed estimation method used in Chapter 3 to other nearby galaxies. Because the number of colliding GMCs at the current time is about one pair per ~ 50 GMCs based on the estimation in Chapter 3, the sample size by the direct CCC observations will not be large enough to allow for a statistical study. The CCC speed estimation established in Chapter 3 is a powerful method to statistically investigate the connection between the environment, the v_{col} , $M_{\text{GMC}}(\rho_{\text{GMC}})$, and the star formation activity. This method can be applied to general disk galaxies as long as we have the GMC catalog and moment 2nd map of the galaxy. We will apply our method to PHANGS sample, which includes $\sim 100,000$ GMCs toward more than 70 nearby disk galaxies with ALMA (A. K. Leroy et al., in preparation). Since the connection between the environment, the CCC speed, and the star formation activity would depend on the properties of the host galaxy (e.g. the presence or absence of bar structure, bar strength, stellar mass), we aim to unveil the connection between the global properties of galaxies and the CCC properties. Using this CCC survey data, we aim to improve the CCC star formation model. Tan (2000) formulated the star formation activity by the CCC as

$$\Sigma_{\text{SFR}} = \frac{\epsilon f_{\text{sf}} N_A M_c}{t_{\text{coll}}}, \quad (5.2.1)$$

where Σ_{SFR} is the surface density of SFR, $\epsilon = 0.2$ is the total fraction of cloud gas converted to stars during a star-forming collision, f_{sf} is the fraction of cloud collisions which successfully lead to star formation, N_A is the surface number density of clouds, M_c is the cloud mass and t_{coll} is the typical time between collisions. As suggested by Takahira et al. (2014, 2018), the production of star-forming cores in a collision strongly depended on the relative velocity and mass (size) of the clouds. Therefore, f_{sf} should depend on v_{col} and $M_{\text{GMC}}(\rho_{\text{GMC}})$. The simulations by Fujimoto et al. (2014a) assume that collisions between 10 and 40 km s⁻¹ are ideally suited to creating stars and set $f_{\text{sf}} = 0.5$ in this range. Outside this velocity region, they assume $f_{\text{sf}} = 0.05$. This setting can reproduce the low SFE in the barred galaxy (They did not consider the dependence of $M_{\text{GMC}}/\rho_{\text{GMC}}$). However, no observational investigation of f_{sf} has been done yet. Thus, we aim to fit the f_{sf} as a function of v_{col} and $M_{\text{GMC}}(\rho_{\text{GMC}})$ to reproduce the observed Σ_{SFR} , which leads to quantifying the conditions under which star formation is induced by the CCC.

Observation of the evolution process from diffuse molecular gas to GMCs

GMCs form from surrounding diffuse gases and star formation occurs inside the GMCs. Thus, it is necessary to unveil the properties of not only the GMCs but also the diffuse molecular gases. In particular, to further understand the star formation suppression, it is important to investigate why a large amount of diffuse molecular gases exists (i.e. do not become GMCs) in the bar regions. The simulation shows the presence of diffuse gases distributed like filaments with 200-500 pc $\times$ a few kpc (Figure 5.1(a)). However, observational studies of the properties of diffuse molecular gases are still few. Using a high angular resolution CO map with total CO flux of a barred galaxy, we will identify the diffuse molecular gases by masking (removing) the regions identified GMCs. We will measure the spatial distribution of the peak temperature, mass, and velocity width of the CO diffuse emission, and the diffuse molecular gas mass fraction. Then we will compare these values between the arm and bar region. If we find a difference in the diffuse gas mass fraction, physical processes of fragmentation from filaments into GMCs may be different between the bar and arm region. There is a possibility that GMCs are hardly formed due to the high turbulence (i.e. large velocity width) of the diffuse gases. In this case, we will find a significant difference in the velocity width between the arm and bar region. To trace the formation process of the GMCs in the large filaments, it is important to distinguish the low mass GMCs ($\leq 10^5 M_\odot$) from the diffuse components. Although NGC 1300 is an ideal laboratory, it is not close enough to distinguish them. Hence, we will target the nearest barred galaxy M83. Thanks to recent ALMA observations toward M83 (PI: J. Koda, ID:2017.1.00079.S), the highest sensitivity CO(1 – 0) map with a mass completeness limit of $\sim 10^4 M_\odot$ will be created. Using this map, we want to answer why a large amount of diffuse molecular gases exist in the bar regions.

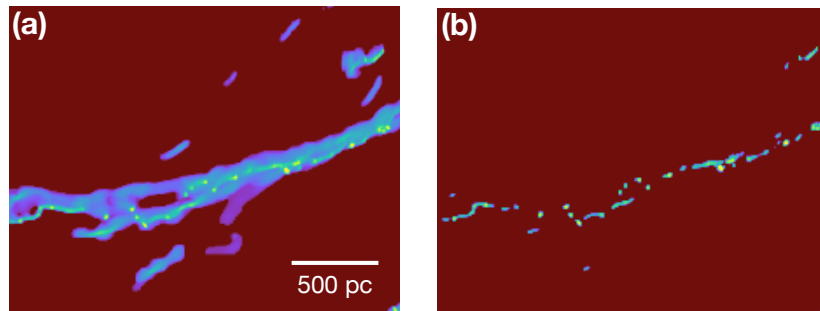


Figure 5.1: (a) Surface gas density of the gas of $\geq 10 \text{ cm}^{-3}$ in the bar regions in the simulation by Fujimoto et al. (2020, Appendix A). (b) Same as (a), but for $\geq 400 \text{ cm}^{-3}$.

Appendix A

A Hydrodynamical Simulation of a Strongly Barred Galaxy

Part of this Appendix has been published as Fujimoto, Maeda et al. 2020, MNRAS, 494, 2131

A.1 Scope of This Appendix

In this appendix, we extend the previous studies of a weakly barred galaxy by Fujimoto et al. (2014b) and Fujimoto et al. (2014a) to the strongly barred galaxy NGC1300 (the V -band image and $^{12}\text{CO}(2-1)$ intensity map are shown in Figure A.1), and investigate the effects of the strong bar on the formation and evolution of GMCs to understand the physical mechanism of the observed lack of active star-forming regions in the strong bar. It is worth emphasizing here that unveiling the cause for the massive star formation suppression is also very important to understand the star formation in high redshift galaxies. For instance, high-speed cloud collisions are expected to happen more frequently in the early universe, then the star formation may be suppressed, which would reduce the overproduction of stars without invoking the various feedback mechanisms proposed.

This appendix is organized as follows. In Section A.2, we present our model of the strongly barred galaxy NGC1300 and discuss details of the three-dimensional hydrodynamical simulation. Section A.3 details our results, discussing first the global evolution of the galactic disk and moving on to exploring cloud properties and cloud-cloud collisions. In Section A.4, we make the discussion of the physical mechanism that causes the unproductive massive star formation in the strong bar more quantitatively by examining the collision frequencies of clouds using clouds' kinematics. Section A.5 presents our conclusions.

A.2 Numerical Methods

A.2.1 The code

The simulations presented in this paper are of an isolated galaxy disk run using the adaptive mesh refinement (AMR) hydrodynamics code ENZO (Bryan et al. 2014; Brummel-Smith et al. 2019). The evolution of the gas is performed using a three-dimensional version of the ZEUS hydrodynamics algorithm (Stone & Norman 1992), which uses an artificial viscosity as a shock-capturing technique with the variable associated with this, the quadratic artificial viscosity, set to the default value of 2.0.

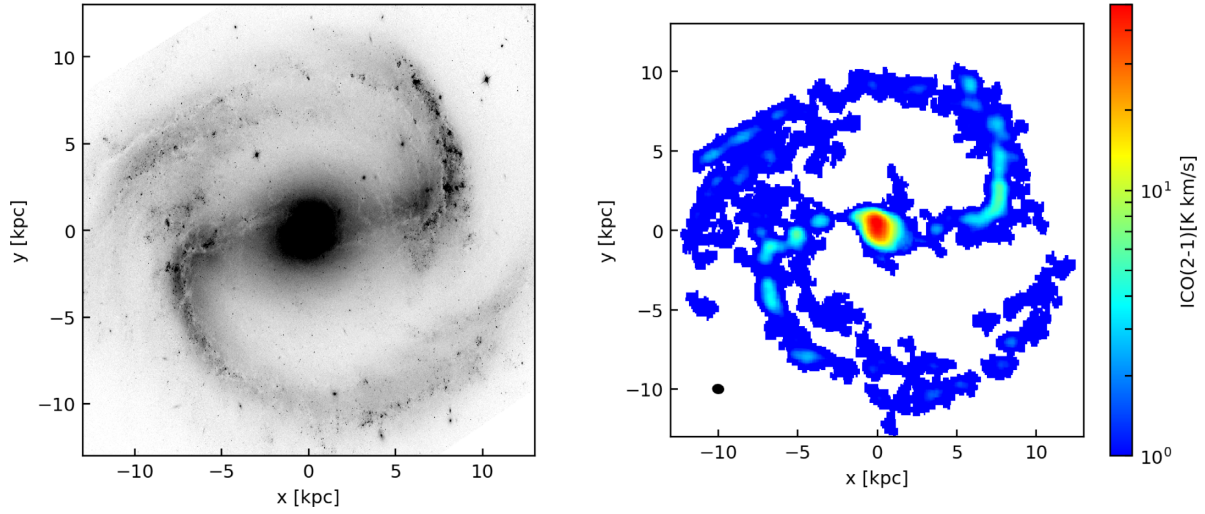


Figure A.1: Face-on views of V-band (F555W filter) image taken with HST (left) and velocity-integrated $^{12}\text{CO}(2-1)$ intensity map (right) corrected for the position angle and inclination of -85.5° and 50.2° (England 1989b), respectively. The V-band image is obtained from the Hubble Legacy Archive (<https://hla.stsci.edu/>). The $^{12}\text{CO}(2-1)$ image is generated from the ALMA archival data under project 2015.1.00925.S as proposed by B. Guillermo et al. We used the significant emission defined as follows: We first identify pixels with $S/N > 4$ in at least two adjacent velocity channels. Next, we grow these regions to include adjacent pixels with $S/N > 1.5$. The beamsize in the face-on view is $766 \text{ pc} \times 645 \text{ pc}$, which is represented as a black ellipse in bottom left corner.

The gas cools radiatively to 10 K using a one-dimensional cooling curve created from the CLOUDY package’s cooling table for metals and ENZO’s non-equilibrium cooling rates for atomic species of hydrogen and helium (Abel et al. 1997; Ferland et al. 1998). This is implemented as tabulated cooling rates as a function of density and temperature (Jin et al. 2017). The Solar values for the metallicity and the dust-to-gas ratio are assumed. In addition to radiative cooling, the gas can also be heated via diffuse photoelectric heating in which electrons are ejected from dust grains via far-ultraviolet (FUV) photons. This is implemented as a constant heating rate of $8.5 \times 10^{-26} \text{ erg s}^{-1}$ per hydrogen atom uniformly throughout the simulation box. This rate is chosen to match the expected heating rate assuming a UV background consistent with the Solar neighbourhood value (Draine 2011). The cosmic ray heating is not considered. Self-gravity of the gas is also implemented.

The galaxy is modelled in a three-dimensional box of $(128 \text{ kpc})^3$ with isolated gravitational boundary conditions and periodic fluid boundaries. The root grid is 128^3 with an additional nine levels of refinement, producing a minimum cell size of $\Delta x = 1.953125 \text{ pc}$. We refine a cell by a factor of 2 whenever the mass included in the cell exceeds $1000 M_\odot$, or whenever the Jeans length, $\lambda_J = c_s \sqrt{\pi/(G\rho)}$, drops below four cell widths, satisfying the Truelove et al. (1998) criterion. To prevent unresolved collapse at the finest resolution level, a pressure floor is implemented that injects energy to halt the collapse once the Jeans length becomes smaller than four cells. Gas in this regime follows a $\gamma = 2$ polytrope, $P \propto \rho^\gamma$. In addition to the static root grid, we impose five levels of statically refined regions enclosing the whole galactic disk of 20 kpc radius and 2 kpc height. This guarantees that the circular motion of the gas in the galactic disk is well resolved, with a maximum cell size of 31.25 pc.

In order to study the formation process of the cold dense clouds formed from the hot/warm diffuse gas, we use a relaxation strategy; in the first 560 Myr, we run the simulation without the cooling nor heating of the gas. The maximum refinement level is seven ($\Delta x = 7.8125 \text{ pc}$). During

this first period, which corresponds to roughly two rotations of the pattern speed, the gaseous galactic structures such as the bar and spiral arms form in accordance with the galactic potential, and the galactic disk then settles into a quasi-equilibrium state. From $t = 560$ Myr, we include the cooling and heating of the gas and additional two levels of refinement ($\Delta x = 1.953125$ pc), that allows the diffuse gas to collapse to the cold dense clouds. In order to focus on the early evolutionary stage of the clouds, we select the snapshot at $t = 600$ Myr when we analyse a single snapshot, and when we discuss time-averaged behaviour, the average is drawn from the time interval between $t = 590 - 610$ Myr. In fact, the median value of our cloud age at $t = 600$ Myr is ~ 5 Myr, which is shorter than the observational estimates of cloud lifetimes (10-40 Myr; e.g. Kawamura et al. 2009; Chevance et al. 2020a).

In order to study the effects of the galactic structures such as the bar on the evolution of the gas clouds alone, there is no star formation or stellar feedback in this simulation.

A.2.2 The structure of the galactic disk

Our galaxy is modelled on the barred spiral galaxy, NGC1300, with the stellar potential and gas distribution taken from observational results. Figure A.1 shows the face-on views of V-band image taken with HST and velocity-integrated $^{12}\text{CO}(2-1)$ intensity map corrected for the position angle and inclination of -85.5° and 50.2° (England 1989b), respectively. To enhance the $^{12}\text{CO}(2-1)$ emitting regions, we show the integrated intensity in the velocity range where the significant CO emission is seen.

Stellar potential

We use 10^6 fixed-motion star particles to create a stellar potential model in keeping with the observed global characteristics of the stellar distribution in NGC1300. This model is based on the work of England (1989a), revised with the Hubble parameter of $H = 73 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and the distance to NGC1300 of $d = 20.7 \text{ Mpc}$. The stellar density, consisting of the disk, bulge, bar and spiral arms, is given by

$$\begin{aligned} \rho_{\text{star}}(r, \theta, z) &= \Sigma(r, \theta)h(z) \\ &= \{\Sigma_{\text{disk}}(r) + \Sigma_{\text{bulge}}(r) \\ &\quad + \Sigma_{\text{bar}}(r) \cos(2\theta) + \Sigma_{\text{arm}}(r) \sin(2\theta)\}h(z), \end{aligned} \quad (\text{A.2.1})$$

where $\Sigma_i(r)$ is the radial distribution of each component and $h(z)$ is the vertical distribution. Each of these are given by

$$\Sigma_{\text{disk}}(r) = \frac{M_{\text{disk}}}{2\pi r_{\text{disk}}^2} \exp\left(-\frac{r}{r_{\text{disk}}}\right), \quad (\text{A.2.2})$$

$$\Sigma_{\text{bulge}}(r) = \frac{M_{\text{bulge}}}{2\pi} \frac{r_{\text{bulge}}}{\left(r^2 + r_{\text{bulge}}^2\right)^{1.5}}, \quad (\text{A.2.3})$$

$$\Sigma_{\text{bar}}(x, y) = \frac{M_{\text{bar}}}{2\pi\sigma_x\sigma_y} \exp\left(-\frac{x^2}{2\sigma_x^2} - \frac{y^2}{2\sigma_y^2}\right), \quad (\text{A.2.4})$$

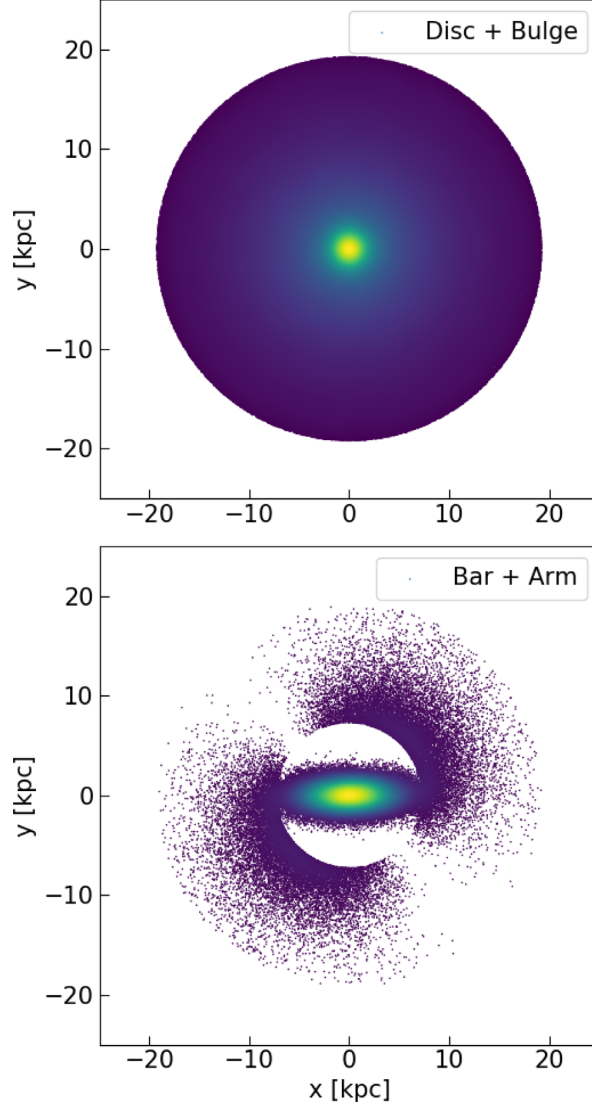


Figure A.2: The stellar component of the galactic potential. Top panel shows the axisymmetric star particle distribution (disk and bulge). Bottom panel shows the non-axisymmetric star particle distribution (bar and arm), which rotates clockwise at a constant pattern speed.

$$\Sigma_{\text{arm}}(r, \theta) = \begin{cases} \frac{M_{\text{arm}}}{2\pi r_{\text{arm}}^2} \exp\left(-\frac{r}{r_{\text{arm}}}\right) \{1 + \sin(2\theta)\} & : r > 7.3 \text{ kpc} \\ 0 & : \text{otherwise,} \end{cases} \quad (\text{A.2.5})$$

where $M_{\text{disk}} = 6.78 \times 10^{10} M_{\odot}$, $M_{\text{bulge}} = 4.0 \times 10^9 M_{\odot}$, $M_{\text{bar}} = 4.0 \times 10^9 M_{\odot}$, $M_{\text{arm}} = 8.3 \times 10^9 M_{\odot}$, $r_{\text{disk}} = 8.4 \text{ kpc}$, $r_{\text{bulge}} = 1.2 \text{ kpc}$, $\sigma_x = 3 \text{ kpc}$, $\sigma_y = 0.34\sigma_x$ and $r_{\text{arm}} = 2.4 \text{ kpc}$. All these parameters are revised using the latest value of the Hubble parameter and the distance to NGC1300. We assume the vertical stellar distribution $h(z)$ is

$$h(z) \propto \text{sech}^2\left(\frac{z}{200 \text{ pc}}\right). \quad (\text{A.2.6})$$

Each star particle has a mass of $8.42 \times 10^4 M_\odot$, giving a total stellar mass of $M_* = 8.42 \times 10^{10} M_\odot$.

Figure A.2 shows the resulting distribution of the star particles. The top panel shows the axisymmetric star particles distribution, and the bottom panel shows the non-axisymmetric star particle distribution, which rotates at a constant pattern speed. We perform test simulations with four different pattern speeds: 16, 18, 20, and 22 $\text{km s}^{-1} \text{kpc}^{-1}$. We select $\Omega = 20 \text{ km s}^{-1} \text{kpc}^{-1}$ for the production run because the size of the gaseous bar formed in the hydrodynamic simulation matches the observational results for NGC1300. In both cases, the distance of the bar-end from the galactic center is 7 – 8 kpc (see Section A.3.1).

The average distance to the neighbouring particle is $\sim 50 \text{ pc}$ at $r = 8 \text{ kpc}$ and $\sim 70 \text{ pc}$ at $r = 16 \text{ kpc}$. To remove the discreteness effects of the star particles, we smooth the particles' gravitational contribution by adding the mass on to the grid at AMR level 3, with a cell size of 125 pc. That is because the star particles should act as an external potential so that the gas feels gravity from the stellar component of the galaxy as a whole. Unlike an N-body galaxy simulation which includes gravitational interactions between particles, our fixed-motion star particles do not interact with each other, and they are put as a gravitational source only for the gas. To treat their gravitational effects as an external galactic potential, we smooth their gravitational contributions at a coarser level of the gas cell (the cell size is 125 pc), rather than putting them at the finest level whose cell size is 2 pc.

Dark matter potential

In addition to the stellar potential, the galaxy sits in a static dark matter halo with an NFW model (Navarro et al. 1996). The halo concentration parameter is set to $c = 0.5$, and the virial mass of the halo (of which the mean density is 200 times the cosmological critical value) is set to $M_{200} = 5.4 \times 10^{10} M_\odot$. These parameters are selected via comparisons between the rotation curve estimated from the stellar and dark matter potential and that from the observational results from NGC1300 (England 1989a). We also compare and roughly match the rotation curve from the simulation with the observational results at around $r > 6 \text{ kpc}$ (see Section A.3.1).

Gas mass

We estimate the H_2 gas mass from the archival $^{12}\text{CO}(2-1)$ data which was observed with ACA (7m + total power) under project 2015.1.00925.S as proposed by B. Guillermo et al. We calibrated raw visibility data using CASA and the observatory-provided calibration script. We imaged the interferometric map using the CLEAN algorithm in CASA by adopting Briggs weighting with robust = 0.5. The resulting image is feathered with the total power image to recover the extended emission. The spatial resolution is $7.6'' \times 4.1''$, corresponding to $760 \text{ pc} \times 410 \text{ pc}$ at the distance of $d = 20.7 \text{ Mpc}$. The rms noise of the data cube is $11.0 \text{ mJy beam}^{-1}$ per 10.0 km s^{-1} bin. The luminosity of the $^{12}\text{CO}(2-1)$ ($L_{\text{CO}(2-1)}$) is $(3.0 \pm 0.3) \times 10^8 \text{ K km s}^{-1} \text{ pc}^2$. The total molecular gas mass is estimated to be $(1.70 \pm 0.78) \times 10^9 M_\odot$ by adopting $\alpha_{\text{CO}} = 4.4 M_\odot (\text{K km s}^{-1} \text{ pc}^2)^{-1}$ (Bolatto et al. 2013) and $R_{21/10} = 0.8$ (Leroy et al. 2009). Combining the H_2 gas mass and the HI gas mass of $(3.72 \pm 0.60) \times 10^9 M_\odot$ taken from the observations by England (1989b), we estimate that the total gas mass in NGC1300 to be $(5.42 \pm 0.98) \times 10^9 M_\odot$.

Initial gas distribution

For the galaxy's radial gas distribution, we assume an initial exponential density profile with a radial scalelength of 8.4 kpc, based on the observations of England (1989a). The initial vertical distribution is assumed to be proportional to $\text{sech}^2(z/z_h)$ with a vertical scaleheight of $z_h = 100 \text{ pc}$.

A.3 Results

The total gas mass of H I and H₂ in the simulation is $5.42 \times 10^9 M_\odot$ as described in Section A.2.2. This gives an initial gas distribution:

$$\rho_{\text{gas}}(r, z) = \rho_0 \exp\left(-\frac{r}{8.4 \text{ kpc}}\right) \text{sech}^2\left(\frac{z}{100 \text{ pc}}\right), \quad (\text{A.2.7})$$

where $\rho_0 = 9.152 \times 10^{-2} M_\odot \text{ pc}^{-3}$. The gas is set in circular motion as calculated via $V_{\text{cir}}(r) = (GM_{\text{tot}}/r)^{1/2}$, where M_{tot} is the enclosed mass of stars, dark matter and gas within the radius r .

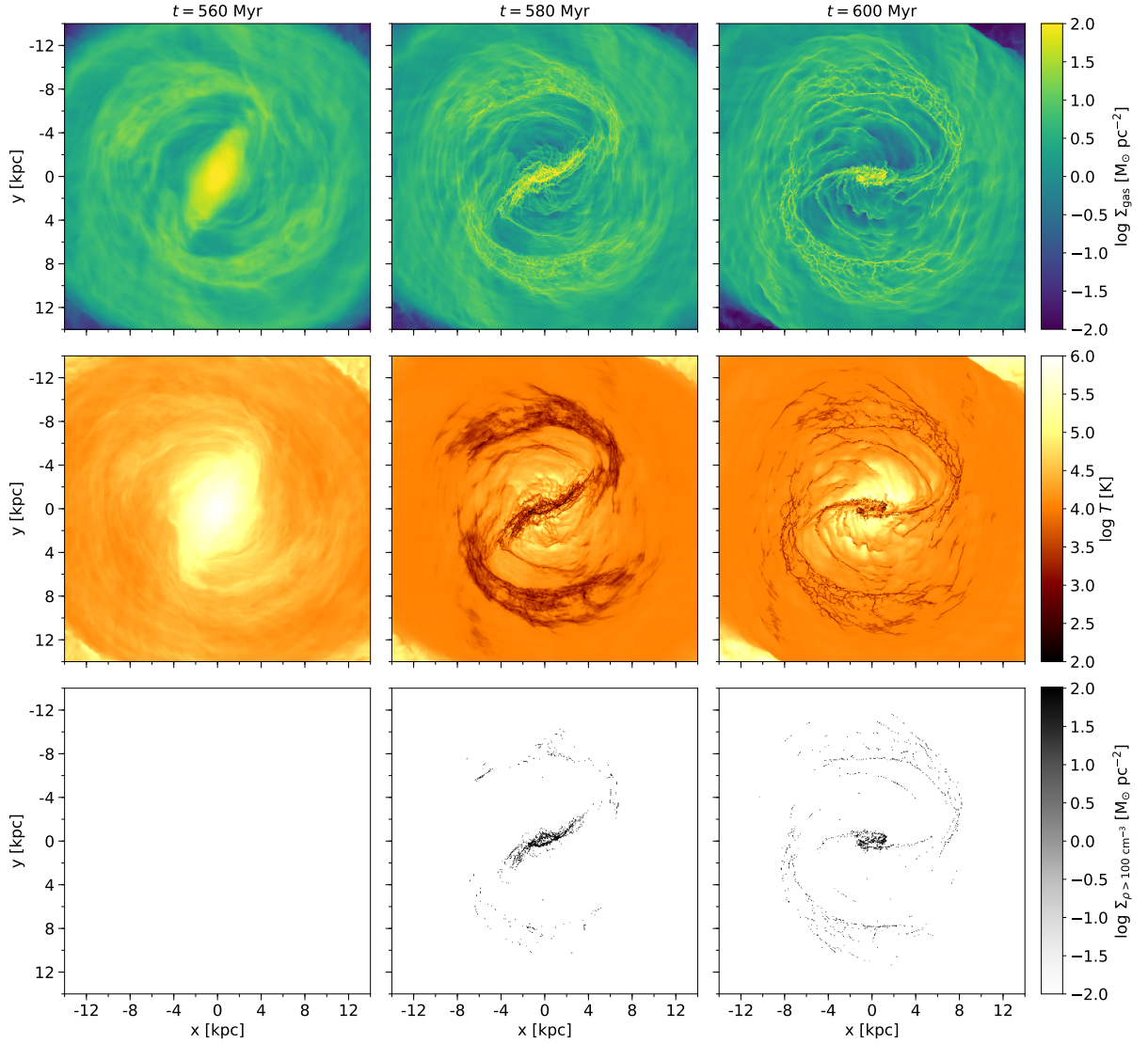


Figure A.3: The global gas distribution in the face-on galactic disk. Left to right, the images show the disk at $t = 560, 580$ and 600 Myr. Top to bottom, the images show the gas surface density, the density-weighted gas temperature and the surface density of dense gas of $\geq 100 \text{ cm}^{-3}$. The galactic disk rotates clockwise.

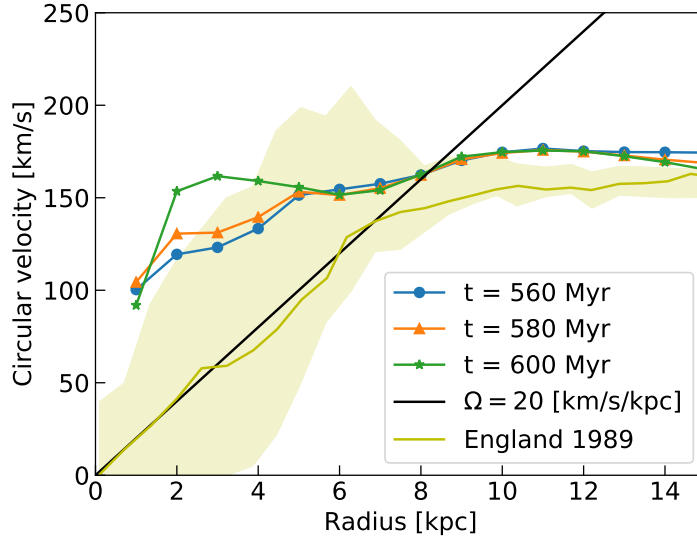


Figure A.4: Azimuthally-averaged radial profiles of the gas circular velocity (mass-weighted average over $-1 < z < 1$ kpc) for the galactic disk at $t = 560, 580$ and 600 Myr. The black solid line shows the constant pattern speed of the non-axisymmetric stellar potential. The dark yellow line shows the observed value from England (1989a), and their errors are shown with a filled area.

A.3 Results

A.3.1 Global structure and disk evolution

In the initial stages of the simulation, the gas profile is smoothly exponential as described in Section A.2.2. As the simulation begins, the gas distribution changes according to the gravitational force by the stellar potential and the self-gravity, and the grand design pattern appears in the gas distribution. After $t = 150$ Myr (a half pattern rotation period), the gaseous bar settles into a quasi-equilibrium with no large structural change. The grand design two spiral arms form and dissipate repeatedly by their outward expansion in a $200 \sim 300$ Myr period.

We include the cooling and heating of the gas from $t = 560$ Myr, and then the gas fragments into knots and filaments. Figure A.3 shows the gas distribution in the galactic disk at three different times: $t = 560, 580$ and 600 Myr. The top row is the gas surface density, the middle is the density-weighted temperature, and the bottom row is the surface density of the dense gas ($\geq 100 \text{ cm}^{-3}$). At $t = 560$ Myr, the galactic gas disk has already been stabilized, and the grand design of the gaseous bar and spiral arms has already formed. The temperature of the gaseous arms is around 10^4 K, while the bar region has much higher temperature because of the shock heating by the strong elliptical gas motion in the stellar bar potential. The dense gas has not yet formed at that time. After the cooling of the gas is included, the gas cools down to several hundred K, and the gas begins to fragment into filaments and to form dense gas clouds as shown in the middle and right panels in Figure A.3.

The global galactic structures of the bar and spiral arms at $t = 600$ Myr are similar to the $^{12}\text{CO}(J = 2 - 1)$ image of NGC 1300 (see the right panel of Figure A.1), with the bar-end at $r = 7 \sim 8$ kpc. The total dense gas mass ($\geq 100 \text{ cm}^{-3}$) is $1.69 \times 10^9 M_{\odot}$, which is consistent with the observed molecular gas mass of $1.7 \times 10^9 M_{\odot}$ as shown in Section A.2.2. The bar and spiral arms rotate in a clockwise sense in the panels with the non-axisymmetric stellar potential.

Figure A.4 shows the radial profile of the mean circular velocity of the gas. This is calculated by using a mass-weighted average over $-1 < z < 1$ kpc. While time-dependent fluctuations are seen

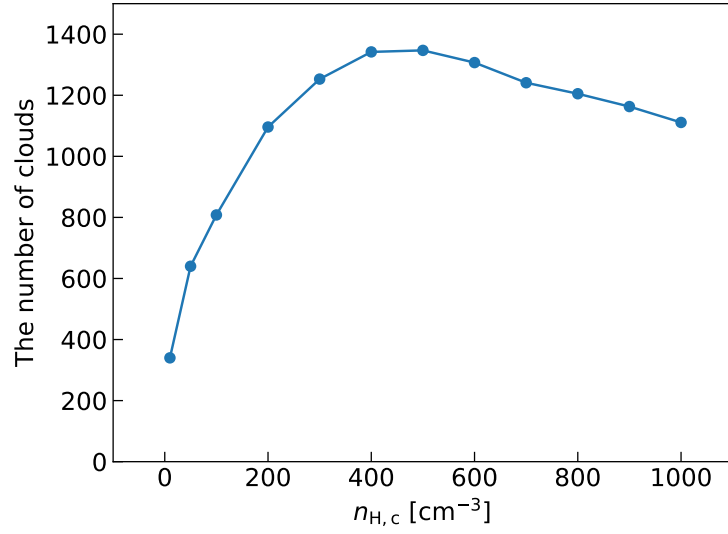


Figure A.5: The total number of clouds identified in the simulated galactic disk, as a function of the threshold number density for cloud definition.

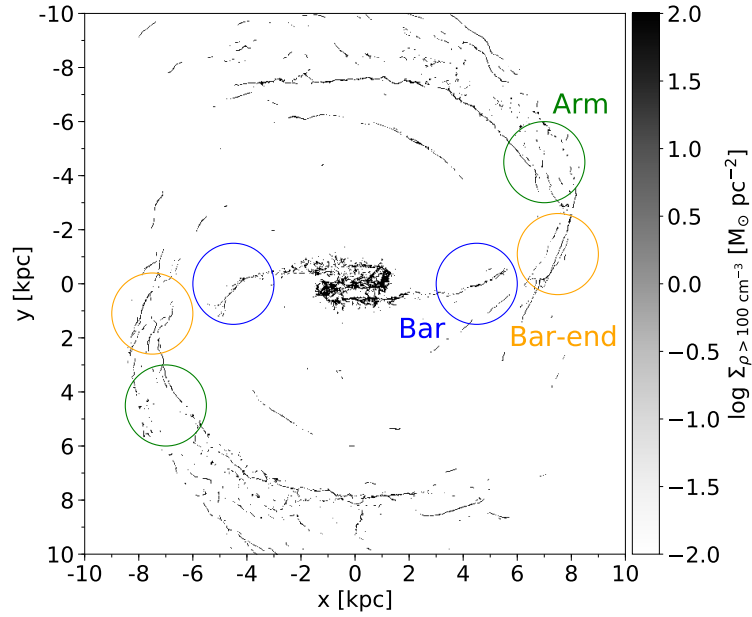


Figure A.6: The three different galactic environments: *Bar* (blue), *Bar-end* (orange), *Arm* (green). Each is a circle which is 3 kpc in diameter. The background color shows the surface density of the dense gas of $\geq 100 \text{ cm}^{-3}$ at $t = 600 \text{ Myr}$.

in the inner region of radius $r < 6 \text{ kpc}$ due to the strong elliptical gas motion inside the bar region, the profile shape remains unchanged in the large radius $r > 6 \text{ kpc}$, keeping the circular velocity $150 \sim 160 \text{ km s}^{-1}$, which is roughly consistent with the observed rotation velocities of NGC 1300 obtained from H I (England 1989a) and $^{12}\text{CO}(2-1)$.

A.3.2 Cloud definition and classification

We define a cloud in our simulation by a connected dense region that is enclosed by a contour at a threshold number density of H atom, $n_{\text{H,c}}$; from the defined clouds in our simulation we exclude small clouds that contain fewer than 3^3 cells, since we cannot properly resolve properties for such small clouds. Previous works have used $n_{\text{H,c}} = 100 \text{ cm}^{-3}$, because it is similar to the mean (volume-averaged) densities of typical Galactic GMCs (Tasker & Tan 2009; Fujimoto et al. 2014b; Li et al. 2018). However, we use a slightly higher threshold density of $n_{\text{H,c}} = 400 \text{ cm}^{-3}$, since we can identify the maximum number of clouds at this threshold density. Figure A.5 shows the number of identified clouds with different threshold densities. When $n_{\text{H,c}} < 400 \text{ cm}^{-3}$, the number of identified clouds increases with increasing the threshold density, since there are clouds that are contained in larger structures at lower threshold densities. On the other hand, when $n_{\text{H,c}} > 400 \text{ cm}^{-3}$, the number of identified clouds decreases with the increase of the threshold density, since relatively diffuse low-density clouds are excluded from the cloud definition. Note that we do not see a significant difference in cloud properties, such as cloud mass and virial parameter (except for cloud radius), between $n_{\text{H,c}} = 100$ and 400 cm^{-3} .

To compare the impact of different galactic environments on cloud properties, we define cloud groups based on the cloud's location in the disk by using three kinds of circles, the *Bar*, *Bar-end* and *Arm*, of which positions at $t = 600 \text{ Myr}$ are shown in Figure A.6. All circles co-rotate around the galactic center with the same pattern speed of the bar and arm potential. In the snapshot at $t = 600 \text{ Myr}$, 99 clouds are in the *Bar* region, 131 are in the *Bar-end* region and 120 are in the *Arm* region.

The three regions are completely different in terms of not only the location in the galactic disk but also the global-scale gas flow. As shown in Figure A.4, the gas in the *Bar* region, where the galactic radius is $\ll 8 \text{ kpc}$, rotates faster than the non-axisymmetric bar potential. On the other hand, the gas in the *Arm* region, where the galactic radius is $\gg 8 \text{ kpc}$, rotates slower than the spiral arm potential. The gas in the *Bar-end* region, where the galactic radius is $\sim 8 \text{ kpc}$, co-rotates with the non-axisymmetric pattern.

A.3.3 Cloud properties

To see the impact of the galactic environment on the cloud formation, we plot the cloud property distributions for clouds in each of our defined regions at $t = 600 \text{ Myr}$ in Figure A.7. The top left panel of Figure A.7 shows the normalized cumulative distribution function of the cloud mass for these three environments, where the cloud mass is calculated by the sum of the total gas mass in each cell belonging to the cloud. In all three cases, the cloud mass ranges from $5 \times 10^3 M_{\odot} < M_{\text{c}} < 5 \times 10^6 M_{\odot}$, and the median values lie at around $M_{\text{c}} \approx 10^5 M_{\odot}$, in reasonable agreement with the GMCs observed in nearby galaxies (e.g. Rosolowsky et al. 2003; Freeman et al. 2017). There is a slight environmental difference between the three regions; the *Bar-end* clouds have the largest fraction of massive clouds, and, on the other hand, the *Bar* clouds have the smallest. However, the difference is no more than 0.3 dex in log-scale.

The top right panel of Figure A.7 shows the normalized cumulative distribution function of the cloud radius. We define the cloud radius as

$$R_{\text{c}} = \left(\frac{3V_{\text{c}}}{4\pi} \right)^{1/3}, \quad (\text{A.3.1})$$

where V_{c} is the cloud volume which is calculated the sum of the cell volumes in the cloud. In all three regions, the median values lie at around $R_{\text{c}} \sim 8 \text{ pc}$, and their shapes of the distribution are

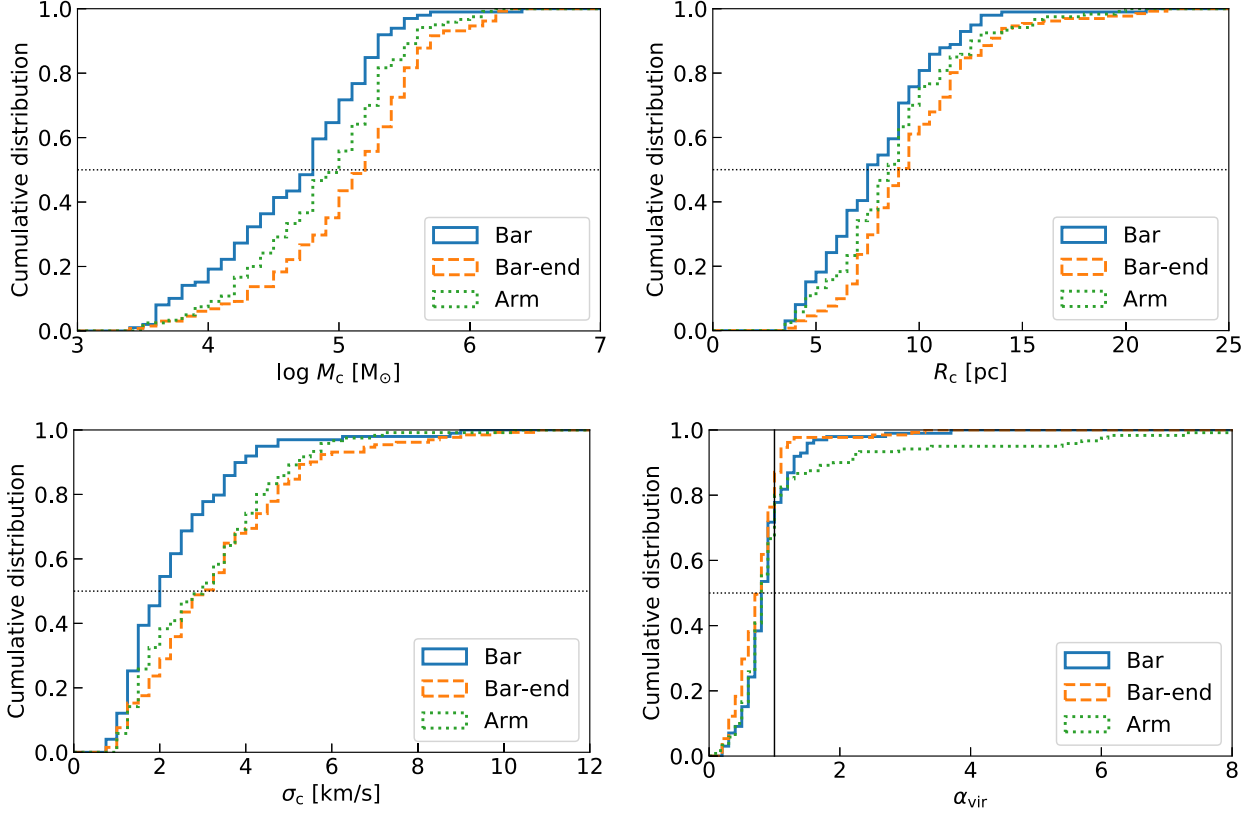


Figure A.7: Normalized cumulative distribution function of cloud masses (top left), radii (top right), velocity dispersion (bottom left), and virial parameters (bottom right).

similar.

The bottom left panel of Figure A.7 shows the normalized cumulative distribution function of the velocity dispersion of the clouds. We define the velocity dispersion as

$$\sigma_c = \sqrt{\sigma_{1D}^2 + c_s^2}, \quad (\text{A.3.2})$$

where σ_{1D} is the mass-averaged one-dimensional velocity dispersion defined as $\sigma_{1D} = \langle \sqrt{|\vec{v} - \vec{v}_{\text{CoM}}|^2/3} \rangle$, where $\vec{v}$ is the velocity of the gas and $\vec{v}_{\text{CoM}}$ is the cloud's center of mass velocity, c_s is the sound speed, and the angle brackets indicate a mass-weighted average over the cells in the cloud. Clouds in the *Bar-end* and *Arm* regions show median values of $\sim 3 \text{ km s}^{-1}$, and the *Bar* clouds have slightly smaller velocity dispersion of $\sim 2 \text{ km s}^{-1}$. This might be because clouds are less massive in the *Bar*. Since the cloud mass is small, their gravitational potential well can be shallow, which could result in failing to catch their surrounding high velocity dispersion gas.

The bottom right panel of Figure A.7 shows the normalized cumulative distribution function of the cloud virial parameter defined as (Bertoldi & McKee 1992),

$$\alpha_{\text{vir}} = \frac{5\sigma_c^2 R_c}{GM_c}. \quad (\text{A.3.3})$$

The distributions show that the median values are around $\alpha_{\text{vir}} \sim 1$, indicating that most clouds are gravitationally bound, and that there is almost no environmental dependence. This result is consistent with Maeda et al. (2020a) who identified GMCs in NGC 1300 by ALMA $^{12}\text{CO}(1-0)$

A.3 Results

Table A.1: The number of cloud-cloud collisions, the number of clouds, the collision frequency per Gyr of clouds in each regions, and the surface density of the estimated SFR assuming that star formation can be triggered only by cloud-cloud collisions, and the observed SFR in NGC1300 (Maeda et al. in preparation).

	<i>Bar</i>	<i>Bar-end</i>	<i>Arm</i>
The number of collisions: n_{ccc} ($t = 590 - 610$ Myr)	28	46	33
The number of clouds: n_{cloud} ($t = 600$ Myr)	99	131	120
Collision frequency: f_{ccc} [Gyr $^{-1}$]	14.1	17.6	13.8
Estimated SFR: Σ_{SFR} [$10^{-3} \text{ M}_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$]	3.38	5.52	2.87
Observed SFR: $\Sigma_{\text{SFR,Obs.}}$ [$10^{-3} \text{ M}_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$]	$\ll 1.0$	3.9 - 4.6	4.7 - 5.9

observations and found that there is no significant variation in the α_{vir} between the arm and bar region. We have shown detailed comparison with the observation in Appendix A.4.3.

We can see a high-end tail of the virial parameter in the *Arm* region. When we make the distributions with smaller regions with 1.5 kpc diameter, the over-all distribution does not change, but the high-end tail disappears, indicating that it appears by chance in the plot. We also check histograms of their properties, and again, we do not find any clearer difference between three regions.

In summary, we do not find any significant dependence of cloud properties on the galactic regions, in particular, the cloud virial parameter. $\alpha_{\text{vir}} \sim 1$ indicates that most clouds are gravitationally bound and that low- and intermediate-mass stars can form in all regions. In terms of massive stars, however, we still cannot explain the observed evidence of the lack of massive star formation in strong bars with the cloud's virial parameters because we find no environmental dependence. In fact, recent ALMA observations also show no significant variation in the virial parameter (Maeda et al. 2020a). Instead, in the following sections, we focus on a cloud-cloud collision, which has been suggested as a triggering mechanism of massive star formation (e.g. Habe & Ohta 1992; Furukawa et al. 2009; Ohama et al. 2010; Fukui et al. 2014, 2016; Fukui et al. 2018; Torii et al. 2017), and look for the cause of the lack of massive stars in strong bars.

A.3.4 Cloud-cloud collisions

To see the impact of galactic environments on the clouds' interactions, we follow the evolution of the clouds, analysing simulation outputs at intervals of 0.2 Myr between $t = 590$ and 610 Myr and mapping the clouds between the outputs with a tag number assigned to each cloud. The algorithm of this cloud tracking is described in Tasker & Tan (2009). We define a collision if we find a single cloud near the positions predicted by two other clouds before 0.2 Myr. Table A.1 shows the number of cloud-cloud collisions occurred in between $t = 590 - 610$ Myr, the number of clouds at $t = 600$ Myr, the collision frequency per clouds per Gyr in each region, the surface density of the estimated SFRs, and the observed ones in NGC1300.

The collision frequency is defined as,

$$f_{\text{ccc}} = \frac{n_{\text{ccc}}}{n_{\text{cloud}} \Delta t}, \quad (\text{A.3.4})$$

where n_{ccc} is the number of collisions, n_{cloud} is the number of clouds, and Δt is the tracking time

of 20 Myr. The collision frequencies are $10 - 20 \text{ Gyr}^{-1}$, which is slightly lower than those in a Milky-Way-type galaxy. Collision frequencies of $30 - 40 \text{ Gyr}^{-1}$ are estimated for Milky-Way-type galaxy simulations (Tasker & Tan 2009; Dobbs et al. 2015). Because the modelling galaxy is different, it is not surprising that we get different collision frequencies. The other possible reason is that our clouds are more compact and smaller because of the higher threshold density for cloud definition, which can make the cross-sections of clouds smaller and then the collision frequencies lower.

We see that there is no significant environmental difference in the collision frequency, suggesting that a frequency of the cloud-cloud collisions does not seem to be the cause of the lack of the massive stars in strong bars in observations.

For a more quantitative discussion, we estimate SFRs assuming that star formation can be initiated only by cloud-cloud collisions and compare the estimates with those of observations. Based on a cloud collision triggered star formation model proposed by Tan (2000), we define the surface density of the SFR as,

$$\Sigma_{\text{SFR}} = \epsilon f_{\text{sf}} \left(\sum_{\Delta t} \sum_A M_{\text{ccc}} \right) / A \Delta t, \quad (\text{A.3.5})$$

where ϵ is the total SFE, f_{sf} is the fraction of cloud collisions which lead to star formation, M_{ccc} is the colliding cloud mass just after the incident, and A is the surface area of each galactic region. For simplicity, we use the default values of $\epsilon = 0.2$ and $f_{\text{sf}} = 0.5$ in Tan (2000).

Again, we do not see a significant environmental dependence as with the collision frequencies. Compared to the observed SFRs in NGC1300 (Maeda et al. in preparation), although the estimates for the *Bar-end* and *Arm* are roughly consistent, the one for the *Bar* is much larger than the upper limit of the observed value; the estimated SFR in the *Bar* is $3.38 \times 10^{-3} \text{ M}_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$, and the observed one is less than $10^{-3} \text{ M}_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$. Fujimoto et al. (2014a) suggested that using the fixed values for ϵ and f_{sf} is too simplistic because not all cloud-cloud collisions should have the same efficiency to form stars, and the efficiency should be changed with properties of the collisions, such as the collision velocity. Hydrodynamical simulations of a cloud-cloud collision have shown that there is a clear dependence of the production rate of massive star-forming cores on the relative speed of the two colliding clouds (Fujimoto et al. 2014a).

We find that there is a clear environmental dependence in the collision speed. Figure A.8 shows the normalized cumulative distribution function of the cloud-cloud collision speed. The samples are the collisions occurred in 20 Myr between $t = 590$ and 610 Myr , as shown in Table A.1. Collisions in the *Bar* have the median of $\sim 15 \text{ km s}^{-1}$ while collisions in the *Bar-end* and *Arm* have $\sim 10 \text{ km s}^{-1}$, which is 5 km s^{-1} smaller than that in the *Bar*. Fraction of collided clouds with collision speed more than 20 km/s is roughly 40 per cent in the *Bar* region, and, on the other hand, less than 10 per cent in the other regions. Such a high-speed cloud-cloud collision can shorten the gas accretion phase of the cloud cores formed, leading to suppression of core growth and massive star formation (Takahira et al. 2014, 2018), suggesting that the fast cloud-collisions is the cause of the lack of massive stars in strong bars.

The fast collisions in the *Bar* do not correlate with cloud mass. Figure A.9 shows the scatter plot between the collision speed and the mass of the most massive cloud in each collision. There is a rough correlation between them in the *Bar-end* and *Arm*, suggesting that the cloud collisions in these regions could be caused by gravitational interactions between clouds. On the other hand, the *Bar* clouds have large scatter. We also investigate correlation between the collision speed and the cloud mass ratio between the colliding partners, and find no correlation between them.

For a more quantitative discussion, we overplot the free-fall speed as a function of cloud mass

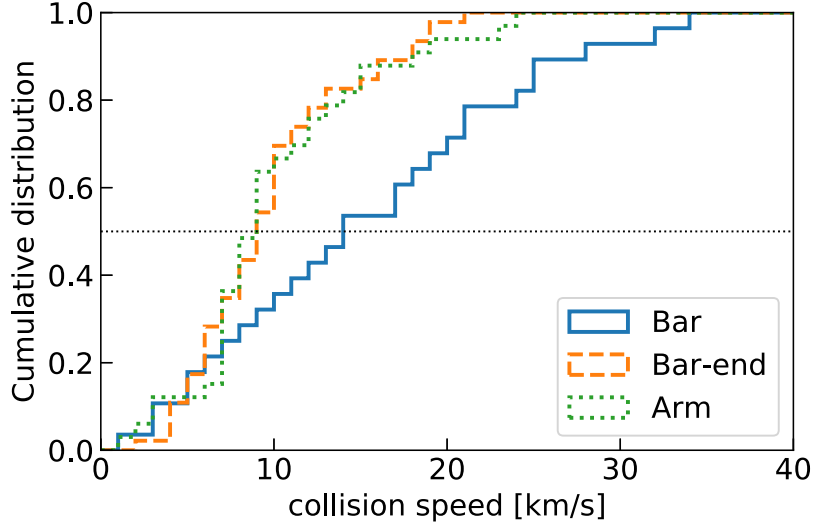


Figure A.8: Normalized cumulative distribution function of the cloud-cloud collision speed. The samples are the collisions occurred in 20 Myr between $t = 590$ and 610 Myr, as shown in Table A.1.

with a black line. The free-fall speed is defined as,

$$v_{\text{ff}} = \sqrt{2GM_c \left(\frac{1}{2R_c} - \frac{1}{D_{\text{nearest}}} \right)}, \quad (\text{A.3.6})$$

where D_{nearest} is the distance to the nearest cloud. For simplicity, we use the median values: $R_c = 8$ pc and $D_{\text{nearest}} = 100$ pc.

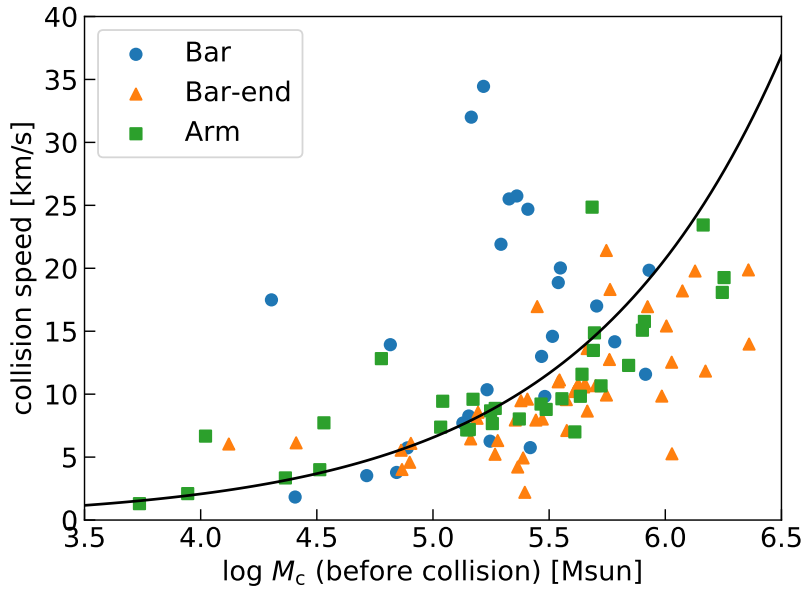


Figure A.9: The scatter plots of the cloud-cloud collision speed versus the mass of the most massive cloud in each collision. The samples are the collisions occurred in 20 Myr between $t = 590$ and 610 Myr, as shown in Table A.1. The black line shows a free-fall speed v_{ff} as a function of cloud mass.

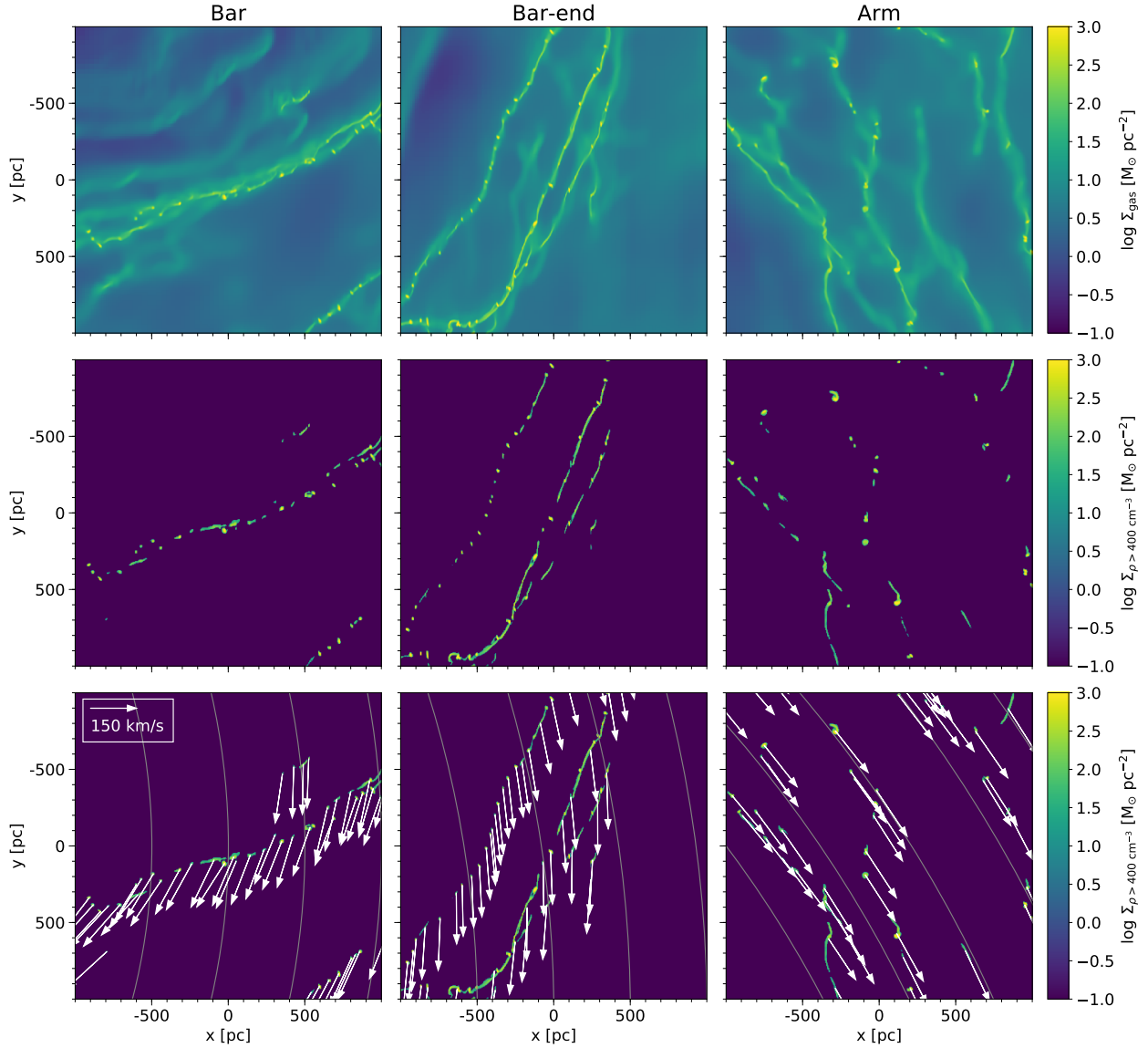


Figure A.10: Zoomed-in on each galactic environments on the right side of the disk at $t = 600$ Myr. Left to right, the images show the *Bar*, *Bar-end* and *Arm* regions. Top to bottom, the images show the gas surface density, the dense gas surface density of $\geq 400 \text{ cm}^{-3}$ and the same plot but overlaid with arrows showing the cloud's bulk projected velocity. The arcs in the bottom images show galactocentric radii at intervals of 500 pc.

It shows that although there is a small deviation, the *Bar-end* and *Arm* clouds roughly fit the free-fall line, supporting the idea of a large contribution of gravitational interactions between clouds to driving collisions. We note that not only gravitational interactions but also other physical mechanism, such as a hydrodynamical drag from the low-density surrounding gas and a coagulation of the ISM around the spiral arm and the resonance point produced by the global galactic potential, could also be the cause of the cloud collisions. That could be the reason we see a small deviation in the scatter plot in those regions.

On the contrary to the *Bar-end* and *Arm*, a large fraction of clouds in the *Bar* region have much faster collision speed than the free-fall speed, indicating that the gravitational interactions have only a small contribution to driving collisions.

We can confirm the origin of the high-speed collisions in the *Bar* region using visual inspection of the galactic disk. Figure A.10 shows 2 kpc patches of the total (top row) and dense (middle and

bottom row) gas surface density in the *Bar*, *Bar-end*, and *Arm* regions. The bottom panels show the projected bulk velocities of the clouds by arrows.

The bottom panels of Figure A.10 show that motion of clouds in the *Bar* region deviates from the galactic circular motion. This is due to the elongated elliptical gas motion shifted by the galactic bar potential. On the other hand, clouds in the *Arm* regions are close to the circular orbit around the galactic center. Clouds in the *Bar-end* are moderate. The elongated motion of the gas in the *Bar* could cause the high speed collisions of clouds, as we have shown that some of the velocity are crossing each other, as seen around at $(x, y) = (-700, 400)$ pc. Such irregular cloud velocities are hardly seen in the *Bar-end* and *Arm* regions. Figure A.11 shows one example of the fast collision occurred in the *Bar* region at $t = 598.8$ Myr. Although most gentle collisions in the *Bar-end* and *Arm* regions occur in filaments, some fast collisions in the *Bar* region are triggered by filament-filament collisions, which is the case shown in this figure. The collision speed is 34.5 km/s, and masses of the colliding clouds are $2.66 \times 10^5 M_\odot$ and $9.55 \times 10^4 M_\odot$. The massive cloud has the internal velocity dispersion of 3.8 km/s and a virial parameter of 0.9 just before collision at $t = -2$ or -1 Myr. During the collision ($t = 0$ Myr), the velocity dispersion and virial parameter increase to 9.6 km/s and 4.3, respectively. After the collision ($t = 2$ Myr), they get back to normal: 4.7 km/s and 0.9.

Lastly, in Figure A.12, we show the normalized cumulative distribution functions of the virial parameter just after cloud-cloud collision. Even though we stated in Section A.3.3 that the virial parameter might not be an important factor for massive star formation, it is still interesting to check the distribution just after collisions because we can see the effects of the high-speed collision on the cloud's internal state. Figure A.12 shows that although there is no difference in the median, the *Bar* clouds have a high end tail which is $\alpha_{\text{vir}} > 2$. It indicates that the high-speed collisions might induce turbulence into the cloud, and then parts of the clouds that had experienced the merger could be gravitationally unbound, that is not suitable for formation of low- and intermediate-mass stars, let alone massive stars.

In summary, we have shown that although there is no significant difference in the cloud's properties such as virial parameter and the frequency of cloud-cloud collision between three galactic regions, the collision speed shows a clear environmental dependence; the *Bar* clouds have $\sim 5 \text{ km s}^{-1}$ higher median value than the other regions. Significant fraction of clouds collides each other with more than 20 km/s in the bar region. The high-speed collisions in the *Bar* originate from the global galactic gas motion; the gas flow is highly elongated by the bar potential, that induces dispersion in the clouds' motion, that can cause violent cloud-cloud collisions. The high-speed collision can make clouds gravitationally unbound, as we have shown that clouds just after merging can have high virial parameters.

A.4 Discussion

A.4.1 The physical mechanism of the fast collision

Here we make the discussion of the physical mechanism that causes the high-speed cloud collisions in the *Bar* region more quantitatively by examining the spatial distributions of clouds and the velocity deviation between the cloud and surrounding gas, and by estimating the collision frequency of clouds assuming that clouds are in random motion.

The top left panel of Figure A.13 shows the normalized cumulative distribution function of the distance to the nearest cloud. Although the difference between regions is only a few tens pc at the median, we see that the *Bar* clouds have a smaller distance to the nearest clouds, indicating that the

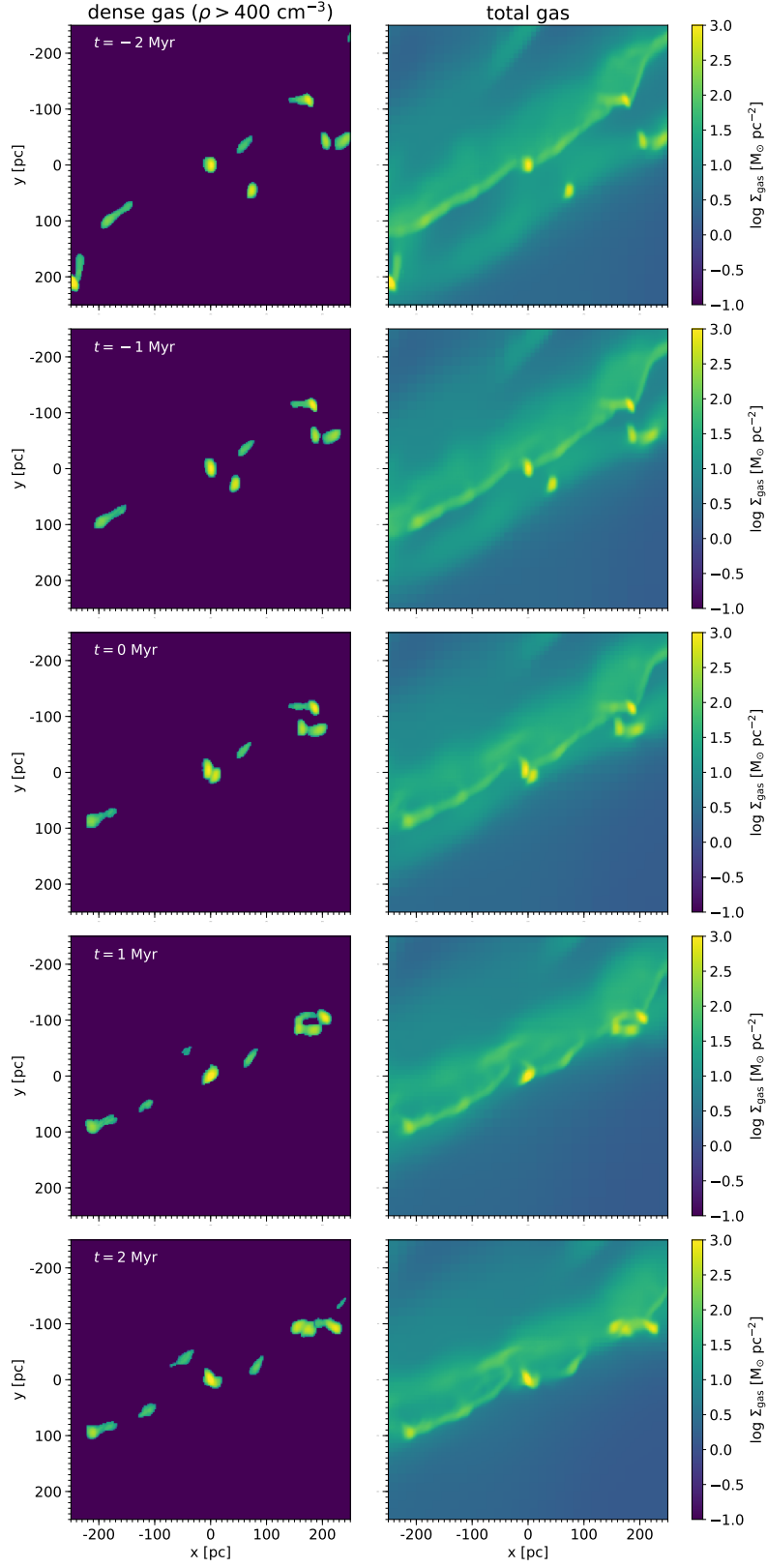


Figure A.11: One example of the fast cloud collision occurred in the *Bar* region. Top to bottom, the images show the time evolution of the collision. Left panels show the dense cloud gas ($\rho > 400 \text{ cm}^{-3}$), and the right panels show the total gas.

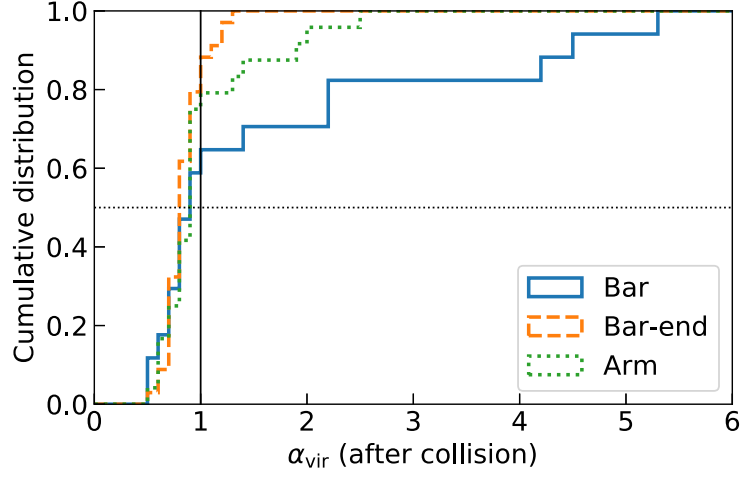


Figure A.12: Normalized cumulative distribution function of the virial parameter of clouds after cloud-cloud collisions. The samples are the collisions occurred in 20 Myr between $t = 590$ and 610 Myr, as shown in Table A.1. The collision whose mass ratio is less than 0.1 is excluded because we do not expect that such a collision can create a compressed shocked region which could possess massive cloud cores.

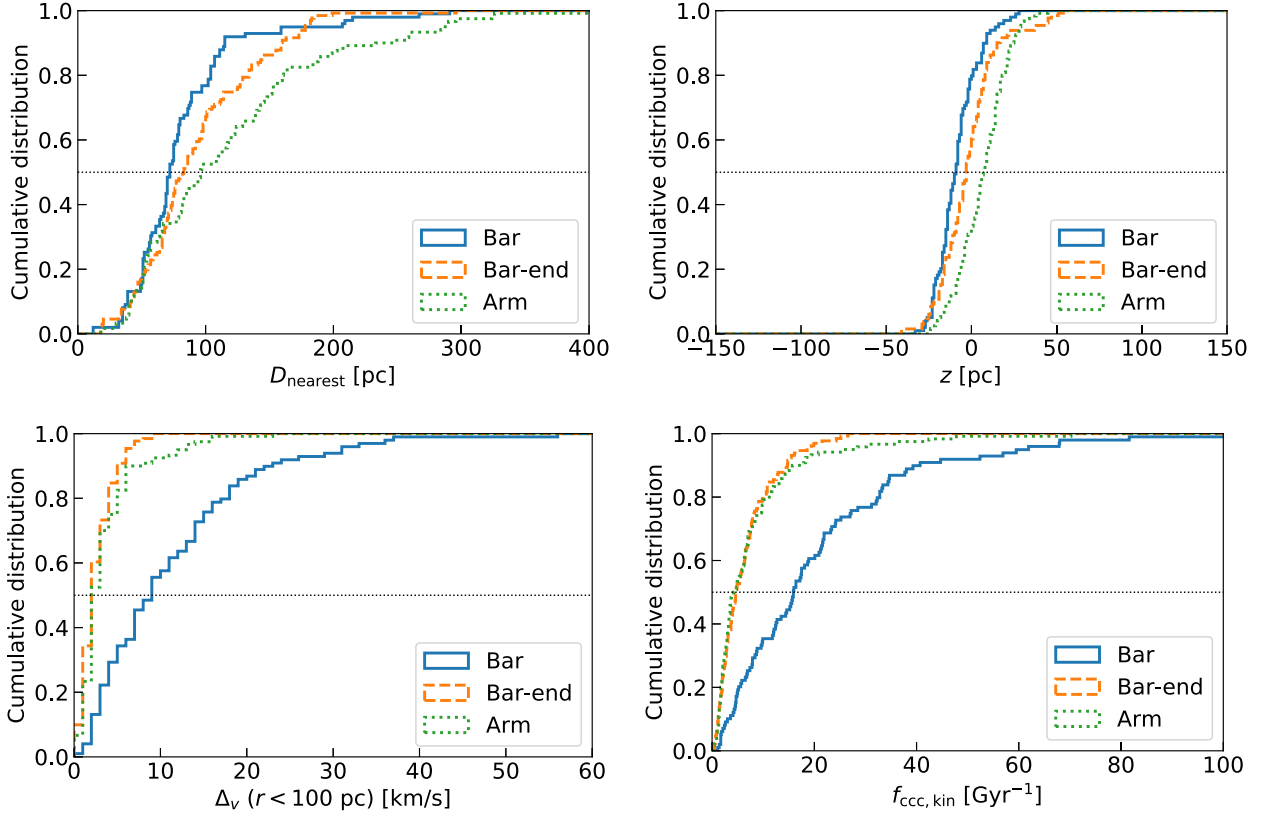


Figure A.13: Normalized cumulative distribution function of the distance to the nearest cloud (top left), the vertical cloud distributions (top right), the velocity deviation between the cloud and its surrounding gas within a radius of $r < 100$ pc (bottom left), and the estimated collision frequency of clouds (bottom right).

spatial distribution of the *Bar* clouds are more crowded and clustered compared to those in other two regions.

The top right panel of Figure A.13 shows the normalized cumulative distribution function of the vertical cloud distributions. We see that almost all clouds lie in the small region between $-30 \text{ pc} < z < 30 \text{ pc}$ around the galactic mid-plane. It indicates that we can neglect the effect of the vertical cloud distribution in discussion of clouds' motion in x - y plane in the following section.

The bottom left panel of Figure A.13 shows the normalized cumulative distribution function of the velocity deviation between the cloud and its surrounding gas within a radius of $r < 100 \text{ pc}$. To calculate velocities of the clouds and its surrounding gas, we use a mass-weighted average over the cells for each. We set a cut-off radius of 100 pc because it is nearly the median of the distance to the nearest cloud, as shown in the top left panel of Figure A.13.

We find that the *Bar* clouds have a substantially higher velocity deviation than the other two regions; the median in the *Bar* is $\sim 10 \text{ km s}^{-1}$, and those in the *Bar-end* and *Arm* are $\sim 2 \text{ km s}^{-1}$. The trend of this environmental dependence is similar to that is seen in the cloud-cloud collision speed, as shown in Figure A.8. It indicates that the galactic region where clouds have a high-velocity deviation can also have fast cloud-cloud collisions. Note that the collision speeds are faster than the velocity deviations. That might be because, in the collision speed plot, we use only clouds which actually collide with others. On the other hand, in the velocity deviation plot, we use all clouds, including those that have low-velocity deviation and are unlikely to collide soon.

Finally, we estimate the collision frequency of clouds using clouds' kinematics. For this estimate, we impose some assumptions. The first is that all clouds have the same spherical shape and size which is much smaller than the average distance between them. The second is that clouds are in constant, rapid, random motion. The third is that clouds undergo random elastic collisions between themselves. The fourth is that except during collisions, the interactions among clouds such as gravity and viscosity are negligible. This model is well known as kinetic theory and often applied to ideal gases. We also assume that clouds move in a two-dimensional plane as we have shown that we can neglect the vertical cloud distributions in the galactic mid-plane. The collision frequency becomes,

$$f_{\text{ccc,kin}} = 2R_{xy}N\Delta_v, \quad (\text{A.4.1})$$

where $R_{xy} = \sqrt{A_{xy}/\pi}$, A_{xy} is the projected area of the cloud in the x - y plane, N is the surface number density of clouds, and Δ_v is the velocity deviation between the cloud and its surrounding gas as defined above. The N and Δ_v are calculated within a sphere whose radius is 100 pc centred at the cloud. To calculate frequencies for every clouds, we use R_{xy} , N , and Δ_v for each cloud. The bottom right panel of Figure A.13 shows the normalized cumulative distribution function of the estimated collision frequency of clouds.

The median frequencies in the *Bar-end* and *Arm* regions are $\sim 5 \text{ Gyr}^{-1}$. They are much lower than the actual frequencies of 17.6 and 13.8 Gyr^{-1} measured by our cloud tracking as shown in Table A.1. It is natural to get this result because the *Bar-end* and *Arm* clouds are in gentle motion, and that the gravitational interactions between clouds seem to have a large contribution to collisions as shown in Figure A.9, which is far different from our assumption that clouds are in rapid random motion and that gravitational interactions among them are negligible.

Surprisingly, on the other hand, the clouds' kinematic estimate seems to work in the *Bar*; the median is $\sim 16 \text{ Gyr}^{-1}$, which is almost consistent with the actual collision frequency of $\sim 14.1 \text{ Gyr}^{-1}$, indicating that their clouds' motion has a large deviation so strong as gravitational interactions can be negligible. It suggests that a random-like motion of clouds induced by the elongated gas stream due to the bar potential could be the physical mechanism of the fast collisions in the *Bar* region.

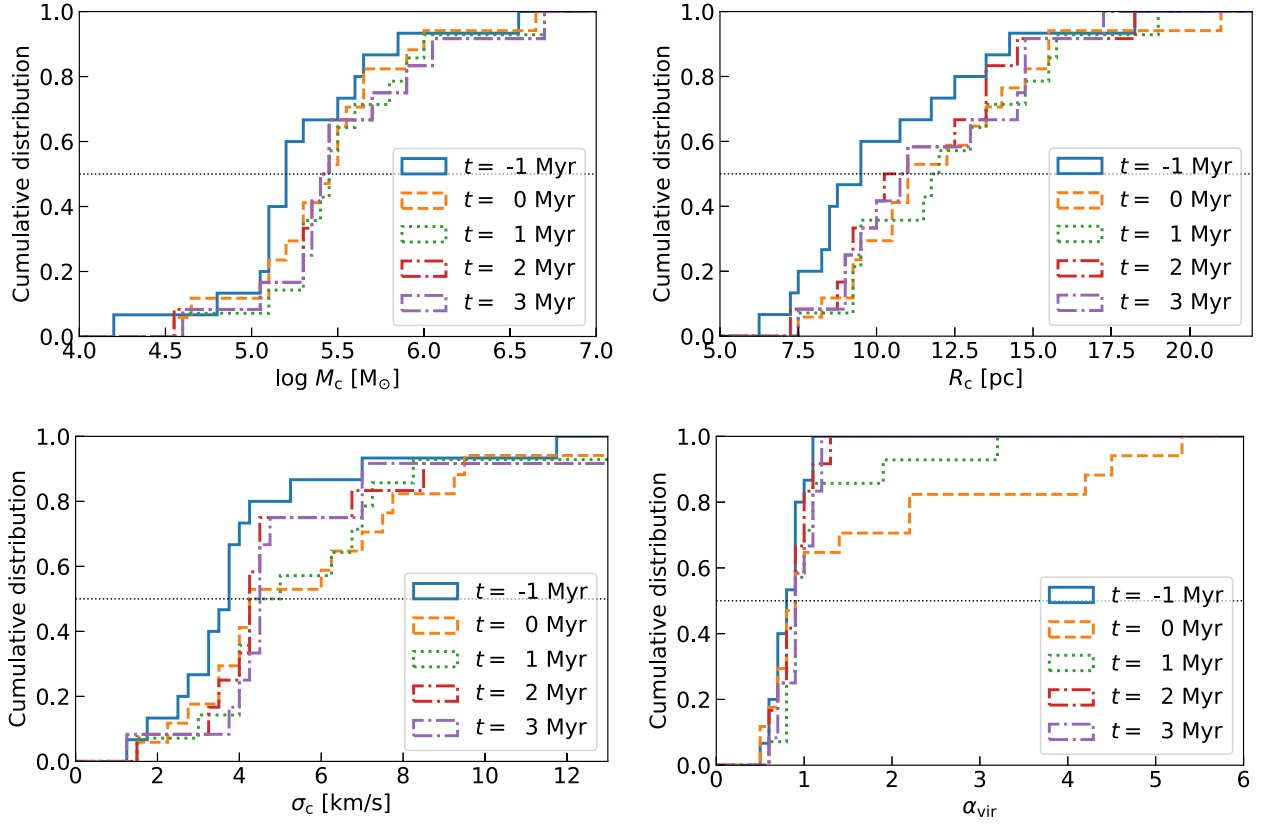


Figure A.14: Time evolution of normalized cumulative distribution functions of cloud masses (top left), radii (top right), velocity dispersions (bottom left), and virial parameters (bottom right) before and after cloud collisions in the *Bar* region. The PDFs are at $t = -1, 0, 1, 2$, and 3 Myr; the time just after collision occurs is set as $t = 0$ Myr. Note that there might be a time lag of at most 0.2 Myr because we analyse simulation outputs at intervals of 0.2 Myr.

A.4.2 Why does not the fast collision affect global distributions of cloud properties?

Here we discuss why the effect of the high-speed collision in the *Bar* region is invisible in the distribution functions of cloud properties; Figure A.7 have shown that there is no significant environmental dependence even though the fast cloud collision, which could inject kinetic energy into clouds and make them gravitationally unbound, should be observable in the velocity dispersion and virial parameter. There are two reasons. The first is that the total number of colliding clouds is too small. As shown in Table A.1, the number of collisions occurred in 20 Myr are $28, 46$ and 33 in the *Bar*, *Bar-end* and *Arm* regions, respectively. It indicates that the number of collisions we could find in a one-time snapshot (assuming that the duration is 1 Myr) are only $1.4, 2.3$, and 1.65 , respectively. These numbers are much smaller than the total number of clouds at $t = 600$ Myr; the number fractions of the colliding clouds are less than 0.02 .

The second reason is that the effects of the collision do not last for long time; the excited internal gas motion induced by the collision decays quickly within a few Myr. We have investigated the time evolution of cloud properties before and after they collide. Figure A.14 shows the cumulative distribution function of the cloud mass, radius, velocity dispersion, and virial parameter at $t = -1, 0, 1, 2$, and 3 Myr (here, $t = 0$ Myr is set as the time just after they collide). To see an extreme case, the plots shows only the *Bar* regions where the collision speed is the fastest. Looking at cloud mass

and radius distribution, we see that the median values slightly increase just after collision, and they do not get back to the initial value within 3 Myr after the collision. It indicates that the collision forms bigger clouds rather than splitting them into smaller clouds or dispersing the clouds to diffuse ambient gas. Looking at the velocity dispersion, on the other hand, we see a significant increase just after collision, and then they get back to the values close to the initial. The behavior of the virial parameter is similar to the one of the velocity dispersion; 40 per cent of colliding clouds becomes highly unstable after collision, but they return to marginally gravitational bound within at most 2 Myr because of the decay of the excited internal gas velocity dispersion. For those two reasons, it is reasonable that we hardly see the effects of the fast cloud-cloud collisions on global distributions of cloud properties, in particular, the velocity dispersion and virial parameter.

We emphasize that even though the number fraction of colliding clouds we find in a one-time snapshot looks low, the SFR estimated with the assumption that star formation is triggered only by cloud-cloud collisions is roughly consistent with the observations of NGC1300 (except for the *Bar* region, as we discussed in Section A.3.4), indicating that the number of collisions is enough to explain the observed star formation activities.

A.4.3 Cloud properties: comparison with observations

We compare the cloud properties with the observational results of the same galaxy of NGC1300 done by Maeda et al. (2020a). They had done $^{12}\text{CO}(1-0)$ observations toward the western bar, arm and bar-end regions with ALMA 12-m array with a beam size of ~ 40 pc. With identification of GMCs using the CPROPS algorithm, they found that there was virtually no significant variations in GMC properties among the galactic regions.

Figure A.15 shows direct comparisons between simulated and observed clouds. Over all, the simulation and observation have the same qualitative features as regards environmental dependence of cloud properties; there is no significant systematic difference between three galactic regions. However, looking at the mean values, there is quantitative difference between simulation and observation. The cloud masses and radii in the simulation are lower than those in the observation; the difference can be one order of magnitude for mass and at least a factor of six for radius.

The situation gets better if we use the same selection criteria used for the observed clouds. In the observation, the mass completeness limit was estimated to be $2.0 \times 10^5 M_{\odot}$, and the mass limit for resolved samples was $5.0 \times 10^5 M_{\odot}$ (see Section 5 in Maeda et al. 2020a). Therefore, the observed cloud samples were selected with $M_c > 2.0 \times 10^5 M_{\odot}$ for masses and velocity dispersion, and with $M_c > 5.0 \times 10^5 M_{\odot}$ for radii and virial parameters. Figure A.16 shows the same normalized cumulative functions of cloud properties, but the simulated clouds are selected with the same selection criteria which are used for the observed clouds. The mean masses for the simulated clouds get close to those for the observed clouds, although the simulated clouds are still smaller and less massive.

Having a systematic difference between simulation and observation is not surprising because the spatial resolution of the ALMA observation is at most 40 pc, which is much larger than the 2 pc resolution of this simulation. The low resolution in the observation could cause non-detection of small clouds or merging smaller clouds to a connected larger structure. We should also mention that the simulated clouds can be relatively small due to the slightly high threshold density of $n_{\text{H,c}} = 400 \text{ cm}^{-3}$ for cloud definition. For those reasons, the simulation and observation might be looking at somewhat different objects; it is possible that some observed clouds could be associations which consist of diffuse ambient molecular gas and/or multiple clouds, and, on the other hand, the simulated clouds could be each dense clumps of which the association consists. For a more complete comparison, there are many things we should do; e.g. we need to convolve the simulation with

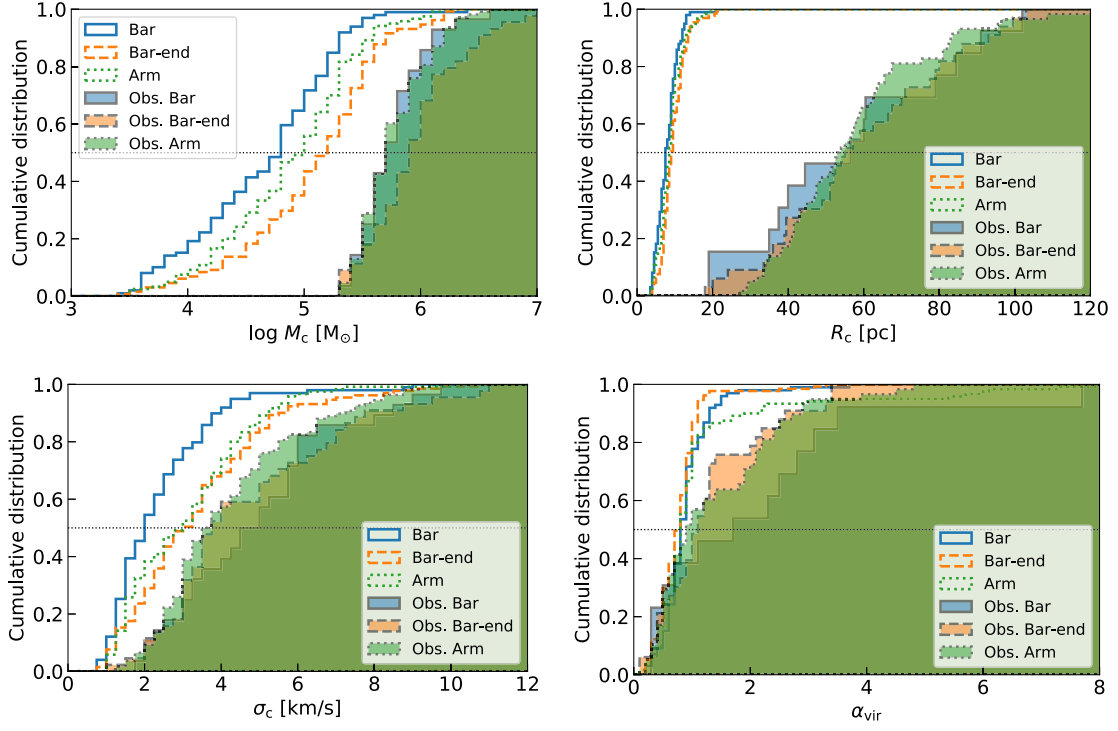


Figure A.15: Normalized cumulative distribution function of cloud masses (top left), radii (top right), velocity dispersion (bottom left), and virial parameters (bottom right), with the observed clouds in the same galaxy of NGC1300 observed by Maeda et al. (2020a). Note that the beam size is 40 pc, and the mass completed limit is $2.0 \times 10^5 M_\odot$ for the observed samples.

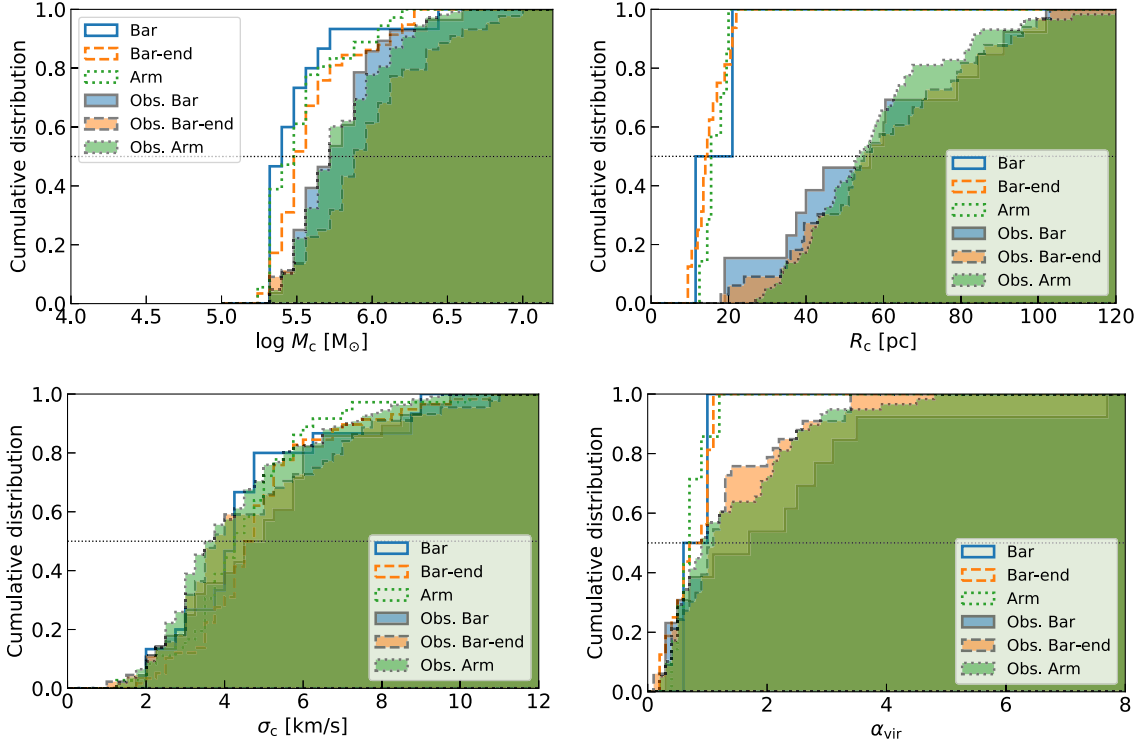


Figure A.16: Same as Figure A.15, but showing the simulated clouds with $M_c > 2.0 \times 10^5 M_\odot$ for cloud masses and velocity dispersion, and with $M_c > 5.0 \times 10^5 M_\odot$ for cloud radii and virial parameters, which are the same selection criteria used for the observed clouds.

the beam size of the observation and fine-tune the threshold density for the cloud definition, as mentioned above. We should also consider the method for cloud identification, which is currently different between observation and simulation: the cloud in the simulation is identified as a coherent structure contained within a contour at the threshold density no matter how many density peaks exist within the cloud, but the observed cloud splits up into multiple clouds when there are multiple density maxima. Moreover, post-processing of the simulation data for a chemical transition from atomic gas to molecular gas or radiative transfer to calculate the CO emission might be needed as well.

With regards to internal velocity dispersion, the difference between simulation and observation is minimal, in particular, in the case we impose the selection criteria of $M_c > 2.0 \times 10^5 M_\odot$, as shown in Figure A.16. That might be because we calculate a mass-weighted velocity dispersion for simulated clouds, so that the ambient low density gas surrounding the denser parts of the clouds hardly affects the over-all value of the velocity dispersion. As a results, we get the virial parameter for the simulated clouds close to those for the observation, as shown in both Figure A.15 and Figure A.16.

A.5 Summary of the Simulation

Bars of the strongly barred galaxies show an absence of prominent HII regions even though there are remarkable dust lanes and molecular gas along the stellar bar. The physical mechanism that prevents gas clouds from forming massive stars is still debated. To address this question, we have performed a hydrodynamical simulation of the strongly barred galaxy NGC1300. Our main results are as follows.

1. We compare the cumulative distribution functions of cloud properties such as mass, radius, internal velocity dispersion, and virial parameter. We find no significant environmental dependence, in particular, in the virial parameter (Figure A.7). It appears that the observational lack of massive star formation in the strong bar cannot be explained by a systematic trend of clouds which are gravitationally unbound.
2. Instead, the relative speed of cloud-cloud collisions shows a clear environmental dependence; the *Bar* clouds collide with others faster than those in the other regions (Figure A.8). It suggests that the observational lack of massive star formation in the strong bar is caused by fast cloud-cloud collisions, which are inefficient in forming massive stars. The fast collisions result in producing clouds whose virial parameters are extremely high just after the collision ($\alpha_{\text{vir}} > 2$; Figure A.12).
3. The high-speed collisions originate from the galactic-scale elliptical gas motion elongated by the stellar bar potential (Figure A.10). The elongated gas motion induces irregular motion of the ISM and makes the velocity deviations between clouds high in the *Bar* region (Figure A.13).
4. We estimate the collision frequency of clouds using the clouds' kinematics and compare it with the actual frequency measured with cloud tracking. The estimated frequency of the *Bar* cloud is consistent with the actual frequency (Figure A.13 and Table A.1), indicating that the high-speed collisions in the *Bar* can be explained by the random-like motion of clouds due to the galactic-scale violent gas motion.

From these results, we conclude that the physical mechanism that causes the lack of massive star forming regions in the bar of strongly barred galaxies is the high-speed cloud-cloud collisions due to the elongated global gas motion by the stellar bar. For further understanding, we will include stellar feedback to our simulations and compare with high-resolution observations in future work.

Appendix B

CPROPS bias on the GMC properties

CPROPS corrects for the sensitivity by extrapolating GMC properties to those we would expect to measure with perfect sensitivity (i.e. 0 K). As described in section 2.4.2, the extrapolated R , σ_v and L_{CO} is typically 1.5 ~ 2.0 times higher than the directly measured values. CPROPS also corrects for the resolution by deconvolution for beam and channel width. The corrected R , σ_v is typically by a factor of 0.7 ~ 0.8 lower than the extrapolated values. Since the accuracy of these corrections (extrapolation and deconvolution) depends on the sensitivity, spatial resolution and velocity resolution (Rosolowsky & Leroy 2006), it is necessary to assess the reliability of the measurements of GMC properties.

Using CASA, we simulated ALMA observation of mock GMCs, which are three-dimensional Gaussian clouds with a given M_{mol} , R , and σ_v in a position-position-velocity space. We create a fits image with 100 mock GMCs centered in fixed positions. The M_{mol} , R , and σ_v are randomly determined in the range of $5.3 \leq \log(M_{\text{mol}}/[M_{\odot}]) \leq 6.8$, $1.5 \leq \log(R/[\text{pc}]) \leq 2.2$, and $0.3 \leq \log(\sigma_v/[\text{km s}^{-1}]) \leq 1.1$, respectively. The GMCs are round clouds (i.e. axis ratio = 1.0). Here, we assume the CO-to-H₂ conversion factor of $4.4 M_{\odot} (\text{K km s}^{-1} \text{ pc}^2)^{-1}$. Then, using the task of `simobserve` in CASA, we simulate observation under the same configuration, pointings, and noise condition of our ALMA observations (see Section 2.2). After reconstructing the image with the same `tclean` parameters (see Section 2.2), we identify the GMCs using CPROPS with the same settings described in section 2.4. We repeated this procedure 12 times, and then we extracted the GMCs with $4 \leq \text{S/N} \leq 10$, corresponding to the observed value.

Fig. B.1 shows the results of this simulation. The superscript *in* denotes the input value of the mock GMC and *out* denotes the output value CPROPS measured and corrected. We plot the ratio of output value to input value as a function of input value for σ_v , R , and M_{mol} , dividing GMCs into lower S/N ($4 \leq \text{S/N} < 7$) and higher S/N ($7 \leq \text{S/N} \leq 10$). In panel (a), we find CPROPS measurements work well for the GMCs whose σ_v^{in} is larger than 5.0 km s^{-1} . However, for the GMCs with $\sigma_v^{\text{in}} \leq 5.0 \text{ km s}^{-1}$, CPROPS overestimates σ_v by a factor of ~ 1.5 regardless of S/N.

According to Rosolowsky & Leroy (2006), the extrapolation works well regardless of the S/N, if the line width of the identified GMC is at least twice the channel width. In Fig. B.2, we plot the $\sigma_v^{\text{out}}/\sigma_v^{\text{in}}$ as a function of the ratio of the velocity dispersion without CPROPS correction (σ_v^{obs}) to channel width ($\sigma_{\text{ch}} = \sqrt{\Delta V_{\text{chan}}^2/2\pi} = 2.0 \text{ km s}^{-1}$). We find that the σ_v^{out} is overestimated by a factor of ~ 1.5 if the σ_v^{obs} is less than half the channel width. Such GMC accounts for 56 %, 64 %, and 64 % in *Bar*, *Arm*, and *Bar-end*, respectively. Therefore, a large number of the cataloged GMCs may be overestimated in the σ_v by a factor of ~ 1.5 .

The CPROPS algorithm performs relatively well for the measurements of the M_{mol} and R in comparison to σ_v . In panel (b), we find CPROPS slightly underestimate radius: the R^{out} is typically

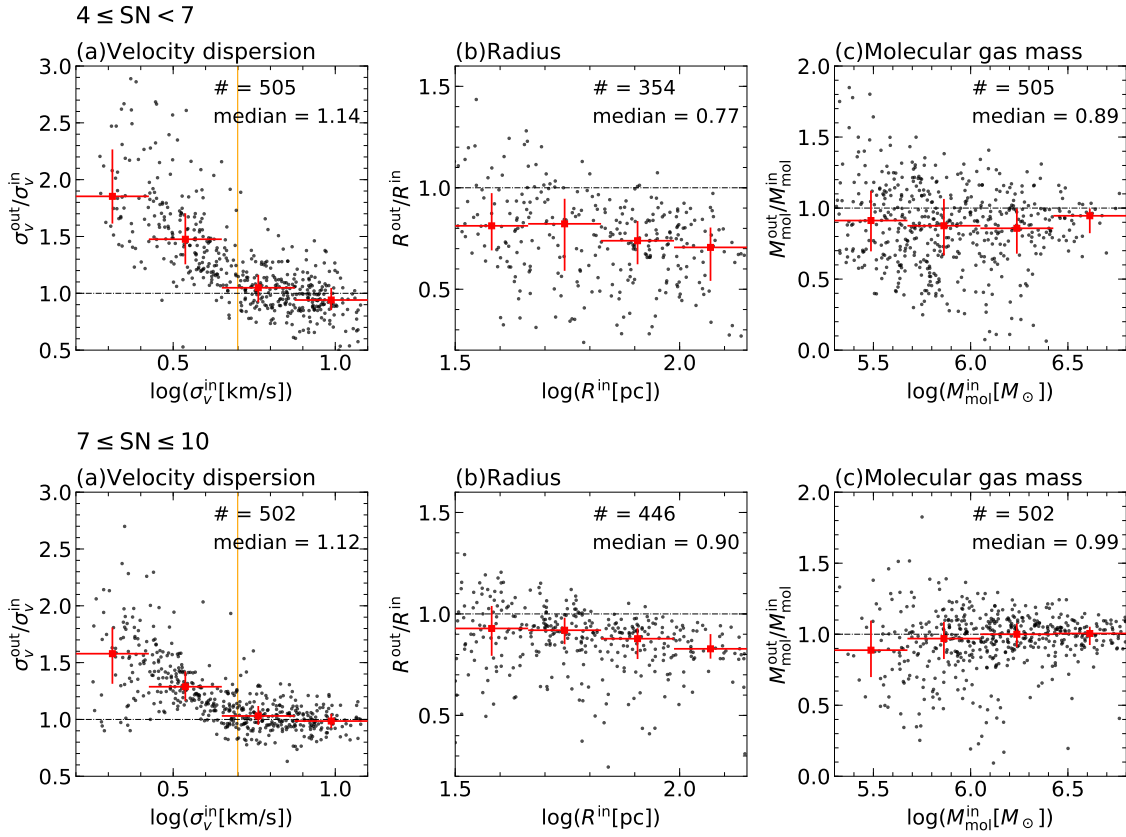


Figure B.1: Results of the ALMA observation simulation of the mock GMCs. (a): Ratio of the output velocity dispersion by CPROPS (σ_v^{out}) to the input (model) velocity dispersion (σ_v^{in}) as a function of the σ_v^{in} . We show the GMCs with lower S/N ($4 \leq \text{S/N} < 7$) and higher S/N ($7 \leq \text{S/N} \leq 10$) in upper and lower panel, respectively. Red square shows the median value in a bin whose range is shown as error bar in x-axis, and a error bar in y-axis shows the ΔQ in the bin. Orange solid line shows the channel width of 5.0 km s^{-1} . Black dash-dotted line shows $\sigma_v^{\text{out}}/\sigma_v^{\text{in}} = 1.0$. (b), (c): Same as panel (a) but for radius and molecular gas mass.

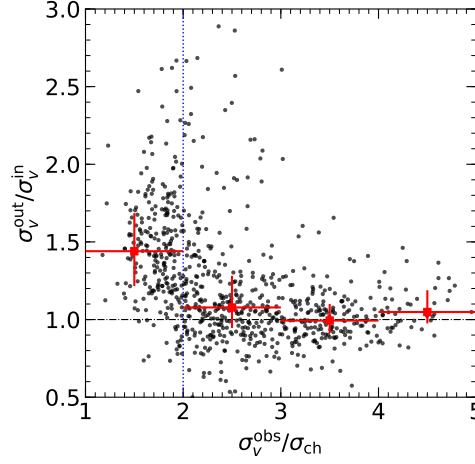


Figure B.2: Ratio of the output velocity dispersion by CPROPS (σ_v^{out}) to the input (model) velocity dispersion (σ_v^{in}) as a function of the ratio of the velocity dispersion without CPROPS correction (σ_v^{obs}) to channel width ($\sigma_{\text{ch}} = \sqrt{\Delta V_{\text{chan}}^2/2\pi} = 2.0 \text{ km s}^{-1}$). Red square shows the median value in a bin whose range is shown as error bar in x-axis, and a error bar in y-axis shows the ΔQ in the bin. Black dash-dotted line shows $\sigma_v^{\text{out}}/\sigma_v^{\text{in}} = 1.0$. Blue dotted line shows $\sigma_v^{\text{obs}}/\sigma_{\text{ch}} = 2.0$.

underestimated by a factor of ~ 0.8 and ~ 0.9 for the GMC with lower S/N and higher S/N, respectively. In panel (c), the corrected M_{mol} is mostly equal to the input M_{mol} for the GMC with higher S/N, but the corrected M_{mol} is typically underestimated by a factor of ~ 0.9 for the GMC with lower S/N. Because about 70 % of the cataloged GMCs were detected with $4 \leq \text{S/N} \leq 7$, R and M_{mol} may be slightly underestimated by a factor of ~ 0.8 and ~ 0.9 . Note that the factors of over/underestimation do not change if the GMC's minor-to-major axis ratio is set to be 0.5.

These over/underestimation can propagate to the measurements of $M_{\text{vir}}, \Sigma_{\text{mol}}, \alpha_{\text{vir}}$, and c , which are a combination of σ_v , R , and M_{mol} . Thus, we recalculated the GMC properties. We corrected the cataloged σ_v by dividing by 1.5 if $\sigma_v^{\text{obs}} \geq 2\sigma_{\text{ch}}$. The cataloged R is corrected by dividing by 0.8 and 0.9 for the GMCs with lower and higher S/N. For the M_{mol} , we corrected by dividing by 0.9 for the GMCs with lower S/N. Then, we recalculated other properties based on the corrected σ_v , R , and M_{mol} . Table B.1 is the same as Tabel 2.2 but corrected for the over/underestimation. We find the recalculated median M_{vir} , Σ_{mol} , and c become by a factor of $0.7 \sim 0.9$ smaller and the correction factor is roughly comparable in the different environments. The α_{vir} becomes by a factor of 0.8, 0.5, and 0.8 smaller in *Bar*, *Arm*, and *Bar-end*, respectively. This suggests we overestimate the fraction of gravitationally unbound clouds. Based on the corrected (uncorrected) values, the number fraction is 50 % (58 %), 29 % (33 %), and 23 % (29 %) in *Bar*, *Arm*, and *Bar-end*, respectively.

We retested the environmental variation of the GMC properties using the corrected catalog. Table B.2 shows the result of the two-sided K-S test. Comparing the Table 2.3, p -values do not change much. Therefore, the over/underestimation of the measurements does not influence on the discussion about the environmental variation described in Section 2.5.1. It is notable that ~ 35 % and ~ 60 % of the GMCs in M51 measured by Colombo et al. (2014) may be underestimated and overestimated by a factor of ~ 1.2 . Thus, the over/underestimation seems not to influence on the discussion about the comparison with the GMCs in M51.

Table B.1: GMC properties in the different environments of NGC 1300 corrected for the CPROPS bias

Envir.	σ_v (km s ⁻¹)	R (pc)	M_{mol} (10 ⁵ M _⊙)	M_{vir} (10 ⁵ M _⊙)	Σ_{mol} (M _⊙ pc ⁻²)	α_{vir}	c (km s ⁻¹ pc ^{-0.5})
All	4.0 ^{+1.8} _{-0.9}	56.4 ^{+12.1} _{-13.7}	5.7 ^{+4.7} _{-1.9}	11.0 ^{+12.6} _{-4.78}	127.8 ^{+45.6} _{-45.9}	1.1 ^{+1.2} _{-0.6}	0.6 ^{+0.2} _{-0.2}
Bar	4.8 ^{+1.3} _{-1.5}	58.4 ^{+22.2} _{-19.3}	6.1 ^{+2.0} _{-2.1}	14.6 ^{+8.5} _{-8.77}	91.7 ^{+64.6} _{-28.6}	2.0 ^{+0.9} _{-1.4}	0.7 ^{+0.1} _{-0.2}
Arm	3.7 ^{+1.5} _{-0.8}	55.0 ^{+10.7} _{-11.8}	5.5 ^{+4.2} _{-1.8}	9.8 ^{+6.4} _{-4.14}	111.4 ^{+55.7} _{-29.3}	0.9 ^{+1.2} _{-0.4}	0.6 ^{+0.2} _{-0.2}
Bar-end	3.9 ^{+2.6} _{-0.7}	57.0 ^{+21.4} _{-15.7}	9.1 ^{+6.4} _{-3.6}	14.0 ^{+17.9} _{-7.69}	143.9 ^{+77.8} _{-33.4}	1.1 ^{+0.6} _{-0.5}	0.7 ^{+0.2} _{-0.2}

Table B.2: Kolmogorov-Smirnov Test for GMC properties corrected for the CPROPS bias

Prop.	Bar vs. Arm	Bar vs. Bar-end	Arm vs. Bar-end
σ_v	0.138 ± 0.062(0.169)	0.538 ± 0.166(0.538)	0.422 ± 0.123(0.460)
R	0.746 ± 0.100(0.914)	0.896 ± 0.078(0.952)	0.556 ± 0.149(0.450)
M_{mol}	0.841 ± 0.103(0.938)	0.028 ± 0.018(0.027)	0.013 ± 0.007(0.006)
M_{vir}	0.571 ± 0.199(0.438)	0.865 ± 0.099(0.865)	0.242 ± 0.092(0.261)
Σ_{mol}	0.547 ± 0.183(0.530)	0.142 ± 0.077(0.142)	0.093 ± 0.055(0.139)
α_{vir}	0.312 ± 0.120(0.283)	0.185 ± 0.077(0.221)	0.669 ± 0.148(0.664)
c	0.409 ± 0.092(0.409)	0.739 ± 0.166(0.712)	0.359 ± 0.111(0.430)

Appendix C

Supplementary results of CO observations with Nobeyama 45-m telescope

Here we present the results in NRO FoV as supplementary results, because the f_{dif} and the relations between f_{dif} and other parameters cannot be measured outside ALMA FoV. Fig. C.1 shows stacked CO spectra in each environment defined as Fig. 3.4(a). The mean values of physical parameters in each environment are listed in Table C.1. In *inter-arm1* and *inter-arm2*, the $\Sigma_{12\text{CO}(1-0)}^{\text{tot}}$ are the lowest ($\sim 4 - 5 \text{ M}_{\odot} \text{ pc}^{-2}$). In *center*, the $\Sigma_{12\text{CO}(1-0)}^{\text{tot}}$ and $R_{21/10}$ are the highest ($32.2 \text{ M}_{\odot} \text{ pc}^{-2}$ and 0.69). However, SFE in *center* is about 3 – 4 times lower than those in *arm* and *bar-end*. This result is clearly seen in K-S law in Fig. C.2(a) and (b), which indicates that SF in center of NGC 1300 is suppressed. However, the adopted $\alpha_{\text{CO}} = 4.4 \text{ M}_{\odot} (\text{K km s}^{-1} \text{ pc}^2)^{-1}$ may not be appropriate in the center region. In central regions of disc galaxies α_{CO} is lower than by a factor of 2 – 3 (some nearby galaxies; Nakai & Kuno 1995; Regan 2000, the Milky Way; Dahmen et al. 1998). Fig. C.2(c) and (d) show the correlation of $R_{21/10}$ with SFE for NRO FoV. The 6.0 arcsec pixels in *arm2*, *inter-arm1*, and *inter-arm2* lie on the tendency we find in bar, arm, and bar-end regions (Fig. 3.16(a) and (b)). Pixels in *center* deviated from the tendency; but this may be due to the systematic variation of α_{CO} .

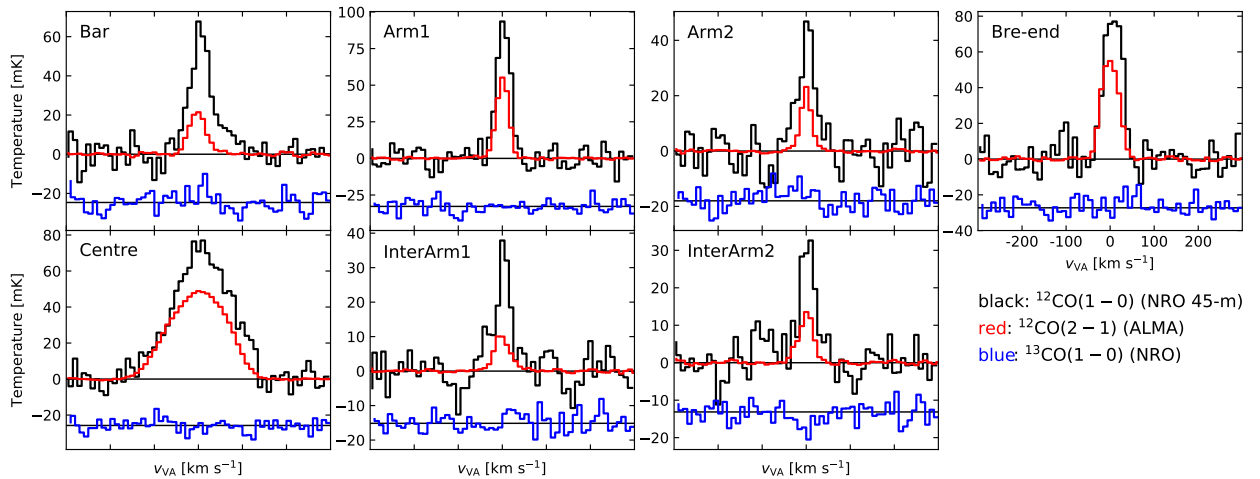


Figure C.1: Stacked CO spectra for each environment in NGC 1300. The black, red, and blue lines indicate $^{12}\text{CO}(1-0)$ emission obtained from the NRO 45-m, $^{12}\text{CO}(2-1)$ emission obtained from ALMA, and $^{13}\text{CO}(1-0)$ emission obtained from the NRO 45-m, respectively. For visualization purpose, base line of $^{13}\text{CO}(1-0)$ spectra is shifted.

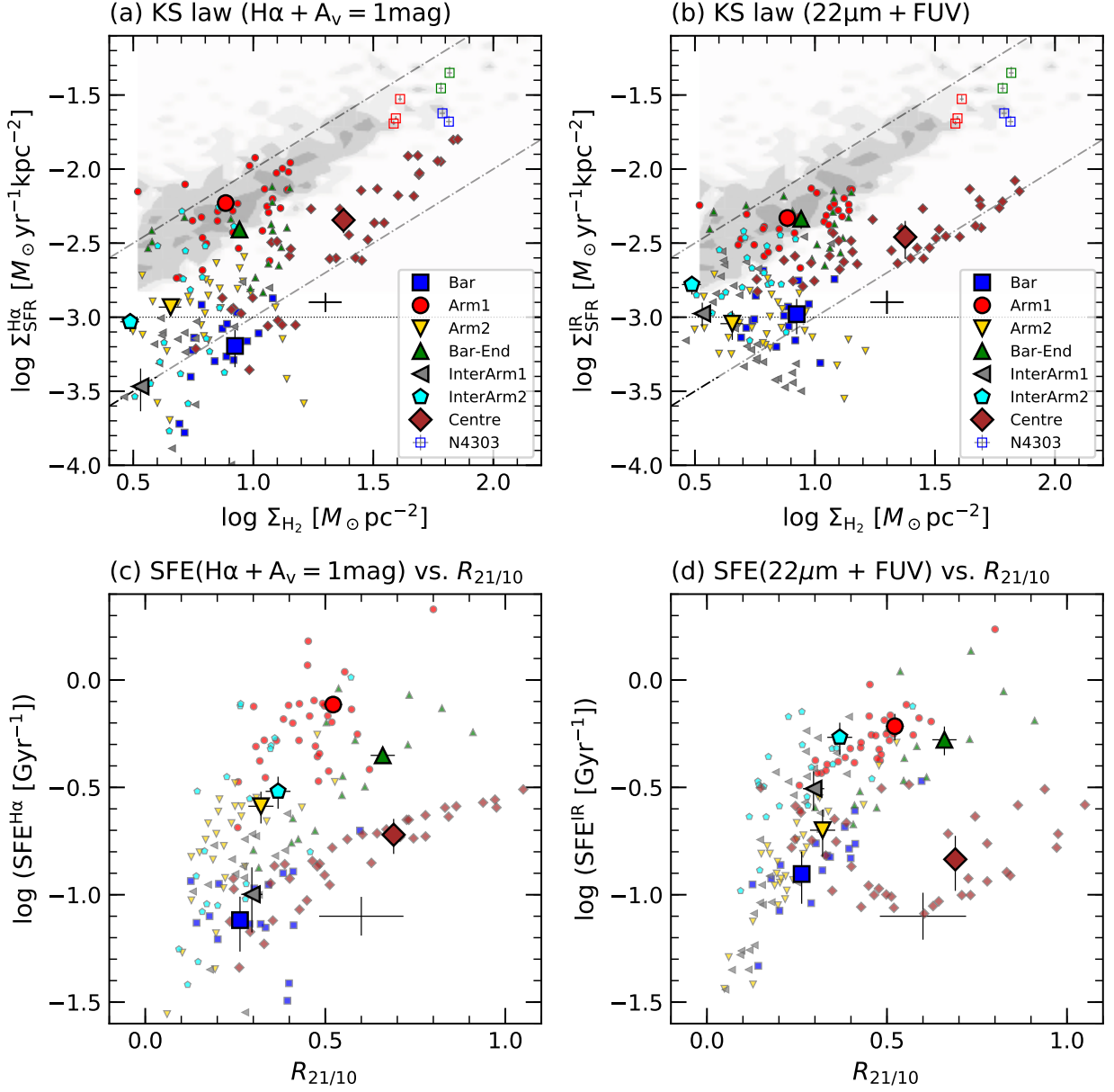


Figure C.2: **(a)** Molecular Kennicutt-Schmidt relation of NGC 1300 for NRO FoV. SFR is derived from the $H\alpha$ emission. The small and large symbols represent the value in individual 6.0 arcsec pixels and the mean value in each environment, respectively. We display the pixels where $^{12}\text{CO}(1-0)$ emission observed with the NRO 45-m was significantly detected. Typical uncertainty for each 6.0 arcsec pixel is shown as a black cross. The grey scale represents the result by Bigiel et al. (2008). The open squares represents the result in NGC 4303 by Yajima et al. (2019) (blue: bar, red: arm, and green: bar-end). The grey dash-dotted lines show the constant SFE of 1.0 and 0.1 Gyr^{-1} . The horizontal dotted line represents $\Sigma_{\text{SFR}} = 10^{-3} M_{\odot} \text{yr}^{-1} \text{kpc}^{-2}$. **(b)** Same as panel (a), but SFR is derived from FUV and IR. **(c)** Correlation of $R_{21/10}$ with SFE for NRO FoV. SFR is derived from the $H\alpha$ emission. The small and large symbols represent the value in individual 6.0 arcsec pixels and the mean value in each environment, respectively. The typical uncertainty for each 6.0 arcsec pixel is shown as a black cross. **(d)** Same as panel (c), but SFR is derived from FUV and IR.

Table C.1: Mean values of physical parameters for NRO FoV.

	Bar	Arm1	Arm2	Bar-end	Center	Inter-arm1	Inter-arm2
$\Sigma_{\text{SFR}}^{\text{H}\alpha}$	0.6 ± 0.2	5.9 ± 0.4	1.2 ± 0.2	3.9 ± 0.3	4.5 ± 0.8	0.34 ± 0.1	0.9 ± 0.1
$\Sigma_{\text{SFR}}^{\text{IR}}$	1.0 ± 0.3	4.7 ± 0.6	0.9 ± 0.2	4.6 ± 0.7	3.5 ± 1.0	1.0 ± 0.2	1.7 ± 0.2
$I_{12\text{CO}(1-0)}^{\text{tot}}$	4.1 ± 0.2	3.7 ± 0.2	2.2 ± 0.2	4.2 ± 0.2	11.5 ± 0.3	1.6 ± 0.2	1.5 ± 0.1
$I_{12\text{CO}(2-1)}^{\text{tot}}$	1.07 ± 0.02	1.93 ± 0.02	0.70 ± 0.01	2.79 ± 0.02	7.92 ± 0.02	0.49 ± 0.01	0.55 ± 0.01
$\Sigma_{12\text{CO}(1-0)}^{\text{tot}}$	11.4 ± 0.6	10.4 ± 0.5	6.2 ± 0.7	11.9 ± 0.6	32.3 ± 0.8	4.6 ± 0.4	4.2 ± 0.4
$\text{SFE}^{\text{H}\alpha}$	0.08 ± 0.02	0.77 ± 0.07	0.26 ± 0.04	0.45 ± 0.04	0.19 ± 0.04	0.10 ± 0.03	0.30 ± 0.05
SFE^{IR}	0.12 ± 0.03	0.61 ± 0.09	0.20 ± 0.05	0.53 ± 0.08	0.15 ± 0.04	0.31 ± 0.06	0.54 ± 0.09
$R_{21/10}$	0.26 ± 0.02	0.52 ± 0.03	0.32 ± 0.03	0.66 ± 0.03	0.69 ± 0.02	0.30 ± 0.03	0.37 ± 0.03
$R_{13/12}$	< 0.09	< 0.07	< 0.12	< 0.06	< 0.03	< 0.11	< 0.10

Appendix D

Catalog of the GMCs in NGC 1300

Table D.1 presents the GMC catalog in NGC 1300, which contains columns as follows:

1. Column 1: ID, GMC identification number
2. Column 2: RA, GMC right ascension as measured by the intensity-weighted 1st moment along this direction
3. Column 3: Dec, GMC declination measured as above
4. Column 4: v_{LSR} , GMC central velocity as measured by the intensity-weighted first moment along the velocity axis
5. Column 5: T_{peak} , GMC's peak brightness temperature in K
6. Column 6: S/N, GMC's peak signal-to-noise ratio
7. Column 7: σ_v , GMC's deconvolved, extrapolated velocity dispersion in km s^{-1} with uncertainty
8. Column 8: R , GMC's deconvolved, extrapolated effective radius in pc with uncertainty
9. Column 9: M_{mol} , GMC's mass in $10^5 M_{\odot}$ calculated from CO luminosity and $\alpha_{\text{CO}} = 4.4 M_{\odot} (\text{K km s}^{-1} \text{pc}^2)^{-1}$ with uncertainty
10. Column 10: M_{vir} , GMC's mass inferred from virial theorem in $10^5 M_{\odot}$ with uncertainty
11. Column 11: α_{vir} , GMC's virial parameter with uncertainty
12. Column 12: Region where a given GMC has been identified, i.e. Bar, Arm, Bar-end, and "other", which represents the GMC outside the three regions
13. Column 13: Flag for the measurement of radius: 0 = actual measurement of radius, 1 = upper limit.

The complete version is also available in machine-readable form in the online journal (<https://doi.org/10.1093/mnras/staa556>).

Table D.1: GMC catalog

ID	RA (J2000)	Dec (J2000)	v_{LSR} (km s ⁻¹)	T_{peak} (K)	SN	σ_v (km s ⁻¹)	R (pc)	M_{mol} (M _⊙)	M_{vir} (M _⊙)	α_{vir}	Reg	Flag
1	3 ^h 19 ^m 35.56 ^s	-19°24'25.1"	1675.8	2.8	5.5	7.9 ± 4.8	43.2 ± 34.9	10.4 ± 6.4	28.3 ± 53.3	3.0 ± 4.9	Bar-end	0
2	3 ^h 19 ^m 35.53 ^s	-19°24'24.6"	1670.1	2.8	5.3	7.9 ± 5.2	<29.6	2.9 ± 4.1	-	-	Bar-end	1
3	3 ^h 19 ^m 35.53 ^s	-19°24'25.7"	1666.2	4.2	7.9	7.7 ± 2.4	77.5 ± 16.8	26.5 ± 6.9	47.9 ± 30.1	2.0 ± 1.2	Bar-end	0
4	3 ^h 19 ^m 35.50 ^s	-19°24'4.8"	1667.9	1.8	4.7	4.4 ± 5.1	<29.6	1.1 ± 1.3	-	-	Arm	1
5	3 ^h 19 ^m 35.46 ^s	-19°24'4.3"	1666.6	2.1	5.3	4.2 ± 2.6	24.7 ± 14.9	2.8 ± 1.7	4.5 ± 6.9	1.8 ± 2.2	Arm	0
6	3 ^h 19 ^m 35.74 ^s	-19°24'28.2"	1662.4	4.2	8.9	5.1 ± 2.0	61.1 ± 26.4	15.5 ± 11.0	16.3 ± 16.0	1.2 ± 1.2	Bar-end	0
7	3 ^h 19 ^m 35.72 ^s	-19°24'19.8"	1662.1	4.0	8.4	6.6 ± 2.2	56.4 ± 20.5	24.1 ± 9.5	25.7 ± 17.6	1.2 ± 0.9	Bar-end	0
8	3 ^h 19 ^m 35.66 ^s	-19°24'18.6"	1666.7	2.9	6.8	6.4 ± 6.4	14.4 ± 21.0	5.1 ± 4.2	6.1 ± 14.6	1.3 ± 3.3	Bar-end	0
9	3 ^h 19 ^m 35.73 ^s	-19°24'17.7"	1663.0	3.5	8.3	5.7 ± 3.8	35.4 ± 26.1	6.6 ± 5.4	11.8 ± 19.4	2.0 ± 2.8	Bar-end	0
10	3 ^h 19 ^m 35.51 ^s	-19°24'3.7"	1659.9	2.2	5.4	3.1 ± 2.3	<29.6	2.7 ± 1.0	-	-	Arm	1
11	3 ^h 19 ^m 35.62 ^s	-19°24'25.2"	1658.6	2.8	5.5	6.9 ± 2.7	31.7 ± 14.6	9.8 ± 3.2	15.6 ± 15.3	1.8 ± 1.5	Bar-end	0
12	3 ^h 19 ^m 35.59 ^s	-19°24'22.8"	1660.7	7.5	15.7	8.8 ± 1.3	86.7 ± 11.9	79.5 ± 12.4	70.5 ± 22.8	1.0 ± 0.3	Bar-end	0
13	3 ^h 19 ^m 35.52 ^s	-19°24'22.3"	1654.1	4.0	8.5	3.0 ± 3.8	21.6 ± 20.4	7.5 ± 14.0	2.0 ± 5.5	0.3 ± 0.8	Bar-end	0
14	3 ^h 19 ^m 35.71 ^s	-19°24'12.7"	1657.1	4.0	10.4	8.0 ± 2.3	57.4 ± 19.9	19.7 ± 9.6	37.9 ± 30.4	2.1 ± 1.8	Arm	0
15	3 ^h 19 ^m 35.69 ^s	-19°24'8.6"	1655.6	3.8	10.5	8.1 ± 3.6	46.7 ± 64.8	14.7 ± 11.0	31.7 ± 54.5	2.4 ± 4.0	Arm	0
16	3 ^h 19 ^m 35.58 ^s	-19°24'6.8"	1655.4	3.9	10.3	5.7 ± 1.5	56.5 ± 26.5	16.0 ± 9.0	18.9 ± 13.6	1.3 ± 1.0	Arm	0
17	3 ^h 19 ^m 35.79 ^s	-19°24'27.9"	1649.6	5.0	10.5	4.6 ± 3.0	30.5 ± 13.0	10.9 ± 6.4	6.8 ± 9.7	0.7 ± 0.9	Bar-end	0
18	3 ^h 19 ^m 35.51 ^s	-19°24'26.5"	1654.4	3.7	7.0	5.3 ± 2.4	18.2 ± 7.9	5.5 ± 2.9	5.3 ± 5.6	1.1 ± 1.2	Bar-end	0
19	3 ^h 19 ^m 35.72 ^s	-19°24'15.8"	1646.2	9.1	22.0	10.8 ± 1.0	69.9 ± 8.2	102.9 ± 5.9	84.4 ± 18.4	0.9 ± 0.2	Bar-end	0
20	3 ^h 19 ^m 35.66 ^s	-19°24'7.2"	1653.2	4.6	12.4	6.8 ± 2.7	53.1 ± 22.0	21.5 ± 10.8	25.9 ± 28.0	1.3 ± 1.4	Arm	0
21	3 ^h 19 ^m 35.62 ^s	-19°24'4.9"	1653.1	4.1	12.7	6.8 ± 4.5	<29.6	9.6 ± 16.1	-	-	Arm	1
22	3 ^h 19 ^m 35.62 ^s	-19°24'4.1"	1653.7	5.2	15.5	6.5 ± 2.8	26.8 ± 19.1	12.1 ± 9.9	11.7 ± 13.9	1.1 ± 1.1	Arm	0
23	3 ^h 19 ^m 35.63 ^s	-19°24'24.1"	1648.1	3.6	7.4	5.4 ± 3.2	92.9 ± 39.1	14.7 ± 10.4	28.4 ± 35.2	2.2 ± 2.3	Bar-end	0
24	3 ^h 19 ^m 35.66 ^s	-19°24'19.3"	1645.9	4.5	9.8	11.0 ± 2.9	84.1 ± 17.1	39.5 ± 13.0	106.0 ± 66.4	3.0 ± 1.8	Bar-end	0
25	3 ^h 19 ^m 35.68 ^s	-19°24'17.8"	1643.8	6.3	15.5	9.6 ± 1.3	71.3 ± 8.7	58.9 ± 7.6	67.6 ± 21.4	1.3 ± 0.4	Bar-end	0
26	3 ^h 19 ^m 35.73 ^s	-19°24'10.3"	1638.3	4.2	11.8	7.5 ± 4.3	47.4 ± 19.2	19.4 ± 19.0	28.0 ± 35.4	1.6 ± 1.9	Arm	0
27	3 ^h 19 ^m 35.84 ^s	-19°24'7.7"	1639.8	2.0	5.8	1.9 ± 2.2	<29.6	3.3 ± 5.0	-	-	Arm	1
28	3 ^h 19 ^m 35.71 ^s	-19°24'6.0"	1642.7	3.1	7.9	4.1 ± 4.7	52.5 ± 25.0	5.3 ± 2.7	9.3 ± 22.7	2.0 ± 4.6	Arm	0
29	3 ^h 19 ^m 35.72 ^s	-19°24'5.1"	1642.6	2.4	6.3	5.7 ± 2.2	37.5 ± 15.2	4.3 ± 1.4	12.7 ± 10.5	3.3 ± 2.7	Arm	0
30	3 ^h 19 ^m 35.88 ^s	-19°24'26.7"	1632.2	3.0	6.6	3.7 ± 4.8	70.8 ± 48.9	1.8 ± 1.6	10.3 ± 24.6	6.5 ± 16.2	Bar-end	0
31	3 ^h 19 ^m 35.77 ^s	-19°24'24.3"	1634.8	4.9	10.0	5.8 ± 3.2	47.3 ± 19.3	25.5 ± 15.7	16.6 ± 19.2	0.7 ± 0.7	Bar-end	0
32	3 ^h 19 ^m 35.69 ^s	-19°24'22.6"	1635.1	4.7	10.4	5.5 ± 1.3	75.7 ± 14.9	32.6 ± 5.9	23.9 ± 13.2	0.8 ± 0.4	Bar-end	0
33	3 ^h 19 ^m 35.63 ^s	-19°24'20.6"	1640.7	3.4	8.1	3.5 ± 4.8	35.5 ± 39.6	6.8 ± 10.9	4.5 ± 13.8	0.7 ± 2.4	Bar-end	0
34	3 ^h 19 ^m 35.69 ^s	-19°24'11.3"	1644.7	4.1	10.7	9.3 ± 4.2	30.8 ± 12.5	14.5 ± 9.8	27.8 ± 26.9	2.1 ± 1.7	Arm	0
35	3 ^h 19 ^m 35.71 ^s	-19°24'9.6"	1635.4	3.9	9.2	4.6 ± 6.3	45.6 ± 47.0	24.7 ± 31.8	9.9 ± 27.2	0.4 ± 1.1	Arm	0

continued GMC catalog

ID	RA (J2000)	Dec (J2000)	v_{LSR} (km s $^{-1}$)	T_{peak} (K)	SN	σ_v (km s $^{-1}$)	R (pc)	M_{mol} ($M_{\odot}$)	M_{vir} ($M_{\odot}$)	α_{vir}	Reg	Flag
36	3 ^h 19 ^m 35.84 ^s	-19°24'9.2"	1639.0	3.5	10.1	8.9 ± 3.0	76.7 ± 20.4	38.3 ± 14.6	63.0 ± 44.0	1.8 ± 1.1	Arm	0
37	3 ^h 19 ^m 35.71 ^s	-19°24'4.2"	1640.5	2.3	5.9	4.7 ± 3.2	<29.6	3.0 ± 1.7	-	-	Arm	1
38	3 ^h 19 ^m 36.28 ^s	-19°24'32.7"	1632.9	3.0	7.6	4.3 ± 2.4	<29.6	2.3 ± 1.2	-	-	Bar-end	1
39	3 ^h 19 ^m 35.97 ^s	-19°24'27.8"	1631.1	4.2	9.6	7.2 ± 1.8	38.7 ± 14.4	12.3 ± 7.0	20.8 ± 11.9	1.9 ± 1.0	Bar-end	0
40	3 ^h 19 ^m 35.90 ^s	-19°24'27.1"	1632.8	3.0	6.7	1.8 ± 3.2	64.2 ± 73.9	8.4 ± 11.5	2.2 ± 7.4	0.3 ± 1.0	Bar-end	0
41	3 ^h 19 ^m 36.02 ^s	-19°24'25.8"	1631.1	3.2	8.0	3.1 ± 2.9	42.6 ± 20.5	4.2 ± 2.0	4.3 ± 8.7	1.2 ± 2.2	Bar-end	0
42	3 ^h 19 ^m 35.85 ^s	-19°24'25.4"	1634.4	4.7	10.2	7.3 ± 3.1	89.5 ± 22.1	47.3 ± 27.5	50.0 ± 45.4	1.2 ± 1.0	Bar-end	0
43	3 ^h 19 ^m 35.87 ^s	-19°24'24.5"	1631.5	3.1	6.8	2.2 ± 3.7	28.8 ± 38.5	3.7 ± 4.9	1.5 ± 5.0	0.5 ± 1.4	Bar-end	0
44	3 ^h 19 ^m 35.67 ^s	-19°24'21.1"	1632.0	5.0	11.2	7.8 ± 2.9	32.5 ± 16.9	9.1 ± 7.9	20.3 ± 19.6	2.5 ± 2.3	Bar-end	0
45	3 ^h 19 ^m 35.71 ^s	-19°24'12.9"	1635.8	3.9	9.7	6.0 ± 2.2	57.6 ± 18.6	23.0 ± 10.5	21.2 ± 18.0	1.0 ± 0.7	Arm	0
46	3 ^h 19 ^m 36.25 ^s	-19°24'30.5"	1622.9	4.4	11.2	5.1 ± 3.7	46.3 ± 38.7	15.6 ± 27.9	12.7 ± 20.7	0.9 ± 1.7	Bar-end	0
47	3 ^h 19 ^m 36.06 ^s	-19°24'29.6"	1626.1	3.3	8.1	5.6 ± 4.0	46.8 ± 26.7	8.1 ± 4.1	15.1 ± 21.4	2.1 ± 3.4	Bar-end	0
48	3 ^h 19 ^m 36.00 ^s	-19°24'29.4"	1625.1	2.0	4.9	7.7 ± 8.5	<29.6	3.4 ± 4.2	-	-	Bar-end	1
49	3 ^h 19 ^m 36.00 ^s	-19°24'28.7"	1625.5	3.7	8.3	8.1 ± 5.5	51.3 ± 23.1	14.4 ± 11.6	35.1 ± 48.4	2.7 ± 3.6	Bar-end	0
50	3 ^h 19 ^m 35.97 ^s	-19°24'26.4"	1623.5	2.7	5.6	4.2 ± 2.6	39.5 ± 22.4	9.8 ± 7.6	7.3 ± 10.8	0.8 ± 1.4	Bar-end	0
51	3 ^h 19 ^m 35.73 ^s	-19°24'17.2"	1627.0	2.0	5.0	3.3 ± 5.0	27.4 ± 28.8	2.3 ± 3.5	3.1 ± 9.8	1.5 ± 4.6	Bar-end	0
52	3 ^h 19 ^m 36.12 ^s	-19°24'29.9"	1622.7	3.1	7.8	6.0 ± 10.5	49.7 ± 33.9	8.4 ± 8.7	18.4 ± 57.9	2.4 ± 6.9	Bar-end	0
53	3 ^h 19 ^m 36.17 ^s	-19°24'29.2"	1620.5	2.4	6.3	5.5 ± 3.0	<29.6	3.3 ± 2.9	-	-	Bar-end	1
54	3 ^h 19 ^m 36.06 ^s	-19°24'28.0"	1622.7	4.2	10.5	7.0 ± 2.7	63.2 ± 18.9	11.9 ± 8.5	32.3 ± 29.7	3.0 ± 3.1	Bar-end	0
55	3 ^h 19 ^m 35.64 ^s	-19°24'22.2"	1623.7	2.5	5.9	5.0 ± 3.4	<29.6	1.8 ± 2.9	-	-	Bar-end	1
56	3 ^h 19 ^m 35.71 ^s	-19°24'21.6"	1624.8	2.3	5.9	4.5 ± 3.8	<29.6	1.8 ± 1.2	-	-	Bar-end	1
57	3 ^h 19 ^m 35.73 ^s	-19°24'16.5"	1623.0	3.4	8.0	4.8 ± 4.4	<29.6	2.3 ± 3.0	-	-	Bar-end	1
58	3 ^h 19 ^m 35.72 ^s	-19°24'14.4"	1622.1	2.2	6.1	7.9 ± 5.0	<29.6	2.8 ± 2.5	-	-	Arm	1
59	3 ^h 19 ^m 36.40 ^s	-19°24'32.9"	1619.1	1.6	4.3	8.0 ± 5.7	16.4 ± 17.5	1.4 ± 1.2	11.0 ± 21.7	8.7 ± 16.5	Bar-end	0
60	3 ^h 19 ^m 36.44 ^s	-19°24'32.5"	1615.7	2.5	6.9	4.7 ± 1.9	<29.6	4.1 ± 1.3	-	-	Bar-end	1
61	3 ^h 19 ^m 36.31 ^s	-19°24'31.2"	1615.3	3.8	9.9	9.5 ± 8.8	31.5 ± 40.0	6.4 ± 3.8	29.8 ± 62.8	5.2 ± 11.3	Bar-end	0
62	3 ^h 19 ^m 35.51 ^s	-19°24'18.1"	1673.3	4.9	10.5	4.6 ± 1.1	59.9 ± 10.0	17.9 ± 3.6	13.0 ± 6.9	0.8 ± 0.4	Bar-end	0
63	3 ^h 19 ^m 35.55 ^s	-19°24'18.5"	1651.5	2.8	6.4	5.8 ± 2.0	47.3 ± 17.5	8.1 ± 4.4	16.4 ± 15.8	2.2 ± 2.0	Bar-end	0
64	3 ^h 19 ^m 35.54 ^s	-19°24'13.3"	1677.4	2.6	6.8	4.7 ± 1.7	<29.6	2.4 ± 0.6	-	-	Arm	1
65	3 ^h 19 ^m 36.45 ^s	-19°24'51.3"	1672.6	2.6	4.5	6.8 ± 4.3	<29.6	2.3 ± 0.9	-	-	other	1
66	3 ^h 19 ^m 35.01 ^s	-19°24'4.5"	1672.0	2.4	5.2	7.6 ± 3.3	14.4 ± 15.6	2.7 ± 1.1	8.7 ± 11.3	3.5 ± 4.5	Arm	0
67	3 ^h 19 ^m 35.69 ^s	-19°23'53.3"	1651.9	2.3	5.6	5.7 ± 2.0	33.2 ± 11.4	6.4 ± 2.0	11.3 ± 9.3	2.0 ± 1.5	Arm	0
68	3 ^h 19 ^m 35.84 ^s	-19°23'52.8"	1649.8	3.1	7.7	4.1 ± 7.5	37.3 ± 49.5	8.2 ± 19.6	6.6 ± 24.4	0.9 ± 3.3	Arm	0
69	3 ^h 19 ^m 36.00 ^s	-19°23'50.6"	1650.7	2.5	6.4	4.5 ± 2.2	49.0 ± 19.0	4.5 ± 3.7	10.2 ± 10.5	2.5 ± 2.4	Arm	0
70	3 ^h 19 ^m 35.79 ^s	-19°23'52.7"	1649.3	4.1	10.1	4.5 ± 3.9	72.9 ± 33.8	10.4 ± 9.9	15.6 ± 30.7	1.7 ± 3.3	Arm	0
71	3 ^h 19 ^m 35.86 ^s	-19°23'51.6"	1652.5	2.0	5.0	6.7 ± 4.0	<29.6	4.3 ± 2.7	-	-	Arm	1

continued GMC catalog

ID	RA (J2000)	Dec (J2000)	v_{LSR} (km s ⁻¹)	T_{peak} (K)	SN	σ_v (km s ⁻¹)	R (pc)	M_{mol} ($M_{\odot}$)	M_{vir} ($M_{\odot}$)	α_{vir}	Reg	Flag
72	3 ^h 19 ^m 35.97 ^s	-19°23'51.4"	1644.5	3.8	9.4	5.1 ± 1.8	74.2 ± 15.5	19.1 ± 4.1	19.8 ± 15.7	1.2 ± 0.9	Arm	0
73	3 ^h 19 ^m 35.00 ^s	-19°24'9.3"	1668.6	2.2	4.1	4.9 ± 3.5	37.0 ± 13.2	3.3 ± 1.8	9.4 ± 15.0	3.1 ± 4.7	Arm	0
74	3 ^h 19 ^m 35.01 ^s	-19°24'8.9"	1665.4	4.1	7.6	5.6 ± 2.2	<29.6	3.0 ± 0.6	-	-	Arm	1
75	3 ^h 19 ^m 35.43 ^s	-19°24'8.2"	1664.7	3.5	8.9	4.6 ± 2.8	<29.6	3.2 ± 0.6	-	-	Arm	1
76	3 ^h 19 ^m 34.93 ^s	-19°24'5.5"	1663.5	2.7	5.2	5.2 ± 1.5	45.8 ± 12.9	7.8 ± 2.0	13.1 ± 8.9	1.9 ± 1.4	Arm	0
77	3 ^h 19 ^m 34.91 ^s	-19°24'4.4"	1663.8	2.3	4.3	6.5 ± 2.2	33.1 ± 25.4	8.4 ± 2.4	14.6 ± 15.7	1.9 ± 2.1	Arm	0
78	3 ^h 19 ^m 34.96 ^s	-19°24'2.3"	1670.6	2.5	5.2	8.3 ± 2.9	18.2 ± 10.5	4.4 ± 1.2	12.9 ± 13.2	3.3 ± 3.1	Arm	0
79	3 ^h 19 ^m 35.49 ^s	-19°23'56.6"	1657.2	5.3	12.6	4.5 ± 0.7	74.8 ± 10.1	24.2 ± 2.0	15.6 ± 5.5	0.7 ± 0.2	Arm	0
80	3 ^h 19 ^m 35.64 ^s	-19°23'54.7"	1650.2	2.5	6.5	2.9 ± 1.6	38.2 ± 15.3	5.6 ± 2.6	3.3 ± 4.3	0.7 ± 0.9	Arm	0
81	3 ^h 19 ^m 35.60 ^s	-19°23'55.7"	1648.8	2.9	7.1	5.1 ± 2.5	50.4 ± 13.9	8.2 ± 3.9	13.8 ± 14.1	1.9 ± 1.9	Arm	0
82	3 ^h 19 ^m 35.60 ^s	-19°23'52.5"	1651.7	2.3	5.0	6.5 ± 4.9	<29.6	5.1 ± 4.1	-	-	Arm	1
83	3 ^h 19 ^m 35.60 ^s	-19°23'51.9"	1648.8	2.4	5.4	5.0 ± 2.9	30.7 ± 16.8	4.0 ± 2.1	8.1 ± 11.3	2.3 ± 3.4	Arm	0
84	3 ^h 19 ^m 35.63 ^s	-19°23'50.7"	1642.4	2.5	6.1	6.6 ± 5.0	33.8 ± 23.4	4.4 ± 4.9	15.3 ± 27.1	3.9 ± 7.6	Arm	0
85	3 ^h 19 ^m 35.64 ^s	-19°23'48.9"	1642.7	2.2	5.2	3.9 ± 4.9	<29.6	1.1 ± 0.8	-	-	Arm	1
86	3 ^h 19 ^m 35.65 ^s	-19°23'48.3"	1648.1	2.4	5.3	7.2 ± 3.3	48.0 ± 14.1	8.4 ± 3.3	26.1 ± 25.4	3.5 ± 2.9	Arm	0
87	3 ^h 19 ^m 35.64 ^s	-19°23'50.1"	1642.3	3.2	7.4	3.9 ± 3.9	<29.6	4.3 ± 3.8	-	-	Arm	1
88	3 ^h 19 ^m 35.00 ^s	-19°24'8.2"	1665.0	2.6	5.0	4.7 ± 2.5	<29.6	2.1 ± 0.8	-	-	Arm	1
89	3 ^h 19 ^m 35.42 ^s	-19°23'54.8"	1664.9	1.7	4.2	5.5 ± 3.4	<29.6	2.3 ± 1.2	-	-	Arm	1
90	3 ^h 19 ^m 35.56 ^s	-19°24'15.9"	1659.2	2.8	6.2	5.2 ± 1.6	41.0 ± 10.8	5.0 ± 1.0	11.6 ± 8.4	2.6 ± 1.8	Bar-end	0
91	3 ^h 19 ^m 35.30 ^s	-19°24'3.8"	1663.4	2.3	5.6	4.1 ± 2.9	<29.6	2.8 ± 0.6	-	-	Arm	1
92	3 ^h 19 ^m 35.70 ^s	-19°24'3.4"	1646.3	3.8	9.9	9.7 ± 2.6	29.2 ± 12.6	14.0 ± 3.7	28.4 ± 18.8	2.3 ± 1.3	Arm	0
93	3 ^h 19 ^m 35.79 ^s	-19°24'2.6"	1646.3	5.6	15.5	5.8 ± 1.0	87.2 ± 11.1	43.1 ± 4.0	30.5 ± 10.4	0.8 ± 0.3	Arm	0
94	3 ^h 19 ^m 35.82 ^s	-19°24'0.5"	1645.7	3.0	8.7	4.1 ± 1.1	73.2 ± 16.1	14.5 ± 3.3	12.6 ± 7.2	1.0 ± 0.6	Arm	0
95	3 ^h 19 ^m 35.93 ^s	-19°24'2.5"	1639.8	4.0	11.9	3.2 ± 2.0	47.9 ± 15.9	14.2 ± 5.4	5.2 ± 7.3	0.4 ± 0.6	Arm	0
96	3 ^h 19 ^m 35.84 ^s	-19°23'59.4"	1645.5	1.7	4.6	5.6 ± 4.8	<29.6	3.8 ± 3.5	-	-	Arm	1
97	3 ^h 19 ^m 35.87 ^s	-19°24'2.6"	1634.8	2.7	8.4	5.0 ± 3.9	34.8 ± 20.5	7.6 ± 6.9	9.0 ± 15.2	1.3 ± 2.2	Arm	0
98	3 ^h 19 ^m 35.99 ^s	-19°24'3.0"	1630.0	1.5	4.0	6.7 ± 5.9	<29.6	0.7 ± 0.6	-	-	Arm	1
99	3 ^h 19 ^m 35.39 ^s	-19°23'57.2"	1660.2	2.0	4.7	3.7 ± 1.7	<29.6	4.1 ± 1.3	-	-	Arm	1
100	3 ^h 19 ^m 36.42 ^s	-19°24'39.2"	1646.1	1.9	4.2	5.0 ± 2.8	25.0 ± 14.5	4.1 ± 2.5	6.5 ± 7.8	1.8 ± 2.3	other	0
101	3 ^h 19 ^m 36.34 ^s	-19°24'38.7"	1647.4	2.3	5.0	6.6 ± 2.5	51.5 ± 16.1	7.3 ± 1.9	23.0 ± 19.5	3.5 ± 2.8	other	0
102	3 ^h 19 ^m 36.04 ^s	-19°24'34.5"	1651.9	2.3	4.6	6.8 ± 2.1	32.7 ± 10.7	6.1 ± 1.6	15.8 ± 12.8	2.9 ± 2.4	other	0
103	3 ^h 19 ^m 38.35 ^s	-19°24'22.5"	1649.7	1.7	4.2	6.0 ± 4.1	<29.6	3.6 ± 1.8	-	-	other	1
104	3 ^h 19 ^m 35.83 ^s	-19°23'58.4"	1651.1	2.5	6.9	5.7 ± 4.7	38.3 ± 21.5	5.3 ± 5.9	13.0 ± 24.8	2.7 ± 6.1	Arm	0
105	3 ^h 19 ^m 35.88 ^s	-19°23'58.5"	1642.2	2.4	6.7	2.2 ± 4.1	35.8 ± 38.8	1.2 ± 1.4	1.8 ± 5.6	1.6 ± 5.1	Arm	0
106	3 ^h 19 ^m 35.90 ^s	-19°24'33.5"	1650.4	2.9	5.5	4.4 ± 1.8	<29.6	3.3 ± 1.0	-	-	other	1
107	3 ^h 19 ^m 35.93 ^s	-19°23'57.4"	1649.9	1.8	5.3	3.8 ± 1.5	40.7 ± 18.3	4.0 ± 2.3	6.3 ± 5.7	1.7 ± 1.5	Arm	0

continued GMC catalog

ID	RA (J2000)	Dec (J2000)	v_{LSR} (km s $^{-1}$)	T_{peak} (K)	SN	σ_v (km s $^{-1}$)	R (pc)	M_{mol} ($M_{\odot}$)	M_{vir} ($M_{\odot}$)	α_{vir}	Reg	Flag
108	3 ^h 19 ^m 35.92 ^s	-19°23'58.1"	1646.3	2.2	6.6	3.9 ± 3.2	<29.6	1.7 ± 1.0	-	-	Arm	1
109	3 ^h 19 ^m 35.82 ^s	-19°24'5.9"	1641.5	3.3	8.9	5.2 ± 1.1	38.8 ± 7.5	9.7 ± 0.8	11.1 ± 5.1	1.3 ± 0.6	Arm	0
110	3 ^h 19 ^m 36.03 ^s	-19°24'2.2"	1639.0	2.6	7.3	5.8 ± 1.9	37.7 ± 8.7	5.5 ± 1.1	13.4 ± 9.3	2.7 ± 1.9	Arm	0
111	3 ^h 19 ^m 35.97 ^s	-19°23'54.9"	1641.9	2.4	6.9	2.0 ± 2.9	<29.6	3.6 ± 3.5	-	-	Arm	1
112	3 ^h 19 ^m 36.02 ^s	-19°23'52.6"	1639.5	2.2	5.7	3.9 ± 3.7	13.6 ± 27.1	2.9 ± 2.9	2.2 ± 5.8	0.8 ± 2.2	Arm	0
113	3 ^h 19 ^m 36.03 ^s	-19°23'54.5"	1630.5	3.6	10.3	7.8 ± 2.8	42.6 ± 12.2	12.2 ± 2.8	26.7 ± 18.8	2.4 ± 1.6	Arm	0
114	3 ^h 19 ^m 36.19 ^s	-19°23'52.5"	1628.2	3.0	7.9	6.9 ± 2.3	59.3 ± 16.7	17.1 ± 7.1	29.5 ± 21.4	1.9 ± 1.2	Arm	0
115	3 ^h 19 ^m 36.21 ^s	-19°23'51.9"	1632.7	2.5	6.7	8.4 ± 4.1	46.3 ± 29.0	6.6 ± 3.8	34.0 ± 44.1	5.8 ± 6.9	Arm	0
116	3 ^h 19 ^m 36.46 ^s	-19°23'50.6"	1647.3	1.5	4.1	3.6 ± 6.0	33.3 ± 44.3	1.6 ± 2.5	4.4 ± 15.8	3.0 ± 9.7	Arm	0
117	3 ^h 19 ^m 36.43 ^s	-19°23'50.4"	1635.5	2.0	5.2	6.5 ± 2.5	23.2 ± 11.2	5.0 ± 2.0	10.1 ± 9.2	2.2 ± 1.9	Arm	0
118	3 ^h 19 ^m 36.59 ^s	-19°23'50.0"	1637.3	1.7	4.7	7.4 ± 4.8	29.2 ± 18.3	2.6 ± 1.3	16.4 ± 24.6	7.0 ± 9.5	Arm	0
119	3 ^h 19 ^m 36.22 ^s	-19°23'49.1"	1638.1	2.5	6.0	4.6 ± 1.8	32.5 ± 11.4	4.9 ± 0.9	7.3 ± 6.6	1.6 ± 1.4	Arm	0
120	3 ^h 19 ^m 37.13 ^s	-19°24'40.6"	1631.2	2.2	6.1	5.8 ± 2.3	35.8 ± 9.1	4.8 ± 0.8	12.4 ± 11.1	2.9 ± 2.6	other	0
121	3 ^h 19 ^m 36.14 ^s	-19°24'0.2"	1638.3	1.7	4.9	4.4 ± 2.2	<29.6	2.2 ± 1.3	-	-	Arm	1
122	3 ^h 19 ^m 36.57 ^s	-19°23'48.2"	1635.9	2.7	6.4	5.0 ± 4.7	76.5 ± 47.6	13.1 ± 10.2	20.0 ± 40.4	1.7 ± 3.6	Arm	0
123	3 ^h 19 ^m 36.52 ^s	-19°23'47.7"	1629.3	3.3	8.6	2.2 ± 1.1	49.0 ± 16.7	8.9 ± 5.7	2.5 ± 2.6	0.3 ± 0.3	Arm	0
124	3 ^h 19 ^m 36.00 ^s	-19°23'47.0"	1635.2	2.1	5.1	4.9 ± 1.9	35.6 ± 14.4	5.2 ± 1.7	8.8 ± 8.1	1.9 ± 1.8	Arm	0
125	3 ^h 19 ^m 36.79 ^s	-19°23'43.8"	1631.4	2.2	4.4	4.7 ± 3.2	27.7 ± 24.5	3.2 ± 1.6	6.4 ± 10.4	2.2 ± 3.8	Arm	0
126	3 ^h 19 ^m 36.86 ^s	-19°23'43.9"	1634.5	2.8	5.3	2.4 ± 2.0	<29.6	4.6 ± 3.3	-	-	Arm	1
127	3 ^h 19 ^m 36.75 ^s	-19°23'43.2"	1627.6	3.1	6.6	3.9 ± 3.8	21.6 ± 16.2	5.0 ± 3.1	3.4 ± 6.6	0.8 ± 1.4	Arm	0
128	3 ^h 19 ^m 36.82 ^s	-19°23'42.9"	1633.0	3.0	5.5	4.9 ± 2.3	44.0 ± 15.5	7.2 ± 1.9	11.1 ± 11.2	1.7 ± 1.7	Arm	0
129	3 ^h 19 ^m 37.04 ^s	-19°23'41.5"	1629.7	4.0	6.6	4.7 ± 1.7	34.6 ± 8.2	8.4 ± 1.4	7.9 ± 6.1	1.0 ± 0.8	Arm	0
130	3 ^h 19 ^m 37.32 ^s	-19°24'43.5"	1620.4	2.2	5.8	5.5 ± 2.0	50.8 ± 9.0	8.7 ± 1.5	16.2 ± 11.7	2.1 ± 1.4	other	0
131	3 ^h 19 ^m 36.70 ^s	-19°24'37.2"	1630.0	2.2	6.2	6.7 ± 3.4	<29.6	3.2 ± 4.1	-	-	other	1
132	3 ^h 19 ^m 36.65 ^s	-19°24'36.7"	1621.8	4.2	11.4	5.4 ± 1.6	48.2 ± 15.4	11.2 ± 3.3	14.7 ± 10.0	1.5 ± 0.8	other	0
133	3 ^h 19 ^m 36.48 ^s	-19°24'35.4"	1631.9	1.7	4.2	5.2 ± 4.2	<29.6	4.1 ± 3.3	-	-	other	1
134	3 ^h 19 ^m 36.50 ^s	-19°24'34.7"	1625.8	2.3	6.9	8.8 ± 4.0	<29.6	3.8 ± 4.9	-	-	Bar	1
135	3 ^h 19 ^m 36.51 ^s	-19°24'33.9"	1627.7	3.4	8.6	6.8 ± 3.3	17.4 ± 10.7	6.5 ± 3.9	8.5 ± 10.8	1.5 ± 1.8	Bar	0
136	3 ^h 19 ^m 36.15 ^s	-19°24'33.3"	1636.0	2.0	4.7	4.8 ± 2.2	8.7 ± 8.5	2.0 ± 1.0	2.1 ± 3.0	1.2 ± 1.5	Bar-end	0
137	3 ^h 19 ^m 36.00 ^s	-19°24'3.8"	1635.7	1.9	5.6	4.4 ± 2.6	<29.6	1.4 ± 0.6	-	-	Arm	1
138	3 ^h 19 ^m 36.21 ^s	-19°24'0.4"	1637.4	1.5	4.3	4.8 ± 2.4	<29.6	2.2 ± 1.0	-	-	Arm	1
139	3 ^h 19 ^m 35.98 ^s	-19°23'59.5"	1630.1	2.1	6.3	3.9 ± 2.7	28.0 ± 21.9	3.4 ± 2.1	4.5 ± 6.8	1.5 ± 2.3	Arm	0
140	3 ^h 19 ^m 35.96 ^s	-19°23'59.0"	1633.6	2.0	5.4	6.7 ± 5.2	27.5 ± 24.8	2.3 ± 2.9	13.0 ± 25.3	6.2 ± 11.4	Arm	0
141	3 ^h 19 ^m 36.68 ^s	-19°23'58.0"	1619.1	2.3	6.8	4.3 ± 3.0	52.5 ± 23.9	5.5 ± 2.3	9.9 ± 14.1	2.0 ± 2.9	Arm	0
142	3 ^h 19 ^m 36.71 ^s	-19°23'57.6"	1616.4	2.2	5.9	5.6 ± 5.5	27.8 ± 22.0	3.4 ± 2.6	9.2 ± 21.1	3.0 ± 5.8	Arm	0
143	3 ^h 19 ^m 36.34 ^s	-19°23'56.8"	1632.7	2.0	5.4	7.2 ± 3.5	<29.6	4.7 ± 2.8	-	-	Arm	1

continued GMC catalog

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144	3 ^h 19 ^m 36.35 ^s	−19°23′55.5″	1631.3	2.8	7.8	6.4 ± 2.1	44.1 ± 20.9	10.9 ± 3.7	19.1 ± 13.2	2.0 ± 1.2	Arm	0
145	3 ^h 19 ^m 36.50 ^s	−19°23′52.7″	1632.9	2.1	5.5	5.9 ± 3.3	<29.6	2.2 ± 0.8	-	-	Arm	1
146	3 ^h 19 ^m 36.33 ^s	−19°23′52.2″	1634.4	2.1	5.3	6.5 ± 2.6	32.5 ± 12.6	4.3 ± 1.0	14.2 ± 12.9	3.7 ± 3.2	Arm	0
147	3 ^h 19 ^m 36.60 ^s	−19°23′47.3″	1633.0	3.0	7.2	4.5 ± 4.4	24.3 ± 20.5	3.7 ± 5.4	5.2 ± 11.5	1.6 ± 3.5	Arm	0
148	3 ^h 19 ^m 36.67 ^s	−19°23′47.3″	1622.2	4.9	11.4	4.9 ± 1.3	51.9 ± 15.0	13.4 ± 4.3	13.1 ± 8.5	1.1 ± 0.7	Arm	0
149	3 ^h 19 ^m 36.63 ^s	−19°23′43.4″	1632.6	2.4	5.0	4.5 ± 2.0	<29.6	3.3 ± 1.3	-	-	Arm	1
150	3 ^h 19 ^m 36.30 ^s	−19°23′40.2″	1634.5	2.7	4.8	4.6 ± 2.2	27.0 ± 11.5	4.8 ± 1.5	6.0 ± 6.6	1.4 ± 1.4	Arm	0
151	3 ^h 19 ^m 37.36 ^s	−19°24′50.5″	1627.9	2.0	4.4	5.2 ± 2.9	<29.6	2.7 ± 1.3	-	-	other	1
152	3 ^h 19 ^m 37.09 ^s	−19°24′32.0″	1602.6	3.3	10.7	9.9 ± 5.0	<29.6	10.4 ± 13.4	-	-	Bar	1
153	3 ^h 19 ^m 37.01 ^s	−19°24′31.5″	1607.2	4.4	13.0	9.0 ± 4.3	<29.6	23.7 ± 15.8	-	-	Bar	1
154	3 ^h 19 ^m 37.14 ^s	−19°24′33.2″	1596.8	1.9	5.3	4.6 ± 3.0	31.7 ± 16.3	3.7 ± 2.4	7.0 ± 9.7	2.1 ± 2.7	Bar	0
155	3 ^h 19 ^m 37.13 ^s	−19°24′32.6″	1584.1	1.4	4.0	4.3 ± 3.3	<29.6	1.1 ± 0.9	-	-	Bar	1
156	3 ^h 19 ^m 36.21 ^s	−19°24′31.7″	1634.4	2.0	4.7	2.4 ± 2.0	<29.6	1.1 ± 0.6	-	-	Bar-end	1
157	3 ^h 19 ^m 36.55 ^s	−19°24′30.4″	1620.2	2.6	8.0	5.2 ± 3.5	25.8 ± 25.4	3.1 ± 2.3	7.2 ± 11.6	2.6 ± 3.7	Bar	0
158	3 ^h 19 ^m 36.54 ^s	−19°24′29.5″	1618.0	1.6	4.6	3.9 ± 3.7	<29.6	0.9 ± 0.7	-	-	Bar	1
159	3 ^h 19 ^m 36.59 ^s	−19°24′32.1″	1609.7	2.1	5.8	2.7 ± 2.2	32.1 ± 24.9	3.0 ± 1.3	2.4 ± 5.0	0.9 ± 1.9	Bar	0
160	3 ^h 19 ^m 36.53 ^s	−19°24′30.7″	1608.2	2.2	6.3	4.8 ± 5.1	44.4 ± 38.7	2.5 ± 2.7	10.6 ± 28.5	4.7 ± 13.1	Bar	0
161	3 ^h 19 ^m 36.65 ^s	−19°24′30.7″	1604.2	3.9	11.8	4.9 ± 6.7	17.4 ± 21.5	8.1 ± 11.6	4.4 ± 14.7	0.6 ± 2.1	Bar	0
162	3 ^h 19 ^m 36.72 ^s	−19°24′30.7″	1598.5	4.6	13.4	5.0 ± 2.4	81.9 ± 23.0	40.2 ± 24.4	21.5 ± 19.7	0.6 ± 0.6	Bar	0
163	3 ^h 19 ^m 36.81 ^s	−19°24′31.2″	1599.3	2.2	7.0	6.1 ± 5.4	35.7 ± 21.4	5.7 ± 5.4	14.0 ± 25.2	2.7 ± 5.2	Bar	0
164	3 ^h 19 ^m 36.60 ^s	−19°24′19.1″	1624.9	1.2	4.2	7.5 ± 6.1	<29.6	1.0 ± 0.6	-	-	other	1
165	3 ^h 19 ^m 36.76 ^s	−19°23′57.2″	1614.1	2.9	7.8	6.8 ± 3.0	34.6 ± 15.2	5.1 ± 2.1	16.4 ± 17.2	3.6 ± 3.7	Arm	0
166	3 ^h 19 ^m 36.83 ^s	−19°23′56.1″	1614.9	2.2	6.2	3.5 ± 1.9	96.7 ± 38.0	14.8 ± 7.4	12.6 ± 14.3	1.0 ± 1.1	Arm	0
167	3 ^h 19 ^m 36.21 ^s	−19°23′55.2″	1630.1	2.0	5.6	8.9 ± 3.4	20.1 ± 11.9	3.1 ± 0.9	16.5 ± 16.6	5.9 ± 5.3	Arm	0
168	3 ^h 19 ^m 36.15 ^s	−19°23′55.0″	1634.7	2.2	6.3	2.4 ± 2.0	<29.6	1.4 ± 0.4	-	-	Arm	1
169	3 ^h 19 ^m 36.23 ^s	−19°23′50.5″	1635.8	1.7	4.4	4.7 ± 3.1	8.1 ± 12.4	0.9 ± 0.7	1.9 ± 4.6	2.4 ± 5.5	Arm	0
170	3 ^h 19 ^m 36.27 ^s	−19°23′50.0″	1625.7	2.0	5.1	2.7 ± 2.2	60.5 ± 18.1	5.5 ± 2.7	4.4 ± 7.5	0.9 ± 1.6	Arm	0
171	3 ^h 19 ^m 36.95 ^s	−19°23′44.7″	1619.7	3.3	6.6	3.7 ± 4.2	38.3 ± 26.4	4.8 ± 5.3	5.4 ± 13.3	1.2 ± 3.2	Arm	0
172	3 ^h 19 ^m 37.08 ^s	−19°23′46.9″	1619.8	2.2	4.3	3.2 ± 4.0	30.0 ± 23.1	3.3 ± 3.9	3.1 ± 7.8	1.1 ± 2.7	Arm	0
173	3 ^h 19 ^m 37.02 ^s	−19°23′45.5″	1617.7	4.8	10.2	3.6 ± 1.8	97.7 ± 22.5	28.9 ± 9.1	13.5 ± 13.4	0.5 ± 0.5	Arm	0
174	3 ^h 19 ^m 37.13 ^s	−19°23′47.3″	1614.6	3.0	6.3	5.3 ± 1.9	42.1 ± 12.8	7.3 ± 1.7	12.2 ± 10.1	1.9 ± 1.3	Arm	0
175	3 ^h 19 ^m 36.99 ^s	−19°23′46.6″	1614.4	2.9	5.9	5.1 ± 2.7	27.0 ± 18.5	7.1 ± 4.3	7.3 ± 8.0	1.1 ± 1.3	Arm	0
176	3 ^h 19 ^m 37.04 ^s	−19°23′43.6″	1624.4	2.9	5.3	5.0 ± 1.8	48.9 ± 12.6	8.5 ± 1.5	12.8 ± 10.1	1.7 ± 1.3	Arm	0
177	3 ^h 19 ^m 36.25 ^s	−19°23′40.5″	1627.2	2.3	4.0	4.1 ± 4.7	<29.6	3.1 ± 1.2	-	-	Arm	1
178	3 ^h 19 ^m 37.09 ^s	−19°23′39.1″	1628.7	3.0	4.4	4.5 ± 3.1	<29.6	2.6 ± 1.3	-	-	other	1
179	3 ^h 19 ^m 37.78 ^s	−19°24′45.8″	1620.1	1.9	4.8	3.4 ± 2.0	20.9 ± 11.8	3.2 ± 1.4	2.5 ± 3.5	0.9 ± 1.2	other	0

continued GMC catalog

ID	RA (J2000)	Dec (J2000)	v_{LSR} (km s $^{-1}$)	T_{peak} (K)	SN	σ_v (km s $^{-1}$)	R (pc)	M_{mol} ($M_{\odot}$)	M_{vir} ($M_{\odot}$)	α_{vir}	Reg	Flag
180	3 ^h 19 ^m 37.28 ^s	−19°24′42.5″	1622.4	2.2	6.0	3.9 ± 1.2	48.0 ± 14.6	4.9 ± 1.3	7.6 ± 5.5	1.7 ± 1.1	other	0
181	3 ^h 19 ^m 36.97 ^s	−19°24′39.3″	1627.7	1.9	5.5	4.2 ± 4.6	25.3 ± 30.2	1.5 ± 1.5	4.6 ± 12.1	3.5 ± 7.9	other	0
182	3 ^h 19 ^m 36.95 ^s	−19°24′39.0″	1624.3	1.7	5.1	5.3 ± 3.8	44.2 ± 29.0	3.8 ± 2.6	13.1 ± 22.2	3.8 ± 5.6	other	0
183	3 ^h 19 ^m 36.88 ^s	−19°24′38.6″	1624.2	2.6	7.1	5.0 ± 1.1	56.0 ± 9.5	9.3 ± 1.1	14.4 ± 7.4	1.7 ± 0.8	other	0
184	3 ^h 19 ^m 36.75 ^s	−19°24′35.5″	1612.5	2.5	7.1	5.4 ± 1.4	51.1 ± 10.4	8.3 ± 1.1	15.4 ± 9.0	2.1 ± 1.1	Bar	0
185	3 ^h 19 ^m 35.97 ^s	−19°24′23.1″	1627.7	2.1	5.4	4.6 ± 2.5	<29.6	1.9 ± 0.6	-	-	Bar-end	1
186	3 ^h 19 ^m 36.19 ^s	−19°24′19.7″	1624.6	1.8	5.1	4.0 ± 1.4	56.9 ± 12.0	6.6 ± 1.6	9.7 ± 7.1	1.6 ± 1.1	Bar-end	0
187	3 ^h 19 ^m 36.55 ^s	−19°24′2.2″	1616.3	1.4	4.9	5.3 ± 2.4	43.4 ± 14.4	3.3 ± 1.0	12.9 ± 11.9	4.4 ± 3.6	Arm	0
188	3 ^h 19 ^m 36.88 ^s	−19°23′46.3″	1624.8	2.7	5.7	6.3 ± 2.3	50.0 ± 14.5	5.5 ± 1.8	20.8 ± 17.6	4.2 ± 3.5	Arm	0
189	3 ^h 19 ^m 36.57 ^s	−19°24′33.2″	1617.9	2.3	6.1	6.2 ± 2.2	81.9 ± 10.4	11.5 ± 2.7	32.5 ± 25.7	3.1 ± 2.5	Bar	0
190	3 ^h 19 ^m 36.89 ^s	−19°24′29.0″	1622.6	1.7	4.8	6.3 ± 4.1	<29.6	1.7 ± 0.6	-	-	Bar	1
191	3 ^h 19 ^m 35.75 ^s	−19°24′15.0″	1621.2	1.6	4.3	5.7 ± 2.6	<29.6	2.1 ± 1.0	-	-	Arm	1
192	3 ^h 19 ^m 37.31 ^s	−19°24′13.3″	1617.7	1.6	4.9	4.5 ± 1.9	<29.6	1.3 ± 0.5	-	-	other	1
193	3 ^h 19 ^m 35.99 ^s	−19°24′8.3″	1620.1	1.6	4.8	4.5 ± 2.8	<29.6	1.4 ± 0.7	-	-	Arm	1
194	3 ^h 19 ^m 36.05 ^s	−19°24′7.3″	1619.4	1.7	5.1	3.8 ± 1.7	<29.6	2.9 ± 1.4	-	-	Arm	1
195	3 ^h 19 ^m 36.71 ^s	−19°24′6.3″	1614.7	1.6	4.8	2.6 ± 1.4	52.4 ± 16.3	3.8 ± 1.9	3.6 ± 4.3	1.0 ± 1.2	other	0
196	3 ^h 19 ^m 36.73 ^s	−19°24′5.4″	1614.5	1.6	4.9	2.0 ± 1.6	<29.6	0.6 ± 0.2	-	-	other	1
197	3 ^h 19 ^m 36.97 ^s	−19°23′54.2″	1614.1	2.6	6.4	3.4 ± 1.5	36.0 ± 14.1	5.1 ± 1.7	4.4 ± 4.6	1.0 ± 0.9	Arm	0
198	3 ^h 19 ^m 37.04 ^s	−19°23′54.0″	1612.9	2.4	6.2	4.5 ± 3.0	35.7 ± 16.5	4.4 ± 1.6	7.6 ± 9.7	2.0 ± 2.5	Arm	0
199	3 ^h 19 ^m 37.14 ^s	−19°23′43.9″	1613.9	3.2	5.3	8.4 ± 2.5	27.7 ± 12.8	5.6 ± 1.5	20.3 ± 16.5	4.0 ± 3.1	Arm	0
200	3 ^h 19 ^m 38.30 ^s	−19°24′38.1″	1589.1	2.9	7.8	5.9 ± 5.3	<29.6	10.4 ± 12.6	-	-	Bar	1
201	3 ^h 19 ^m 38.44 ^s	−19°24′37.0″	1567.9	2.4	5.4	3.3 ± 4.7	32.3 ± 25.9	6.9 ± 6.1	3.7 ± 10.9	0.6 ± 1.7	Bar	0
202	3 ^h 19 ^m 38.41 ^s	−19°24′37.6″	1563.1	2.4	5.9	6.6 ± 3.6	48.5 ± 28.2	6.9 ± 4.9	21.7 ± 31.6	3.5 ± 4.5	Bar	0
203	3 ^h 19 ^m 37.13 ^s	−19°24′37.9″	1620.0	2.2	6.6	3.1 ± 0.9	<29.6	2.0 ± 0.5	-	-	Bar	1
204	3 ^h 19 ^m 37.12 ^s	−19°24′31.0″	1611.4	1.6	5.0	5.9 ± 1.9	<29.6	3.1 ± 1.1	-	-	Bar	1
205	3 ^h 19 ^m 37.17 ^s	−19°24′7.3″	1608.3	2.1	6.6	5.0 ± 2.0	<29.6	3.6 ± 0.7	-	-	other	1
206	3 ^h 19 ^m 37.21 ^s	−19°23′49.7″	1615.0	3.5	7.4	2.8 ± 0.8	61.0 ± 8.9	9.7 ± 1.7	5.0 ± 3.1	0.6 ± 0.4	Arm	0
207	3 ^h 19 ^m 37.23 ^s	−19°23′44.5″	1607.0	3.4	6.1	7.5 ± 2.3	67.0 ± 12.0	16.7 ± 2.3	38.9 ± 25.4	2.6 ± 1.6	Arm	0
208	3 ^h 19 ^m 36.74 ^s	−19°24′32.4″	1606.9	1.8	5.0	6.3 ± 3.1	28.1 ± 13.4	5.6 ± 2.2	11.5 ± 13.8	2.3 ± 2.5	Bar	0
209	3 ^h 19 ^m 36.83 ^s	−19°24′32.3″	1606.1	2.1	6.4	3.6 ± 1.8	30.1 ± 10.7	4.6 ± 1.5	4.1 ± 4.9	1.0 ± 1.1	Bar	0
210	3 ^h 19 ^m 36.91 ^s	−19°24′5.4″	1614.8	1.3	4.2	3.0 ± 1.8	<29.6	0.9 ± 0.5	-	-	other	1
211	3 ^h 19 ^m 36.97 ^s	−19°24′5.3″	1610.0	2.0	5.9	5.4 ± 2.5	<29.6	2.6 ± 0.6	-	-	other	1
212	3 ^h 19 ^m 36.58 ^s	−19°23′50.2″	1613.6	1.7	4.3	4.6 ± 2.3	<29.6	1.6 ± 0.6	-	-	Arm	1
213	3 ^h 19 ^m 37.39 ^s	−19°23′44.7″	1607.9	3.7	6.3	3.6 ± 1.1	54.2 ± 11.2	10.1 ± 1.7	7.1 ± 4.5	0.8 ± 0.5	Arm	0
214	3 ^h 19 ^m 36.95 ^s	−19°24′34.1″	1603.4	1.7	5.2	6.1 ± 2.4	16.5 ± 10.5	2.6 ± 0.9	6.4 ± 6.7	2.8 ± 2.5	Bar	0
215	3 ^h 19 ^m 37.60 ^s	−19°24′30.8″	1601.1	2.3	6.5	6.5 ± 1.3	63.4 ± 8.1	13.7 ± 1.6	27.7 ± 11.7	2.3 ± 0.8	Bar	0

continued GMC catalog

ID	RA (J2000)	Dec (J2000)	v_{LSR} (km s^{-1})	T_{peak} (K)	SN	σ_v (km s^{-1})	R (pc)	M_{mol} ($M_{\odot}$)	M_{vir} ($M_{\odot}$)	α_{vir}	Reg	Flag
216	3 ^h 19 ^m 38.09 ^s	-19°24'27.0"	1599.6	1.6	5.0	7.2 ± 4.2	<29.6	1.5 ± 0.5	-	-	other	1
217	3 ^h 19 ^m 38.20 ^s	-19°24'25.9"	1604.8	1.9	5.1	3.4 ± 2.1	<29.6	2.1 ± 0.5	-	-	other	1
218	3 ^h 19 ^m 37.03 ^s	-19°24'5.0"	1600.6	2.1	5.7	5.8 ± 2.5	21.4 ± 7.8	3.2 ± 0.9	7.4 ± 7.4	2.6 ± 2.4	other	0
219	3 ^h 19 ^m 37.06 ^s	-19°24'1.6"	1609.1	2.4	6.5	2.3 ± 1.2	35.9 ± 11.2	3.5 ± 0.7	2.0 ± 2.3	0.6 ± 0.7	other	0
220	3 ^h 19 ^m 37.18 ^s	-19°23'52.2"	1602.6	2.0	4.6	4.4 ± 1.7	24.5 ± 10.9	4.1 ± 1.3	4.9 ± 4.5	1.3 ± 1.3	Arm	0
221	3 ^h 19 ^m 38.06 ^s	-19°24'31.5"	1592.3	1.5	4.1	4.7 ± 1.6	67.8 ± 14.3	6.9 ± 2.7	15.4 ± 11.4	2.5 ± 1.8	Bar	0
222	3 ^h 19 ^m 37.79 ^s	-19°24'27.5"	1599.8	1.5	4.4	1.9 ± 0.9	29.2 ± 15.0	1.7 ± 0.8	1.0 ± 1.2	0.7 ± 0.7	Bar	0
223	3 ^h 19 ^m 37.26 ^s	-19°23'45.7"	1602.8	2.8	5.1	4.5 ± 2.8	23.2 ± 11.8	3.9 ± 1.3	5.0 ± 7.0	1.4 ± 1.8	Arm	0
224	3 ^h 19 ^m 37.03 ^s	-19°24'32.9"	1594.2	2.3	7.2	4.1 ± 1.5	24.5 ± 11.5	3.5 ± 0.7	4.2 ± 3.9	1.3 ± 1.1	Bar	0
225	3 ^h 19 ^m 37.79 ^s	-19°23'50.9"	1585.5	2.7	4.6	8.8 ± 3.9	35.5 ± 17.9	5.8 ± 2.7	28.8 ± 33.1	5.5 ± 6.2	other	0
226	3 ^h 19 ^m 38.28 ^s	-19°24'36.6"	1580.6	2.1	5.6	5.0 ± 5.0	28.0 ± 20.7	3.9 ± 3.4	7.1 ± 15.9	2.1 ± 4.2	Bar	0
227	3 ^h 19 ^m 38.29 ^s	-19°24'36.9"	1567.0	1.6	4.4	8.1 ± 10.5	48.0 ± 33.8	5.3 ± 9.8	32.5 ± 88.4	6.8 ± 19.7	Bar	0
228	3 ^h 19 ^m 38.39 ^s	-19°24'35.7"	1584.1	2.2	5.6	5.1 ± 2.6	25.3 ± 8.2	3.7 ± 0.8	6.8 ± 7.7	2.1 ± 2.2	Bar	0
229	3 ^h 19 ^m 37.94 ^s	-19°24'35.4"	1580.6	1.8	4.7	8.7 ± 3.9	9.8 ± 7.8	4.0 ± 1.2	7.7 ± 9.6	2.2 ± 2.4	Bar	0
230	3 ^h 19 ^m 38.17 ^s	-19°24'33.4"	1587.7	2.0	5.7	4.7 ± 3.4	<29.6	1.4 ± 0.5	-	-	Bar	1
231	3 ^h 19 ^m 37.84 ^s	-19°24'32.7"	1585.2	2.3	6.5	4.8 ± 2.7	<29.6	1.4 ± 0.3	-	-	Bar	1
232	3 ^h 19 ^m 37.01 ^s	-19°24'14.3"	1581.9	1.4	4.7	8.8 ± 4.8	<29.6	1.3 ± 0.7	-	-	other	1
233	3 ^h 19 ^m 36.59 ^s	-19°23'37.3"	1578.5	3.1	4.9	5.6 ± 2.6	<29.6	2.9 ± 1.8	-	-	Arm	1

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Bibliography

- Abel, T., Anninos, P., Zhang, Y., & Norman, M. L. 1997, *New Astronomy*, 2, 181
- Aouad, C. J., James, P. A., & Chilingarian, I. V. 2020, *MNRAS*, 496, 5211
- Athanassoula, E. 1992, *MNRAS*, 259, 345
- Böker, T., Falcón-Barroso, J., Schinnerer, E., Knapen, J. H., & Ryder, S. 2008, *AJ*, 135, 479
- Bertoldi, F. & McKee, C. F. 1992, *ApJ*, 395, 140
- Beuther, H., Meidt, S., Schinnerer, E., Paladino, R., & Leroy, A. 2017, *A&A*, 597, A85
- Bigiel, F., Leroy, A., Walter, F., et al. 2008, *AJ*, 136, 2846
- Bigiel, F., Leroy, A. K., Jiménez-Donaire, M. J., et al. 2016, *ApJ*, 822, L26
- Bolatto, A. D., Leroy, A. K., Rosolowsky, E., Walter, F., & Blitz, L. 2008, *ApJ*, 686, 948
- Bolatto, A. D., Wolfire, M., & Leroy, A. K. 2013, *ARAA*, 51, 207
- Bolatto, A. D., Wong, T., Utomo, D., et al. 2017, *ApJ*, 846, 159
- Boselli, A., Cortese, L., Boquien, M., et al. 2014, *A&A*, 564, A66
- Bresolin, F., Garnett, D. R., & Kennicutt, Robert C., J. 2004, *ApJ*, 615, 228
- Brummel-Smith, C., Bryan, G., Butsky, I., et al. 2019, *The Journal of Open Source Software*, 4, 1636
- Bryan, G. L., Norman, M. L., O’Shea, B. W., et al. 2014, *ApJS*, 211, 19
- Caldú-Primo, A., Schrubba, A., Walter, F., et al. 2015, *AJ*, 149, 76
- Calzetti, D., Kennicutt, R. C., Engelbracht, C. W., et al. 2007, *ApJ*, 666, 870
- Casasola, V., Cassarà, L. P., Bianchi, S., et al. 2017, *A&A*, 605, A18
- Chevance, M., Kruijssen, J. M. D., Hygate, A. P. S., et al. 2020a, *MNRAS*, 493, 2872
- Chevance, M., Kruijssen, J. M. D., Vazquez-Semadeni, E., et al. 2020b, *Space Science Reviews*, 216, 50
- Cohen, R. S., Dame, T. M., Garay, G., et al. 1988, *ApJL*, 331, L95
- Colombo, D., Hughes, A., Schinnerer, E., et al. 2014, *ApJ*, 784, 3
- Cornwell, T. J. 2008, *IEEE J. Sel. Top. Signal Process.*, 2, 793
- Daddi, E., Dannerbauer, H., Krips, M., et al. 2009a, *ApJL*, 695, L176
- Daddi, E., Dannerbauer, H., Stern, D., et al. 2009b, *ApJ*, 694, 1517
- Daddi, E., Elbaz, D., Walter, F., et al. 2010, *ApJL*, 714, L118

- Dahmen, G., Huttemeister, S., Wilson, T. L., & Mauersberger, R. 1998, *A&A*, 331, 959
- Davies, R. D., Elliott, K. H., & Meaburn, J. 1976, *MNRAS*, 81, 89
- Dekel, A., Birnboim, Y., Engel, G., et al. 2009, *Nature*, 457, 451
- Dessauges-Zavadsky, M., Richard, J., Combes, F., et al. 2019, *Nature Astronomy*, 3, 1115
- Dobbs, C. L. 2008, *MNRAS*, 391, 844
- Dobbs, C. L., Burkert, A., & Pringle, J. E. 2011, *MNRAS*, 417, 1318
- Dobbs, C. L., Pringle, J. E., & Duarte-Cabral, A. 2015, *MNRAS*, 446, 3608
- Donovan Meyer, J., Koda, J., Momose, R., et al. 2013, *ApJ*, 772, 107
- Draine, B. T. 2011, *Physics of the Interstellar and Intergalactic Medium*, Princeton Univ. Press, Princeton, NJ
- Egusa, F., Hirota, A., Baba, J., & Muraoka, K. 2018, *ApJ*, 854, 90
- Elmegreen, B. G. 2018, *ApJ*, 854, 16
- Emsellem, E., Renaud, F., Bournaud, F., et al. 2015, *MNRAS*, 446, 2468
- Engargiola, G., Plambeck, R. L., Rosolowsky, E., & Blitz, L. 2003, *ApJS*, 149, 343
- England, M. N. 1989a, *ApJ*, 344, 669
- England, M. N. 1989b, *ApJ*, 337, 191
- Enokiya, R., Torii, K., & Fukui, Y. 2019, *PASJ*, psz119, doi:10.1093/pasj/psz119
- Faesi, C. M., Lada, C. J., & Forbrich, J. 2018, *ApJ*, 857, 19
- Ferland, G. J., Korista, K. T., Verner, D. A., et al. 1998, *PASP*, 110, 761
- Field, G. B., Goldsmith, D. W., & Habing, H. J. 1969, *ApJL*, 155, L149
- Finn, M. K., Johnson, K. E., Brogan, C. L., et al. 2019, *ApJ*, 874, 120
- Freyer, D. T., Koda, J., Pope, A., et al. 2008, *ApJL*, 680, L21
- Freeman, P., Rosolowsky, E., Kruijssen, J. M. D., Bastian, N., & Adamo, A. 2017, *MNRAS*, 468, 1769
- Fujimoto, Y., Bryan, G. L., Tasker, E. J., Habe, A., & Simpson, C. M. 2016, *MNRAS*, 461, 1684
- Fujimoto, Y., Chevance, M., Haydon, D. T., Krumholz, M. R., & Kruijssen, J. M. D. 2019, *MNRAS*, 487, 1717
- Fujimoto, Y., Maeda, F., Habe, A., & Ohta, K. 2020, *MNRAS*, 494, 2131
- Fujimoto, Y., Tasker, E. J., & Habe, A. 2014a, *MNRAS*, 445, L65
- Fujimoto, Y., Tasker, E. J., Wakayama, M., & Habe, A. 2014b, *MNRAS*, 439, 936
- Fukui, Y., Habe, A., Inoue, T., Enokiya, R., & Tachihara, K. 2020, preprint(arXiv:2009.05077)
- Fukui, Y., Harada, R., Tokuda, K., et al. 2015, *ApJL*, 807, L4
- Fukui, Y. & Kawamura, A. 2010, *ARAA*, 48, 547
- Fukui, Y., Kawamura, A., Minamidani, T., et al. 2008, *ApJS*, 178, 56
- Fukui, Y., Mizuno, N., Yamaguchi, R., Mizuno, A., & Onishi, T. 2001, *PASJ*, 53, L41

- Fukui, Y., Mizuno, N., Yamaguchi, R., et al. 1999, PASJ, 51, 745
- Fukui, Y., Ohama, A., Hanaoka, N., et al. 2014, ApJ, 780, 36
- Fukui, Y., Torii, K., Hattori, Y., et al. 2018, ApJ, 859, 166
- Fukui, Y., Torii, K., Ohama, A., et al. 2016, ApJ, 820, 26
- Furukawa, N., Dawson, J. R., Ohama, A., et al. 2009, ApJ, 696, L115
- Gallagher, M. J., Leroy, A. K., Bigiel, F., et al. 2018, ApJ, 858, 90
- Gao, Y. & Solomon, P. M. 2004, ApJ, 606, 271
- Garcia-Burillo, S., Guelin, M., Cernicharo, J., & Dahlem, M. 1992, A&A, 266, 21
- Gerin, M., Nakai, N., & Combes, F. 1988, A&A, 203, 44
- Gil de Paz, A., Boissier, S., Madore, B. F., et al. 2007, ApJS, 173, 185
- Gilden, D. L. 1984, ApJ, 279, 335
- Gratier, P., Braine, J., Rodriguez-Fernandez, N. J., et al. 2012, A&A, 542, A108
- Greve, T. R., Bertoldi, F., Smail, I., et al. 2005, MNRAS, 359, 1165
- Grisdale, K., Agertz, O., Renaud, F., & Romeo, A. B. 2018, MNRAS, 479, 3167
- Gutiérrez, L., Beckman, J. E., & Buenrostro, V. 2011, AJ, 141, 113
- Habe, A. & Ohta, K. 1992, PASJ, 44, 203
- Hakobyan, A. A., Karapetyan, A. G., Barkhudaryan, L. V., et al. 2016, MNRAS, 456, 2848
- Handa, T., Nakai, N., Sofue, Y., Hayashi, M., & Fujimoto, M. 1990, PASJ, 42, 1
- Hasegawa, T., Sato, F., Whiteoak, J. B., & Miyawaki, R. 1994, ApJL, 429, L77
- Heyer, M., Krawczyk, C., Duval, J., & Jackson, J. M. 2009, ApJ, 699, 1092
- Heyer, M. H. & Brunt, C. M. 2004, ApJL, 615, L45
- Hirota, A., Egusa, F., Baba, J., et al. 2018, PASJ, 70
- Hirota, A., Kuno, N., Baba, J., et al. 2014, PASJ, 66, 46
- Hollyhead, K., Bastian, N., Adamo, A., et al. 2015, MNRAS, 449, 1106
- Houghton, S., Whiteoak, J. B., Koribalski, B., et al. 1997, A&A, 325, 923
- Hsieh, P.-Y., Matsushita, S., Liu, G., et al. 2011, ApJ, 736, 129
- Hughes, A., Meidt, S., Colombo, D., et al. 2016, in IAU Symp. 315, From Interstellar Clouds to Star-forming Galaxies: Universal Processes?, ed. P. Jablonka, P. André, & F. van der Tak (Cambridge: Cambridge Univ. Press), 30
- Hughes, A., Meidt, S. E., Colombo, D., et al. 2013, ApJ, 779, 46
- Hygate, A. P. S., Kruijssen, J. M. D., Chevance, M., et al. 2019, MNRAS, 488, 2800
- Ikuta, C. & Sofue, Y. 1997, PASJ, 49, 323
- Inoue, T. & Inutsuka, S.-i. 2009, ApJ, 704, 161
- Inoue, T., Yamazaki, R., & Inutsuka, S.-i. 2009, ApJ, 695, 825

- Inutsuka, S.-i., Inoue, T., Iwasaki, K., & Hosokawa, T. 2015, *A&A*, 580, A49
- Israel, F. P., Johansson, L. E. B., Lequeux, J., et al. 1993, *A&A*, 276, 25
- Israel, F. P., Johansson, L. E. B., Rubio, M., et al. 2003, *A&A*, 406, 817
- James, P. A., Bretherton, C. F., & Knapen, J. H. 2009, *A&A*, 501, 207
- James, P. A. & Percival, S. M. 2018, *MNRAS*, 474, 3101
- Jarrett, T. H., Cohen, M., Masci, F., et al. 2011, *ApJ*, 735, 112
- Jin, K., Salim, D. M., Federrath, C., et al. 2017, *MNRAS*, 469, 383
- Kaneda, H., Yamagishi, M., Suzuki, T., & Onaka, T. 2009, *ApJL*, 698, L125
- Kaneko, H., Kuno, N., & Saitoh, T. R. 2018, *ApJ*, 860, L14
- Kawamura, A., Mizuno, Y., Minamidani, T., et al. 2009, *ApJS*, 184, 1
- Kenney, J. D. P. & Lord, S. D. 1991, *ApJ*, 381, 118
- Kennicutt, R. C. 1998a, *ARAA*, 36, 189
- Kennicutt, R. C. & Evans, N. J. 2012, *ARAA*, 50, 531
- Kennicutt, Jr., R. C. 1989, *ApJ*, 344, 685
- Kennicutt, Jr., R. C. 1998b, *ApJ*, 498, 541
- Knapen, J. H., Stedman, S., Bramich, D. M., Folkes, S. L., & Bradley, T. R. 2004, *A&A*, 426, 1135
- Kobayashi, M. I. N., Inutsuka, S.-i., Kobayashi, H., & Hasegawa, K. 2017, *ApJ*, 836, 175
- Koda, J., Sawada, T., Sakamoto, K., et al. 2020, *ApJL*, 890, L10
- Koda, J., Scoville, N., Hasegawa, T., et al. 2012, *ApJ*, 761, 41
- Koda, J., Scoville, N., Sawada, T., et al. 2009, *ApJ*, 700, L132
- Kohno, M., Tachihara, K., Torii, K., et al. 2020, *PASJ*, psaa015, doi:10.1093/pasj/psaa015
- Kreckel, K., Faesi, C., Kruijssen, J. M. D., et al. 2018, *ApJ*, 863, L21
- Kruijssen, J. M. D., Schrubba, A., Chevance, M., et al. 2019, *Nature*, 569, 519
- Kuno, N., Sato, N., Nakanishi, H., et al. 2007, *PASJ*, 59, 117
- Kwan, J. 1979, *ApJ*, 229, 567
- Laine, S., Kenney, J. D. P., Yun, M. S., & Gottesman, S. T. 1999, *ApJ*, 511, 709
- Lang, P., Meidt, S. E., Rosolowsky, E., et al. 2020, *ApJ*, 897, 122
- Larson, R. B. 1981, *MNRAS*, 194, 809
- Law, K.-H., Gordon, K. D., & Misselt, K. A. 2011, *ApJ*, 738, 124
- Leroy, A. K., Bigiel, F., de Blok, W. J. G., et al. 2012, *AJ*, 144, 3
- Leroy, A. K., Bolatto, A. D., Ostriker, E. C., et al. 2015, *ApJ*, 801, 25
- Leroy, A. K., Walter, F., Bigiel, F., et al. 2009, *AJ*, 137, 4670
- Leroy, A. K., Walter, F., Brinks, E., et al. 2008, *AJ*, 136, 2782

- Leroy, A. K., Walter, F., Sandstrom, K., et al. 2013, *AJ*, 146, 19
- Li, Q., Tan, J. C., Christie, D., Bisbas, T. G., & Wu, B. 2018, *PASJ*, 70, S56
- Lindblad, P. A. B., Kristen, H., Joersaeter, S., & Hoegbom, J. 1997, *A&A*, 317, 36
- Liszt, H. S. & Pety, J. 2012, *A&A*, 541, A58
- Longmore, S. N., Bally, J., Testi, L., et al. 2013, *MNRAS*, 429, 987
- Lord, S. D. & Kenney, J. D. P. 1991, *ApJ*, 381, 130
- Loren, R. B. 1976, *ApJ*, 209, 466
- Lundgren, A. A., Wiklind, T., Olofsson, H., & Rydbeck, G. 2004, *A&A*, 413, 505
- Maeda, F., Ohta, K., Fujimoto, Y., & Habe, A. 2020a, *MNRAS*, 493, 5045
- Maeda, F., Ohta, K., Fujimoto, Y., Habe, A., & Baba, J. 2018, *PASJ*, 70, 37
- Maeda, F., Ohta, K., Fujimoto, Y., Habe, A., & Ushio, K. 2020b, *MNRAS*, 495, 3840
- McKee, C. F. & Ostriker, J. P. 1977, *ApJ*, 218, 148
- Meidt, S. E., Hughes, A., Dobbs, C. L., et al. 2015, *ApJ*, 806, 72
- Meidt, S. E., Schinnerer, E., García-Burillo, S., et al. 2013, *ApJ*, 779, 45
- Minamidani, T., Nishimura, A., Miyamoto, Y., et al. 2016, in *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, Vol. 9914, *Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy VIII*, 99141Z
- Momose, R., Okumura, S. K., Koda, J., & Sawada, T. 2010, *ApJ*, 721, 383
- Morokuma-Matsui, K. & Muraoka, K. 2017, *ApJ*, 837, 137
- Morokuma-Matsui, K., Sorai, K., Watanabe, Y., & Kuno, N. 2015, *PASJ*, 67, 2
- Motte, F., Nguyễn Luong, Q., Schneider, N., et al. 2014, *A&A*, 571, A32
- Mould, J. R., Huchra, J. P., Freedman, W. L., et al. 2000, *ApJ*, 529, 786
- Muraoka, K., Kohno, K., Tosaki, T., et al. 2009, *PASJ*, 61, 163
- Muraoka, K., Kohno, K., Tosaki, T., et al. 2007, *PASJ*, 59, 43
- Muraoka, K., Kondo, H., Tokuda, K., et al. 2020, *ApJ*, 903, 94
- Muraoka, K., Sorai, K., Kuno, N., et al. 2016, *PASJ*, 68, 89
- Murphy, E. J., Condon, J. J., Schinnerer, E., et al. 2011, *ApJ*, 737, 67
- Myers, P. C. 1978, *ApJ*, 225, 380
- Nakai, N. & Kuno, N. 1995, *PASJ*, 47, 761
- Nakano, M., Ichikawa, T., Tanaka, Y. D., Nakai, N., & Sofue, Y. 1987, *PASJ*, 39, 57
- Navarro, J. F., Frenk, C. S., & White, S. D. M. 1996, *ApJ*, 462, 563
- Nimori, M., Habe, A., Sorai, K., et al. 2013, *MNRAS*, 429, 2175
- Ohama, A., Dawson, J. R., Furukawa, N., et al. 2010, *ApJ*, 709, 975
- Ohta, K., Sasaki, M., & Saito, M. 1986, *PASJ*, 38, 677

- Ohta, K., Sasaki, M., & Saito, M. 1988, PASJ, 40, 653
- Ohta, K., Sasaki, M., Yamada, T., Saito, M., & Nakai, N. 1992, PASJ, 44, 585
- Ohta, K., Tomita, A., Saito, M., Sasaki, M., & Nakai, N. 1993, PASJ, 45, L21
- Osterbrock, D. E. 1989, *Astrophysics of gaseous nebulae and active galactic nuclei*, Univ. Science Books, Mill Valley, CA
- Pan, H.-A. & Kuno, N. 2017, ApJ, 839, 133
- Pety, J., Schinnerer, E., Leroy, A. K., et al. 2013, ApJ, 779, 43
- Querejeta, M., Lelli, F., Schinnerer, E., et al. 2020, arXiv:2011.01287 [astro-ph], preprint(arXiv:2011.01287)
- Querejeta, M., Schinnerer, E., Schrubba, A., et al. 2019, A&A, 625, A19
- Rand, R. J., Lord, S. D., & Higdon, J. L. 1999, ApJ, 513, 720
- Randriamampandry, T. H., Combes, F., Carignan, C., & Deg, N. 2015, MNRAS, 454, 3743
- Randriamampandry, T. H., Deg, N., Carignan, C., & Widrow, L. M. 2018, A&A, 618, A106
- Rebolledo, D., Wong, T., Leroy, A., Koda, J., & Meyer, J. D. 2012, ApJ, 757, 155
- Rebolledo, D., Wong, T., Xue, R., et al. 2015, ApJ, 808, 99
- Regan, M. W. 2000, ApJ, 541, 142
- Regan, M. W., Sheth, K., & Vogel, S. N. 1999, ApJ, 526, 97
- Regan, M. W., Thornley, M. D., Helfer, T. T., et al. 2001, ApJ, 561, 218
- R  my-Ruyer, A., Madden, S. C., Galliano, F., et al. 2014, A&A, 563, A31
- Renaud, F., Bournaud, F., Emsellem, E., et al. 2015, MNRAS, 454, 3299
- Reynaud, D. & Downes, D. 1997, A&A, 319, 737
- Reynaud, D. & Downes, D. 1998, A&A, 337, 671
- Reynaud, D. & Downes, D. 1999, A&A, 347, 37
- Rich, J. W., de Blok, W. J. G., Cornwell, T. J., et al. 2008, AJ, 136, 2897
- Riechers, D. A., Walter, F., Carilli, C. L., et al. 2006, ApJ, 650, 604
- Rogstad, D. H., Lockhart, I. A., & Wright, M. C. H. 1974, ApJ, 193, 309
- Roman-Duval, J., Heyer, M., Brunt, C. M., et al. 2016, ApJ, 818, 144
- Rosolowsky, E. 2007, ApJ, 654, 240
- Rosolowsky, E. & Blitz, L. 2005, ApJ, 623, 826
- Rosolowsky, E., Engargiola, G., Plambeck, R., & Blitz, L. 2003, ApJ, 599, 258
- Rosolowsky, E., Keto, E., Matsushita, S., & Willner, S. P. 2007, ApJ, 661, 830
- Rosolowsky, E. & Leroy, A. 2006, PASP, 118, 590
- Rubio, M., Garay, G., Montani, J., & Thaddeus, P. 1991, ApJ, 368, 173
- Rubio, M., Lequeux, J., & Boulanger, F. 1993, A&A, 271, 9

- Rubio, M., Lequeux, J., Boulanger, F., et al. 1996, *ApJS*, 118, 263
- Saigo, K., Onishi, T., Nayak, O., et al. 2017, *ApJ*, 835, 108
- Saintonge, A., Kauffmann, G., Kramer, C., et al. 2011, *MNRAS*, 415, 32
- Saito, T. 2019, in *ALMA2019: Science Results and Cross-Facility Synergies*, held 14-18 October, 2019 in Cagliari, Italy, doi:10.5281/zenodo.3585440
- Sakamoto, K., Matsushita, S., Peck, A. B., Wiedner, M. C., & Iono, D. 2004, *ApJ*, 616, L59
- Sakamoto, S., Hasegawa, T., Hayashi, M., Handa, T., & Oka, T. 1995, *ApJS*, 100, 125
- Sakamoto, S., Hayashi, M., Hasegawa, T., Handa, T., & Oka, T. 1994, *ApJ*, 425, 641
- Salmi, F., Daddi, E., Elbaz, D., et al. 2012, *ApJL*, 754, L14
- Salpeter, E. E. 1955, *ApJ*, 121, 161
- Sandage, A. & Tammann, G. A. 1981, *A Revised Shapley-Ames Catalog of Bright Galaxies*, Carnegie Institution, Washington
- Sandqvist, A. 1999, *A&A*, 343, 367
- Sandqvist, A., Joersaeter, S., & Lindblad, P. O. 1995, *A&A*, 295, 585
- Sano, H., Tsuge, K., Tokuda, K., et al. 2020, *PASJ*, psaa045, doi:10.1093/pasj/psaa045
- Sawada, T., Ikeda, N., Sunada, K., et al. 2008, *PASJ*, 60, 445
- Schinnerer, E., Meidt, S. E., Colombo, D., et al. 2017, *ApJ*, 836, 62
- Schinnerer, E., Meidt, S. E., Pety, J., et al. 2013, *ApJ*, 779, 42
- Schmidt, M. 1959, *ApJ*, 129, 243
- Schmidt, T. M., Bigiel, F., Klessen, R. S., & de Blok, W. J. G. 2016, *MNRAS*, 457, 2642
- Schruba, A., Kruijssen, J. M. D., & Leroy, A. K. 2019, *ApJ*, 883, 2
- Schruba, A., Leroy, A. K., Walter, F., et al. 2011, *AJ*, 142, 37
- Schruba, A., Leroy, A. K., Walter, F., et al. 2012, *AJ*, 18
- Scoville, N. Z., Sanders, D. B., & Clemens, D. P. 1986, *ApJL*, 310, L77
- Sellwood, J. A. & Sánchez, R. Z. 2010, *MNRAS*, 404, 1733
- Sempere, M. J., Combes, F., & Casoli, F. 1995, *A&A*, 299, 371
- Sheffer, Y., Rogers, M., Federman, S. R., et al. 2008, *ApJ*, 687, 1075
- Sheth, K., Regan, M. W., Vogel, S. N., & Teuben, P. J. 2000, *ApJ*, 532, 221
- Sheth, K., Vogel, S. N., Wilson, C. D., & Dame, T. M. 2008, *ApJ*, 675, 330
- Snow, T. P. & McCall, B. J. 2006, *ARAA*, 44, 367
- Sofue, Y. & Nakai, N. 1993, *PASJ*, 45, 139
- Solomon, P. M., Downes, D., Radford, S. J. E., & Barrett, J. W. 1997, *ApJ*, 478, 144
- Solomon, P. M., Rivolo, A. R., Barrett, J., & Yahil, A. 1987, *ApJ*, 319, 730
- Sorai, K., Kuno, N., Muraoka, K., et al. 2019, *PASJ*, 71S, 14

- Sorai, K., Kuno, N., Nishiyama, K., et al. 2012, PASJ, 64, 51
- Spekkens, K. & Sellwood, J. A. 2007, ApJ, 664, 204
- Spinoso, D., Bonoli, S., Dotti, M., et al. 2017, MNRAS, 465, 3729
- Stark, A. A. & Brand, J. 1989, ApJ, 339, 763
- Stephens, M. A. 1970, Journal of the Royal Statistical Society: Series B (Methodological), 32, 115
- Stewart, K. R. 2017, ApJ, 15
- Stone, J. M. & Norman, M. L. 1992, ApJS, 80, 753
- Stone, M. E. 1970a, ApJ, 159, 277
- Stone, M. E. 1970b, ApJ, 159, 293
- Sun, J., Leroy, A. K., Schrubba, A., et al. 2018, ApJ, 860, 172
- Tacconi, L. J., Genzel, R., Neri, R., et al. 2010, Nature, 463, 781
- Takahira, K., Shima, K., Habe, A., & Tasker, E. J. 2018, PASJ, 70, S58
- Takahira, K., Tasker, E. J., & Habe, A. 2014, ApJ, 792, 63
- Tan, J. C. 2000, ApJ, 536, 173
- Tasker, E. J. & Tan, J. C. 2009, ApJ, 700, 358
- Tasker, E. J., Wadsley, J., & Pudritz, R. 2015, ApJ, 801, 33
- Tokuda, K., Muraoka, K., Kondo, H., et al. 2020, ApJ, 896, 36
- Torii, K., Fujita, S., Nishimura, A., et al. 2019, PASJ, 71, S2
- Torii, K., Hattori, Y., Hasegawa, K., et al. 2017, ApJ, 835, 142
- Tosaki, T., Kohno, K., Harada, N., et al. 2017, PASJ, 69, 18
- Truelove, J. K., Klein, R. I., McKee, C. F., et al. 1998, ApJ, 495, 821
- Tubbs, A. D. 1982, ApJ, 255, 458
- Tumlinson, J., Peebles, M. S., & Werk, J. K. 2017, ARAA, 55, 389
- Usero, A., Leroy, A. K., Walter, F., et al. 2015, AJ, 150, 115
- Utomo, D., Blitz, L., Davis, T., et al. 2015, ApJ, 803, 16
- Vanzella, E., Calura, F., Meneghetti, M., et al. 2019, MNRAS, 483, 3618
- Vogel, S. N., Boulanger, F., & Ball, R. 1987, ApJL, 321, L145
- Wada, K. 2008, ApJ, 675, 188
- Watanabe, Y., Sorai, K., Kuno, N., & Habe, A. 2011, MNRAS, 411, 1409
- Weiß, A., Neininger, N., Hüttemeister, S., & Klein, U. 2001, A&A, 365, 571
- Williams, J. P. & McKee, C. F. 1997, ApJ, 476, 166
- Wilson, C. D. & Reid, I. N. 1991, ApJL, 366, L11
- Wilson, C. D. & Scoville, N. 1990, ApJ, 363, 435

BIBLIOGRAPHY

- Wilson, C. D., Warren, B. E., Israel, F. P., et al. 2009, *ApJ*, 693, 1736
- Wilson, R. W., Jefferts, K. B., & Penzias, A. A. 1970, *ApJL*, 161, L43
- Wolfire, M. G., Hollenbach, D., McKee, C. F., Tielens, A. G. G. M., & Bakes, E. L. O. 1995, *ApJ*, 443, 152
- Wright, E. L., Eisenhardt, P. R. M., Mainzer, A. K., et al. 2010, *AJ*, 140, 1868
- Wu, B., Tan, J. C., Nakamura, F., et al. 2017, *ApJ*, 835, 137
- Yajima, Y., Sorai, K., Kuno, N., et al. 2019, *PASJ*, 71, S13
- Zurita, A., Relaño, M., Beckman, J. E., & Knapen, J. H. 2004, *A&A*, 413, 73