*Resolving the Rise and Fall of Star Formation in Galaxies*
*Proceedings IAU Symposium No. 373, 2023*
*T. Wong & W.-T. Kim, eds.*
doi:10.1017/S1743921322004367



# Investigating the Drivers of CO-to-$H_2$ Conversion Factor Variations in Nearby Galaxy Centers

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**Abstract.** The CO-to-$H_2$ conversion factor ($\alpha_{CO}$) is crucial for accurate estimation of the amount and properties of molecular gas. However, $\alpha_{CO}$ is known to vary with environmental conditions, and previous kpc-scale studies have revealed lower $\alpha_{CO}$ in the centers of some barred galaxies, including NGC 3351, 3627, and 4321. We present ALMA Band 3, 6, and 7 observations toward the inner ∼2 kpc of these galaxies tracing $^{12}$CO, $^{13}$CO, and C$^{18}$O lines at ∼100 pc resolution. We show that dynamical effects resulting from turbulence/shear can lead to substantially lower $\alpha_{CO}$ in the bar-driven inflows of NGC 3351 due to lower optical depth. A clear, positive correlation between $\alpha_{CO}$ and $^{12}$CO optical depth is seen in all three galaxy centers. We also find that the CO/$^{13}$CO(2–1) ratio mainly traces the $^{12}$CO optical depth, and thus it may be a useful observable in predicting $\alpha_{CO}$ variation in galaxy centers.

**Keywords.** Barred spiral galaxies (136); CO line emission (262); Galaxy nuclei (609); Molecular gas (1073); Star forming regions (1565)

## 1. Introduction

Molecular gas plays an important role in star formation and galaxy evolution. To trace the cold molecular gas where stars are born, most studies use the low-$J$ rotational lines of carbon monoxide ($^{12}$C$^{16}$O; hereafter CO). Because of this, the CO-to-$H_2$ conversion factor ($\alpha_{CO}$) is the basis of measuring the amount and properties of molecular gas. $\alpha_{CO}$ is defined as the ratio of molecular gas mass to the CO 1–0 luminosity. While most studies assume a constant $\alpha_{CO}$ value similar to the Milky Way disk average, $\alpha_{CO}$ varies within and between galaxies, and it can vary by as much as orders of magnitude depending on environmental conditions such as metallicity, density, temperature, and opacity (Bolatto *et al.* (2013)). Thus, investigating the variation of $\alpha_{CO}$ and its relation to gas properties is critical to understanding molecular gas and star formation in galaxies.

Recent studies have shown that galaxy centers, especially those with spiral arms or stellar bars, tend to have lower $\alpha_{CO}$ than the typical Galactic value (Sandstrom *et al.* (2013); Israel (2020)). The specific environmental properties that drive such $\alpha_{CO}$ variations are not fully understood. With diverse gas conditions and/or altered gas dynamics, galaxy centers are ideal nearby laboratories for studying how $\alpha_{CO}$ depends on physical properties. In this work, we present a combination of results on three nearby galaxy centers: NGC 3351, 3627, and 4321. This will include our preliminary results on NGC 3627 and 4321, as well as the published results on NGC 3351 from Teng *et al.* (2022).

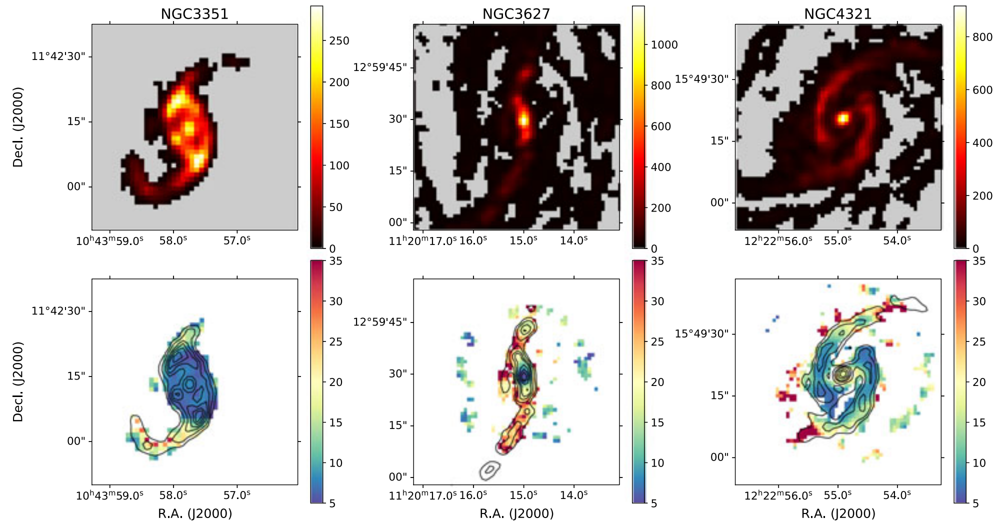


**Figure 1.** Maps of the CO 2–1 integrated intensity (top) and CO(2–1)/$^{13}$CO(2–1) line ratio (bottom). *Top:* The gray areas show regions with $< 3\sigma$ detection in CO 2–1. *Bottom:* The masking ensure pixels with S/N $> 3$ in both lines and 12-m/total flux recovered rate $> 70\%$. The overlaid contours represent the CO 2–1 integrated intensity shown in top panels.

## 2. ALMA Observations and Multi-line Modeling

To study what physical processes cause the $\alpha_{\rm CO}$ variations in galaxy centers, we select three nearby barred galaxies that were found by previous kpc-scale observations to have lower-than-Galactic $\alpha_{\rm CO}$ in their central few kpc. To accurately measure the gas properties and $\alpha_{\rm CO}$, we need optically-thin tracers like $^{13}$CO and C$^{18}$O to estimate the optical depths in different lines. Therefore, we observe the inner $\sim$2 kpc regions of these galaxies with six low-$J$ CO (1–0 and 2–1), $^{13}$CO (2–1 and 3–2), and C$^{18}$O (2–1 and 3–2) lines using the Atacama Large Millimeter/submillimeter Array (ALMA).

Figure 1 shows the integrated intensity maps in CO 2–1 as well as the CO(2–1)/ $^{13}$CO(2–1) line ratios with intensity units of K km s$^{-1}$. We match the beam sizes of all the lines to $\sim$100 pc, which corresponds to the scale of Giant Molecular Clouds. In the central $\sim$1 kpc of NGC 3351, we see a clear star-forming ring around the nucleus, and the ring is connected to two inflow arms driven by the stellar bar in the galaxy center. Interestingly, these bar-driven inflow arms also show a significantly higher CO/$^{13}$CO 2–1 line ratio, which could be due to variations in optical depths or CO isotopologue abundances. In NGC 3627 and 4321, the observations reveal a bright nucleus in the inner $\sim$300 pc of both galaxies, and those nuclei show distinct CO/$^{13}$CO line ratios from other regions.

To determine the molecular gas properties in different regions of these galaxies, we use the non-LTE radiative transfer code *RADEX* (van der Tak *et al.* (2007)) to jointly model the intensities of all six observed lines under various combination of CO column density per linewidth, kinetic temperature, $H_2$ volume density, CO/$^{13}$CO and $^{13}$CO/C$^{18}$O abundances, and the beam-filling factor. Using a Bayesian likelihood analysis, we derive probability distributions for each parameter on a pixel-by-pixel basis (see Teng *et al.* (2022) for modeling details). We further derive $\alpha_{\rm CO}$ distributions via the modeled parameters and CO 1–0 intensities, assuming a CO-to-$H_2$ abundance of $3 \times 10^{-4}$. We present our $\alpha_{\rm CO}$ results and possible implications in the next section.

https://doi.org/10.1017/S1743921322004367 Published online by Cambridge University Press

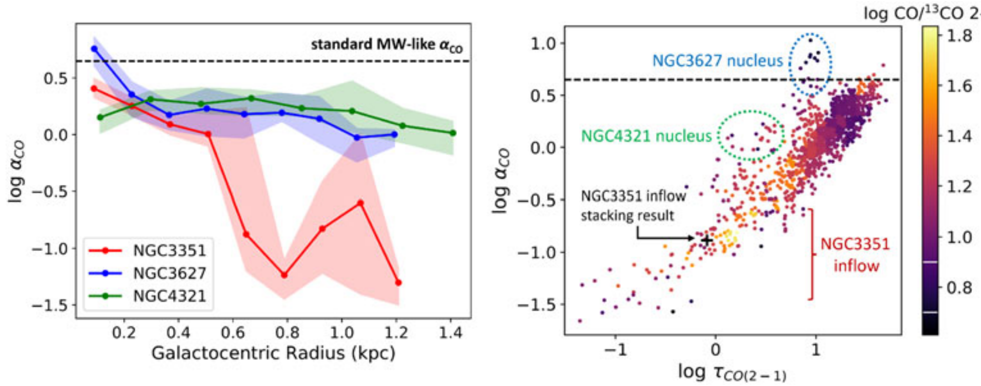


**Figure 2.** *Left*: Medians of the modeled $\alpha_{CO}$ within ∼100 pc galactocentric radius bins in the central kpc of NGC 3351, 3627, and 4321. Shaded areas span the 25th and 75th percentile ranges. *Right*: Relation between the modeled $\alpha_{CO}$ and CO 2–1 optical depth from all three galaxies. Data points are color-coded by 2D-binned medians of the observed CO/$^{13}$CO 2–1 ratios. White lines on the color bar indicates the range of Galactic disk-like ratio.

## 3. Results and Discussion

Figure 2 shows how the derived $\alpha_{CO}$ varies with galactocentric radius and CO optical depths ($\tau_{CO}$). Except for the NGC 3627 nucleus reaching a near-Galactic $\alpha_{CO}$, all pixels have lower-than-Galactic $\alpha_{CO}$ values. The diverse $\alpha_{CO}$ trend in the nuclei is likely related to the denser and hotter gas condition as suggested by our modeling. In addition, substantially lower $\alpha_{CO}$ is found in the bar-driven inflows of NGC 3351, where $\tau_{CO}$ is low. We find a tight, positive correlation of $\alpha_{CO}$ with $\tau_{CO}$ in all three galaxy centers. Since $\tau_{CO}$ is proportional to CO column density per line width, this means that nuclear gas concentration and turbulence/shear effects play important roles in setting $\alpha_{CO}$ in these regions. Thus, the overall lower-than-Galactic $\alpha_{CO}$ may be explained by the higher velocity dispersion in barred galaxy centers which decreases the $\tau_{CO}$ (Sun *et al.* (2020)).

Furthermore, the right panel in Figure 2 shows that the CO/$^{13}$CO 2–1 ratio generally reflects $\tau_{CO}$ inversely. Using NGC 3351 as an example, the higher CO/$^{13}$CO 2–1 ratio we observe in the inflow arms is likely related to the significantly lower $\tau_{CO}$ and $\alpha_{CO}$. Since the decreasing $\tau_{CO}$ can lead to more fraction of escaped CO emission, this would increase the CO/$^{13}$CO line ratio or the CO intensity per unit gas mass, and thus lower the $\alpha_{CO}$ by definition. With the strong dependence seen between $\alpha_{CO}$ and $\tau_{CO}$, we conclude that the CO/$^{13}$CO ratio can be a useful observational tracer for $\alpha_{CO}$ variations, particularly in galaxy centers where optical depth effects are dominant.

## Acknowledgements

This work would not have been possible without our collaborators: Jiayi Sun, Adam Leroy, Cliff Johnson, Alberto Bolatto, Diederik Kruijssen, Andreas Schruba, Antonio Usero, Guillermo Blanc, Brent Groves, Frank Israel, Daizhong Liu, Erik Rosolowsky, Eva Schinnerer, John-David Smith, Fabian Walter, and the PHANGS Team.

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