



Slow Star Formation in the Milky Way: Theory Meets Observations

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Abstract

The observed star formation rate of the Milky Way can be explained by applying a metallicity-dependent factor to convert CO luminosity to molecular gas mass and a star formation efficiency per freefall time that depends on the virial parameter of a molecular cloud. These procedures also predict the trend of star formation rate surface density with Galactocentric radius. The efficiency per freefall time variation with virial parameter plays a major role in bringing theory into agreement with observations for the total star formation rate, while the metallicity dependence of the CO luminosity-to-mass conversion is most notable in the variation with Galactocentric radius. Application of these changes resolves a factor of over 100 discrepancy between observed and theoretical star formation rates that has been known for nearly 50 yr.

Unified Astronomy Thesaurus concepts: [Molecular clouds \(1072\)](#); [Star formation \(1569\)](#)

1. Introduction

The observed star formation rate in the Milky Way (SFR_{obs}), averaged over the recent history of the Galaxy, is estimated to be $1.65\text{--}1.9 M_{\odot} \text{yr}^{-1}$ (Chomiuk & Povich 2011; Licquia & Newman 2015). In contrast, the SFR predicted if all the clouds identified in CO surveys are collapsing at freefall exceeds the observed rate by at least two orders of magnitude. With a total molecular mass of $1 \times 10^9 M_{\odot}$ (Heyer & Dame 2015) and a freefall time of 3.34×10^6 yr, taking a characteristic density of 100cm^{-3} , if all molecular gas ($M_{\text{mol,tot}}$) forms stars with complete efficiency in a freefall time ($t_{\text{ff,mol}}$), the freefall SFR, $\text{SFR}_{\text{th,ff}} \equiv M_{\text{mol,tot}}/t_{\text{ff,mol}} = 300 M_{\odot} \text{yr}^{-1}$ (Evans et al. 2021). We characterize this issue by $Q_{\text{th}} = \text{SFR}_{\text{th}}/\text{SFR}_{\text{obs}}$, the ratio of the SFR predicted by a given theory to the observed SFR. Thus, for the Galaxy, $Q_{\text{ff}} = 158\text{--}182$.

This problem can be restated as the slowness of star formation (see, e.g., reviews of McKee & Ostriker 2007; Krumholz et al. 2014; Padoan et al. 2014), with a need to explain why the efficiency per freefall time $\epsilon_{\text{ff,obs}} \equiv \text{SFR}_{\text{obs}}/\text{SFR}_{\text{th,ff}}$ is at most only a few percent. As noted above, the average $\epsilon_{\text{ff,obs}} = 1/Q_{\text{ff}}$ needed to bring current estimates of molecular cloud properties and SFRs into agreement on a Galaxy-scale level is even lower: $\epsilon_{\text{ff,obs}} = 0.006$. Alternatively, the molecular gas depletion time is $t_{\text{dep}} \equiv M_{\text{mol,tot}}/\text{SFR}_{\text{obs}} = 0.5\text{--}0.6$ Gyr, longer than the freefall time by a factor Q_{ff} .

This huge discrepancy captured by Q_{ff} is one of the oldest (Zuckerman & Evans 1974; Zuckerman & Palmer 1974) and most embarrassing in the field of star formation. It has been identified as the first of the three “big problems” in star formation, along with understanding stellar clustering and the origin of the initial mass function (Krumholz 2014).

The problem cannot be solved by rotational stabilization as rotational energies are far less than gravitational or turbulent energies (Braine et al. 2020 and references therein). Some combination of magnetic fields, turbulence, and feedback is

generally invoked to explain why star formation is slow, but simulations with comparable gravitational and turbulent energies have difficulty matching the observations ($\epsilon_{\text{ff,obs}} = 0.006$), instead producing $\epsilon_{\text{ff}} \gtrsim 0.1$, unless turbulence is continuously driven (with an artificial stirring force) and/or very strong magnetic fields are included (e.g., Padoan et al. 2012; Federrath 2015; Raskutti et al. 2016; Cunningham et al. 2018; Kim et al. 2021). However, both theory and simulations suggest that ϵ_{ff} drops steeply with increasing virial parameter (e.g., Krumholz & McKee 2005; Clark et al. 2008; Padoan & Nordlund 2011; Federrath & Klessen 2012; Padoan et al. 2012; Kim et al. 2021), and recent observations suggest that the relative importance of gravity compared to turbulence in giant molecular clouds is less than traditionally thought (e.g., Sun et al. 2020; Evans et al. 2021).

Reproducing the SFR of the whole Galaxy provides the stringent test of the theory. Comparisons to samples of clouds leave open issues of sample selection and time-varying efficiency (Krumholz et al. 2019). Because observations sample clouds at an undetermined time in their history, large variations in star formation efficiency are observed from cloud to cloud (e.g., Lee et al. 2016; Vutisalchavakul et al. 2016). Simulations show that due to the expansion of clouds produced by feedback, the instantaneous measured ϵ_{ff} is positively correlated with the instantaneous virial parameter, whereas ϵ_{ff} is inversely correlated with the virial parameter prior to the onset of star formation (Kim et al. 2021, Figure 16 versus Figure 15). Simulations also show that various star formation tracers systematically overpredict and underpredict the actual ϵ_{ff} at different times in the cloud history (e.g., Figure 7 in Grudić et al. 2022). In contrast, the whole-Galaxy SFR based on young populations (like H II regions) averages over all clouds over the last 5–10 Myr and is quite well determined. Any credible star formation theory must be able to predict the observed value within reasonable uncertainties.

Furthermore, star formation in the Milky Way is not uniquely slow, lying near the Kennicutt–Schmidt relation between the SFR and gas surface densities (Figure 11 in Kennicutt & Evans 2012). In a study of 14 nearby galaxies analyzed with the “Milky Way” conversion from CO luminosity to molecular mass, including all the CO emission, Utomo et al. (2018) found

a median overall line of sight of $\epsilon_{\text{ff,obs}} = 0.007 \pm 0.003$, essentially identical to the Milky Way. The solution to the problem for the Milky Way may point the way to a better understanding of star-forming galaxies more generally.

In this paper, we take a fresh look at this problem by reconsidering the determinations of masses of molecular clouds and using measurements of ϵ_{ff} from MHD simulations with different virial parameters in combination with estimates of observed virial parameters in Milky Way clouds.

2. Observational Constraints

The basic constraints are the observed SFR and the observed properties of molecular structures (CO luminosity, size, and velocity dispersion) that allow us to compute the mass, freefall time, and virial parameter.

For our purposes, the relevant estimates of the SFR should average over times similar to the lifetimes of molecular clouds—several megayears (Heyer & Dame 2015). Chomiuk & Povich (2011) collected such estimates of the total SFR of the Galaxy and derived an average value of $1.9 \pm 0.4 M_{\odot} \text{ yr}^{-1}$. A more recent analysis of the same data using hierarchical Bayesian analysis found $1.65 \pm 0.19 M_{\odot} \text{ yr}^{-1}$ (Licquia & Newman 2015). We adopt this value while noting that systematic uncertainties, especially assumptions about the initial mass function as discussed by Licquia & Newman (2015), likely allow uncertainties of about 50%.

The most complete catalog of structures identified from the most complete CO survey of the Galaxy (Dame et al. 2001) is that of Miville-Deschênes et al. (2017), hereafter referred to as MD. They were able to assign 98% of the CO emission to 8107 structures, to which they assigned sizes and velocity dispersions. They found that much of the mass was in unbound structures, with the virial parameter $\alpha_{\text{vir}} > 2$. Here, we follow the convention in the literature of defining a virial parameter using the observed cloud effective radius, mass, and one-dimensional velocity dispersion as

$$\alpha_{\text{vir}} \equiv \frac{5\sigma_{\text{1d}}^2 R}{GM}; \quad (1)$$

this ignores magnetic terms, surface terms, internal inhomogeneity and stratification, and tidal gravity, all of which may be important at the factor of ~ 2 level (e.g., McKee & Zweibel 1992; Hernandez & Tan 2015; Mao et al. 2020; Kim et al. 2021). However, this definition has the advantage that it is relatively easily measured in observations, and it is also straightforward to control this parameter in the initial conditions of simulations.

Recently, Evans et al. (2021) found that only 19% of the mass in the MD structures was in gravitationally bound structures (i.e., having $\alpha_{\text{vir}} \leq 2$). If only bound clouds form stars at the freefall rate, the predicted SFR can be decreased to $46 M_{\odot} \text{ yr}^{-1}$, decreasing the discrepancy by a factor of 6.5. This simple analysis assumed that the masses in the MD catalog were correct and took a very simple (step-function) model of how ϵ_{ff} depends on α_{vir} .

In this paper, we further investigate implications for the predicted SFR of correcting cloud properties for the known gradient in metallicity in the Milky Way and applying a formula for ϵ_{ff} based on simulations of clouds with various initial values of α_{vir} .

3. Reconsidering the Mass and Related Properties of Galactic Molecular Structures

Central to the determination of both the freefall time and virial parameter is an independent measure of the mass of the structure. For large-scale studies of the molecular gas, the most common mass tracer is the line luminosity of low- J transitions of CO. The mass of the structure traced by CO, generally called a molecular cloud, comes from $M_{\text{mol}} = \alpha_{\text{CO}} L_{\text{CO}}$, where L_{CO} is the CO luminosity and α_{CO} (hereafter in units of $M_{\odot} (\text{K km s}^{-1} \text{ pc}^2)^{-1}$) is the CO-to- H_2 mass conversion factor accounting for the mass contributions from associated helium and metals. There is growing recognition that the conversion of CO luminosity into mass is unlikely to be the same in all environments (see Tacconi et al. 2020 and references therein). The most obvious source of variation in the conversion factor is variation in metallicity. We use the symbol Z to represent the metallicity relative to that of the solar neighborhood.

Observers of other galaxies tend to correct α_{CO} for Z , and various formulae have been developed (Bolatto et al. 2013; Accurso et al. 2017; Madden et al. 2020; Tacconi et al. 2020). Many references adopt a conversion factor of the form

$$\alpha_{\text{CO}} = \alpha_{\text{CO},0} Z^{-a}, \quad (2)$$

with $a = 1.6$ a common choice (e.g., Sun et al. 2020) for nearby star-forming galaxies. The weakness of CO emission in dwarf galaxies with very low metallicity has led to larger estimates for a : 2.0–2.8 (Schruba et al. 2012) or even 3.39 (Madden et al. 2020)

For the Milky Way, most studies have assumed that a commonly adopted local calibration, taken to be $\alpha_{\text{CO}} = 4.35$, applies throughout the Galaxy. This luminosity-to-mass conversion is related to the commonly used relation for the H_2 column density, $N_{\text{H}_2} = X_{\text{CO}} W_{\text{CO}}$, with W_{CO} the integral of the main-beam temperature over velocity and the CO-to- H_2 column density conversion factor X_{CO} (hereafter in units of $\text{cm}^{-2} (\text{K km s}^{-1})^{-1}$). Based on local calibration, the most commonly used value is $X_{\text{CO}} = 2 \times 10^{20}$. However, Lada & Dame (2020) have suggested a correction factor that removes an apparent Galactic gradient in the mean surface density of clouds defined by CO,

$$X_{\text{CO,LD}} = \frac{83 \times 10^{20}}{54.5 - 3.7(R_{\text{gal}}/\text{kpc})}, \quad (3)$$

for Galactocentric radius $2 \text{ kpc} < R_{\text{gal}} \leq 10 \text{ kpc}$ and $X_{\text{CO}} = 6.0 \times 10^{20}$ for $R_{\text{gal}} > 10 \text{ kpc}$. While we do not find the arguments for this particular dependence of X_{CO} on R_{gal} compelling, the idea α_{CO} varying in the Milky Way would be consistent with the practice for other galaxies.

Recently, Gong et al. (2020) have computed simulated CO emission from a set of kiloparsec-scale numerical MHD simulations of the ISM and fitted the results to determine the column density conversion factors X_{CO} that depend on Z and other observational parameters. Gong et al. (2020) provide several possible formulas for X_{CO} for the $J = 1 \rightarrow 0$ transition. The first is a simple formula involving only Z (“Gong1a”),

$$X_{\text{CO,Gong1a}} = 1.4 \times 10^{20} Z^{-0.80}, \quad (4)$$

which has a substantially less steep dependence on Z than is often adopted in extragalactic observations. A similar dependence ($Z^{-0.7}$) was found in simulations including time-

dependent effects by Hu et al. (2022). Improved comparison to the actual values of N_{H_2} in the Gong et al. (2020) simulations is provided by a formula that also accounts for the intensity (W_{CO}) of the emission and the spatial resolution of the survey (r_{beam}). This expression (“Gong4a”) is

$$X_{\text{CO,Gong4a}} = 6.1 \times 10^{20} Z^{-0.80} r_{\text{beam}}^{-0.25} \times W_{\text{CO}}^{-0.54+0.19 \log r_{\text{beam}}}, \quad (5)$$

where r_{beam} is in pc and W_{CO} is in K km s^{-1} . This formula is recommended only if the effective resolution is $\lesssim 100$ pc. The resolution of the Dame et al. (2001) survey is about $8'.5$, translating to $r_{\text{beam}} = 2.5(d/\text{kpc})$ pc, which reaches 100 pc only for $d = 40$ kpc; the formula is suitable for the Milky Way.

We will test each of the above formulations for converting CO emission to molecular mass. To obtain W_{CO} from the values tabulated as “WCO” in the machine-readable table in Miville-Deschênes et al. (2017), we divide by the number of pixels, also given in that table, in accordance with Equation (13) of Miville-Deschênes et al. (2017). The value of W_{CO} is then an average over the structure.

To convert these column density factors to mass conversion factors, we use

$$\Sigma_{\text{mol}} = \mu_{\text{H}_2} m_{\text{H}} N_{\text{H}_2}, \text{ or} \\ \Sigma_{\text{mol}} (M_{\odot} \text{ pc}^{-2}) = 8.015 \times 10^{-21} \mu_{\text{H}_2} N_{\text{H}_2} (\text{cm}^{-2}), \quad (6)$$

where $N_{\text{H}_2} = X_{\text{CO}} W_{\text{CO}}$ for the region identified by CO emission, and Σ_{mol} includes helium and metals. Using the values for $M_{\text{X}}/M_{\text{H}}$ for the latest protosolar abundances from Asplund et al. (2021), the mean molecular weight $\mu_{\text{H}_2} = 2.809$, $\Sigma_{\text{mol}} (M_{\odot} \text{ pc}^{-2}) = 2.251 \times 10^{-20} N_{\text{H}_2} (\text{cm}^{-2})$, and

$$\alpha_{\text{CO}} = 4.50 \left(\frac{X_{\text{CO}}}{2.0 \times 10^{20}} \right). \quad (7)$$

This conversion is about 3% higher than the usual choice of $\alpha_{\text{CO}} = (4.35/2 \times 10^{20}) X_{\text{CO}}$.

To convert the Z dependence of α_{CO} into a dependence on R_{gal} , we use measured radial gradients in Z . There is compelling evidence for a gradient in Z in the Milky Way, with consistent evidence from the pulsation of Cepheids (e.g., Lemasle et al. 2018), to H II region electron temperatures from radio recombination lines (e.g., Wenger et al. 2019), to direct determinations of abundances in H II regions from optical spectral lines. We use abundances measured in H II regions because these represent abundances within the last 5–10 Myr and so are the most relevant to current conditions in molecular clouds (Deharveng et al. 2000). The most recent measurements find a steady decrease in metal abundances from 4 to 17 kpc in R_{gal} (Wang et al. 2018; Arellano-Córdova et al. 2020, 2021; Méndez-Delgado et al. 2022). The last reference combines all the data with EDR3 distances from Gaia to provide gradients for both oxygen and carbon, both with and without corrections for temperature inhomogeneities.

The two constituents of CO appear to have different gradients, and the O/H gradient depends slightly on assumptions about temperature inhomogeneities. Because the various formulas for varying α_{CO} assumed that all abundances (including dust) scale together, characterized by Z , with $Z=1$ at the solar circle, we need to choose one gradient. Which relation to use is not entirely clear. Because carbon is

less abundant than oxygen, the CO abundance is likely limited by carbon rather than oxygen. The dust opacity in the ultraviolet, important to the shielding in the simulations, is contributed roughly equally by carbonaceous and silicate dust (Figure 23.11 of Draine 2011). Carbon has the additional advantage that corrections for temperature variations do not affect the gradient in C, unlike the case of O. On the other hand, the oxygen abundance has been determined in more H II regions over a wider range of R_{gal} (5–17 kpc) versus 6–12 kpc for carbon. Because no variation of α_{CO} with Z has been usually assumed for Galactic studies, we make a “conservative” choice of the smallest gradient: that for O/H without correction for temperature inhomogeneities. This gradient is $-0.044 \text{ dex kpc}^{-1}$ (Méndez-Delgado et al. 2022). The gradient measured from double-mode pulsating Cepheids ($-0.045 \pm 0.007 \text{ dex kpc}^{-1}$) agrees with this choice (Lemasle et al. 2018). We consider the effect of other choices in Section 6.3.

To translate these gradients into Z , the metallicity used by Gong et al. (2020), we normalize to $Z=1$ at the distance from the center of the Galaxy to the solar neighborhood of $R_{\text{gal},\odot} = 8.178 \pm 0.013_{\text{stat.}} \pm 0.022_{\text{sys.}}$ kpc (Gravity Collaboration et al. 2019). We assume

$$Z = 10^{c(R_{\text{gal}} - R_{\text{gal},\odot})}, \quad (8)$$

with $c = -0.044 \text{ dex kpc}^{-1}$. This is plotted in the top panel of Figure 1.

We plot the relation labeled Gong1a (Gong et al. 2020) with the adopted Z gradient, along with that used by Sun et al. (2020) for other galaxies (but with $\alpha_{\text{CO},0}$ rescaled from 4.35 to 4.5), and the relation from Lada & Dame (2020) in the bottom panel of Figure 1. There are quite large differences, especially at large radii.

The Gong1a formula predicts a local value of $X_{\text{CO},0} = 1.4 \times 10^{20}$, smaller than the usually accepted $X_{\text{CO},0} = 2.0 \times 10^{20}$ (Pineda et al. 2010; Bolatto et al. 2013). The lower value was the best fit to all the simulations, but their R4 and R8 simulations, more representative of the local molecular gas, favored values closer to $X_{\text{CO},0} = 2.0 \times 10^{20}$, as can be seen in Figures 6 and 9 of Gong et al. (2020). The median and mean W_{CO} in the MD catalog are 3.8 and 7.2 K km s^{-1} , values for which Gong1a underestimates $X_{\text{CO},0}$ (Figure 13 of Gong et al. 2020). For these reasons, we also include a modified Gong1a model (labeled G1a-4.5), with $X_{\text{CO}} = 2.0 \times 10^{20} Z^{-0.80}$, leading to $\alpha_{\text{CO}} = 4.50 Z^{-0.80}$.

4. The Dependence of ϵ_{ff} on α_{vir}

A very simple treatment of the star formation efficiency was adopted by Evans et al. (2021), who assumed a step function with a transition from 1 to 0 at $\alpha_{\text{vir}} = 2$. More realistically, theory and simulations predict that for a given molecular cloud mass and size, the SFR would be systematically lower if the turbulence amplitude is higher, corresponding to a higher virial parameter.

Based on a set of self-gravitating driven-turbulence simulations, Padoan et al. (2012) proposed that the efficiency per freefall time, ϵ_{ff} , depends exponentially on the ratio of freefall time to dynamical time: $\epsilon_{\text{ff}} = \epsilon_{\text{cs}} \exp(-C t_{\text{ff}}/t_{\text{dyn}})$, where ϵ_{cs} is the core-to-star efficiency and C is determined from simulations that resolve cloud-to-core scales (but not core-to-star scales). Their simulations were for a periodic box; defining $t_{\text{dyn}} = r/\sigma_{1d}$ for r half the box length, their proposed star formation law

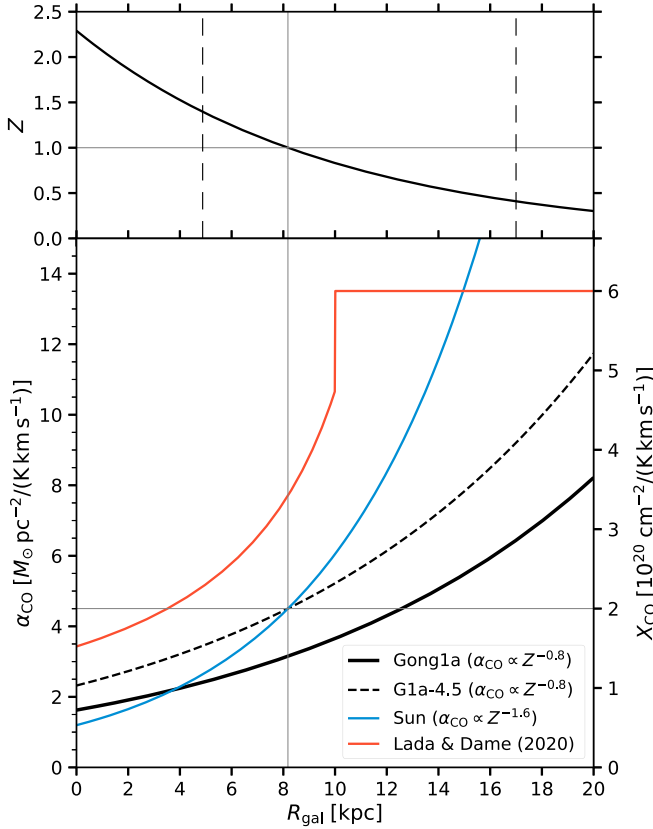


Figure 1. (Top) Assumed variation of Z with R_{gal} based on the radial abundance gradient of oxygen in H II regions: $c = -0.044 \text{ dex kpc}^{-1}$ (Méndez-Delgado et al. 2022). The dashed vertical lines represent the range of R_{gal} for which the abundance gradient is measured. (Bottom) Various models of α_{CO} vs. R_{gal} . The gray vertical line marks the solar circle, $R_{\text{gal},\odot} = 8.178 \text{ kpc}$ (Gravity Collaboration et al. 2019), and the gray horizontal lines indicate the usual assumptions for the solar neighborhood, $Z = 1$ and $\alpha_{\text{CO},0}$ updated to $4.50 M_{\odot} (\text{K km s}^{-1} \text{pc}^2)^{-1}$.

corresponds to $C = 2.77$. For a spherical cloud, the ratio of freefall to dynamical times is related to the virial parameter by $t_{\text{ff}}/t_{\text{dyn}} = \pi(\alpha_{\text{vir}}/40)^{1/2}$, so we can rewrite the proposed expression for the cloud-to-core efficiency per freefall time as

$$\epsilon_{\text{ff,cc}} = \exp(-b\alpha_{\text{vir}}^{1/2}), \quad (9)$$

where $b = C\pi/\sqrt{40}$. The Padoan et al. (2012) fit to their simulations corresponds to $b = 1.38$ (indicated by “PN” in the figures).

Kim et al. (2021, hereafter KOF) conducted a set of isolated, turbulent-cloud simulations with UV radiation feedback for varying initial virial parameters $\alpha_{\text{vir},0}$ and fit their results for the SFR to find a best-fitting value of $C = 4.06$, or $b = 2.02$ in Equation (9), indicating a somewhat stronger dependence than originally suggested by Padoan et al. (2012). The KOF simulations considered clouds of fixed initial mass and radius $(M_0, R_0) = (10^5 M_{\odot}, 20 \text{ pc})$. We have run additional simulations of more massive, low-density clouds $(M_0, R_0) = (10^6 M_{\odot}, 60 \text{ pc})$ with $\alpha_{\text{vir},0} = 1, 2, 5,$ and 10 . Because these clouds are relatively long-lived compared to UV-emitting stars, effects of supernova explosions are also included following the procedures of Kim & Ostriker (2017). We found that with these extensions, $b \approx 2$ still well describes the decreasing trend of measured efficiency per freefall time with $\alpha_{\text{vir},0}$.

Because the simulations of Padoan et al. (2012) and KOF were not resolved at the core-to-star level, their efficiency was

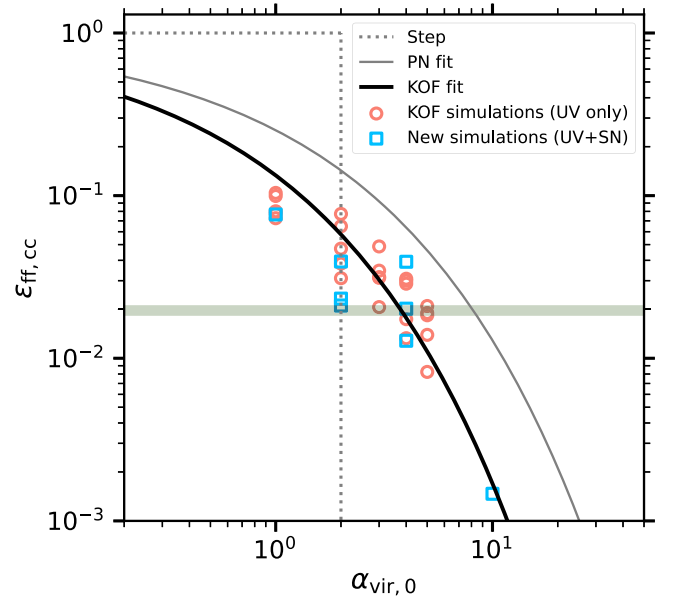


Figure 2. Assumed relation between cloud-to-core efficiency per freefall time and the virial parameter of a molecular cloud. The thick black line shows our standard choice with $b = 2.02$ (see Equation (9)), which is a fit to the α -series simulations of KOF (open circles) with UV radiation feedback. The squares show the results of new simulations of more massive clouds including both UV radiation and supernova feedback. The thin gray line shows the relation proposed by Padoan et al. (2012) with $b = 1.38$. The dotted line shows the simple step-function relation adopted by Evans et al. (2021). The green shaded region indicates the observational constraint $\epsilon_{\text{ff,obs}}/\epsilon_{\text{cs}} = (\text{SFR}_{\text{obs}}/\text{SFR}_{\text{ff}})/\epsilon_{\text{cs}}$ for $\text{SFR}_{\text{ff}}/\text{SFR}_{\text{obs}} = 158\text{--}182$ and $\epsilon_{\text{cs}} = 0.3$.

really the core formation efficiency and the core-to-star efficiency (ϵ_{cs}) must come from other considerations. Padoan et al. (2012) chose $\epsilon_{\text{cs}} = 0.5$ to account for mass lost through jets and winds. Comparison of the core-mass function to the stellar-mass function (Alves et al. 2007; Enoch et al. 2008; Könyves et al. 2015) and simulations of envelope clearing by winds (Dunham et al. 2010) suggest $\epsilon_{\text{cs}} = 0.20$ to 0.40 ; we adopt $\epsilon_{\text{cs}} = 0.30$. Using ϵ_{cs} implies that the mass removed from a core by outflows is no longer available for star formation in the cloud. Outflow velocities typically exceed the cloud’s escape velocity, and breakouts from the cloud are observed (e.g., Noriega-Crespo et al. 2004). In comparing to the observed value, $\epsilon_{\text{ff,obs}}$, we use the product of $\epsilon_{\text{ff,cc}}$ from simulations and ϵ_{cs} .

In Figure 2, we show results from simulations for $\epsilon_{\text{ff,cc}}$ as a function of the initial virial parameter (symbols) and the fit to simulation results (lines), in comparison to the mean observed $\epsilon_{\text{ff,obs}}/\epsilon_{\text{cs}}$ (shaded region) with $\epsilon_{\text{cs}} = 0.30$.

5. Comparison of Model and Observations

We follow Evans et al. (2021) in using all the entries in the Miville-Deschênes et al. (2017) catalog that satisfy the conditions $M_{\text{mol}} > 1 M_{\odot}$, $R_{\text{gal}} < 30 \text{ kpc}$, and $\alpha_{\text{vir}} < 100$. There is very little mass outside these restrictions but they remove some outliers.

We calculated the freefall SFR as

$$\text{SFR}_{\text{th,ff}} = \sum_{\text{cl}} M_{\text{mol}}/t_{\text{ff}} \equiv M_{\text{mol,tot}}/\langle t_{\text{ff}} \rangle, \quad (10)$$

where $t_{\text{ff}} = [3\pi/(32G\rho)]^{1/2}$ with $\rho = 3M_{\text{mol}}/(4\pi R^3)$ and the summation is taken over the cloud sample defined above and $\langle t_{\text{ff}} \rangle$ is the mass-weighted harmonic mean of the freefall time.

Table 1
Summary of Results

α_{CO}	SFE	$M_{\text{mol,tot}}$ ($10^9 M_{\odot}$)	$\langle t_{\text{ff}} \rangle$ (Myr)	SFR_{th} ($M_{\odot} \text{ yr}^{-1}$)	Q_{th}	$\langle \epsilon_{\text{ff}} \rangle$ (%)
(1)	(2)	(3)	(4)	(5)	(6)	(7)
4.50	Step	1.7	7.4	52.7	32	23
LD	Step	2.3	7.5	120	73	39
Sun	Step	1.3	10.4	33.2	20	26
Gong1a	Step	1.0	10.9	5.67	3.4	6.3
Gong4a	Step	1.1	12.3	8.47	5.1	9.6
4.50	KOF	1.7	7.4	2.66	1.6	1.2
LD	KOF	2.3	7.5	5.93	3.6	1.9
Sun	KOF	1.3	10.4	1.99	1.2	1.5
Gong1a	KOF	1.0	10.9	0.50	0.30	0.55
Gong4a	KOF	1.1	12.3	0.57	0.35	0.65
G1a-4.5 ^a	KOF	1.4	9.2	1.46	0.89	0.95

Notes. Column (1) gives the model treatment adopted for α_{CO} (see Section 2). Column (2) gives the model treatment adopted for ϵ_{ff} to set the efficiency of star formation (see Section 4). Columns (3)–(5) give the total cloud mass, the mean value of t_{ff} , and the total predicted SFR. Column (6) gives the ratio of predicted to observed SFR. Column (7) gives the mean efficiency per freefall time from Equation (11).

^a Gong1a with $\alpha_{\text{CO},0} = 4.50$.

The theoretical prediction allowing for the variation of ϵ_{ff} is

$$\text{SFR}_{\text{th}} = \sum_{\text{cl}} \epsilon_{\text{ff}} M_{\text{mol}} / t_{\text{ff}} \equiv \langle \epsilon_{\text{ff}} \rangle \text{SFR}_{\text{th,ff}}, \quad (11)$$

where $\langle \epsilon_{\text{ff}} \rangle$ is the average ϵ_{ff} weighted by the freefall SFR. For simulations that do not resolve the core-to-star efficiency, $\epsilon_{\text{ff}} = \epsilon_{\text{cs}} \epsilon_{\text{ff,cc}}$. To match observations, $\langle \epsilon_{\text{ff,cc}} \rangle$ must equal $\epsilon_{\text{ff,obs}} / \epsilon_{\text{cs}} = 0.006 / 0.3 = 0.02$.

First, we explore the effects of a varying α_{CO} while retaining the simplistic assumption by Evans et al. (2021) of a step function for ϵ_{ff} : $\epsilon_{\text{ff}} = 1$ for $\alpha_{\text{vir}} \leq 2$ and $\epsilon_{\text{ff}} = 0$ for $\alpha_{\text{vir}} > 2$ (with ϵ_{cs} as unity). For this test, we consider (1) a constant $\alpha_{\text{CO}} = 4.5$, (2) the formula based on Equation (3) labeled Lada & Dame in Figure 1 and LD in Table 1, (3) the expression in Equation (2) with $a = 1.6$ labeled Sun, (4) the expression in Equation (4) labeled Gong1a, and (5) the expression in Equation (5) labeled Gong4a.

Entries 1–5 in Table 1 for $Q_{\text{step}} = \text{SFR}_{\text{step}} / \text{SFR}_{\text{obs}}$ show that these predictions are all better than allowing all clouds to form stars at the freefall rate, which has $Q_{\text{ff}} = 158$. However, the LD formulation overproduces stars by the largest factor ($Q_{\text{step}} = 73$) while the Gong1a formula minimized the problem, with $Q_{\text{step}} = 3.4$. The trends are partially explained by the column showing the total molecular mass. The decreasing α_{CO} in the inner Galaxy decreases the total mass of molecular gas to $1.0 \times 10^9 M_{\odot}$ for the Gong1a formula, while the LD formula actually increases the Galaxy’s molecular mass to $2.3 \times 10^9 M_{\odot}$. An additional contributing factor is shown by column 4 with $\langle t_{\text{ff}} \rangle$, which is longer for the two Gong entries and the Sun entry. The full effect of $\alpha_{\text{CO},0}$, including the higher α_{vir} , is indicated in column 7 with $\langle \epsilon_{\text{ff}} \rangle$. Clearly, taking into account the variation of α_{CO} has a very large effect on the predicted SFR, but it does not by itself solve the problem entirely.

Second, we explore the effects of including the dependence of ϵ_{ff} on α_{vir} from Equation (9). We adopt the KOF model setting $\epsilon_{\text{ff}} = \epsilon_{\text{cs}} \epsilon_{\text{ff,cc}}$ and $\epsilon_{\text{ff,cc}} = \exp(-2.02 \alpha_{\text{vir}}^{1/2})$ with α_{vir} equal to the

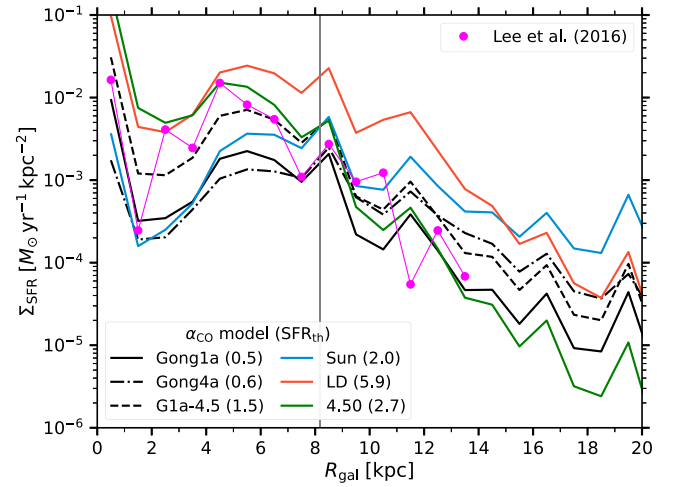


Figure 3. The log of the SFR surface density is plotted vs. R_{gal} . The magenta circles are observational estimates taken from Figure 9 of Lee et al. (2016), with the total SFR scaled to $1.65 M_{\odot} \text{ yr}^{-1}$. The other lines are those predicted by different models of the dependence of α_{CO} on R_{gal} , as indicated by the label. The numbers in parentheses indicate the predicted total SFR, SFR_{th} , in $M_{\odot} \text{ yr}^{-1}$ (see also Table 1). All use the KOF formula for $\epsilon_{\text{ff,cc}}$ with $b = 2.02$.

observed value in each cloud and $\epsilon_{\text{cs}} = 0.30$. The results of this exercise are shown in entries 6–10 of Table 1. For constant $\alpha_{\text{CO}} = 4.50$, with $\epsilon_{\text{cs}} = 0.30$, we obtain a predicted SFR of $2.66 M_{\odot} \text{ yr}^{-1}$, nearly consistent with the observational constraint. Combining the LD conversion factors with the KOF prediction for $\epsilon_{\text{ff,cc}}$ predicts too high an SFR. If we apply either of the Gong et al. (2020) formulas for α_{CO} , the SFR is actually slightly underpredicted. Entry 11 in Table 1 (denoted G1a-4.5) uses the scaled-up Gong1a formula; the resulting $\text{SFR}_{\text{th}} = 1.46 M_{\odot} \text{ yr}^{-1}$, the closest to the observed values. Given uncertainties in quantities like ϵ_{cs} , and the R_{gal} dependence of α_{CO} , the agreement with observations is reasonable for several combinations.

We can also compare predicted and observed distributions of the SFR over R_{gal} . In Figure 3 we show the predictions of the six models for α_{CO} , all using the KOF model for $\epsilon_{\text{ff,cc}}$ to predict the surface density of SFR Σ_{SFR} in bins of R_{gal} . The points representing the observations are taken from Lee et al. (2016) but scaled up so that the total SFR is $1.65 M_{\odot} \text{ yr}^{-1}$. These are based on 191 associations of the strongest WMAP free-free emission with molecular clouds in the MD survey.

The model of a constant α_{CO} clearly exceeds the observations in the inner Galaxy but performs well at large R_{gal} . The LD formula for α_{CO} overpredicts Σ_{SFR} over almost all of the Galaxy. The Sun formula, with its very strong dependence on Z , underpredicts the SFR in the inner Galaxy and predicts substantial star formation in the far outer Galaxy. The Gong1a and Gong4a formulae predict a distribution that is too flat in R_{gal} , with very little star formation from 2 to 8 kpc. The G1a-4.5 model does quite well but may exceed the observations beyond about 11 kpc.

There is a well-known issue that star formation in the Central Molecular Zone (CMZ; inner few 100 pc) is far less than predicted by the most commonly used models (Barnes et al. 2017). We do not specifically consider the CMZ, but the G1a-4.5 model predicts an SFR close to the observed value at $R_{\text{gal}} = 0.5$ kpc. The anomalously low SFR in the CMZ may result in part from using a constant α_{CO} .

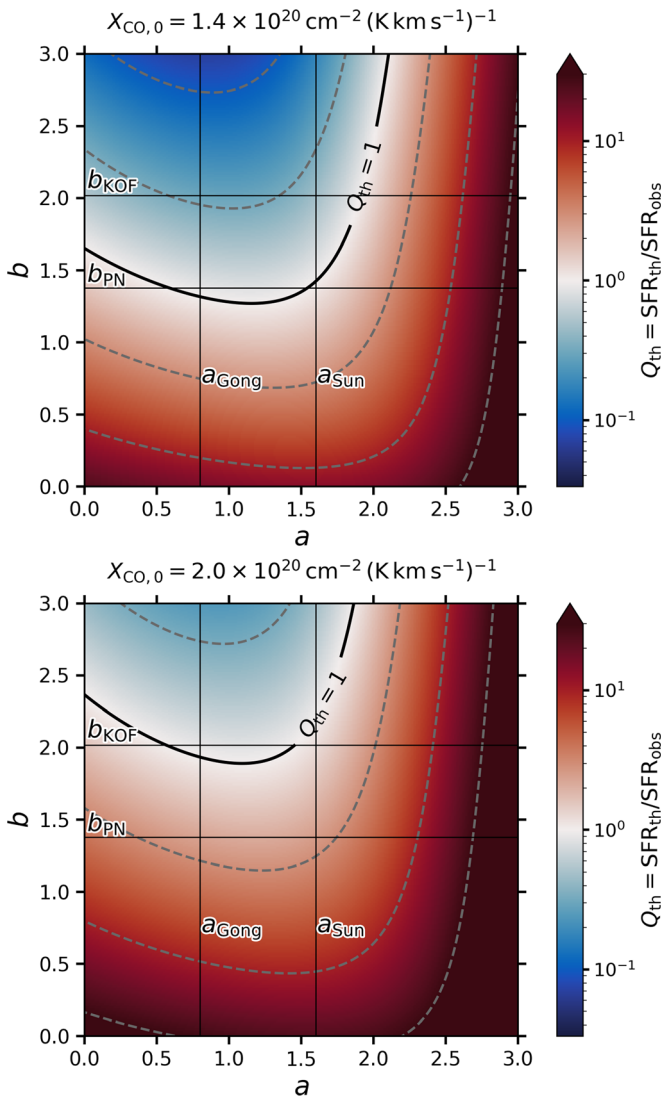


Figure 4. Plots of Q_{th} in the plane of (a, b) , where b is the coefficient in the formula for ϵ_{ff} and a is the exponent in the formula for the Z dependence of α_{CO} . The upper panel assumes $X_{\text{CO},0} = 1.4 \times 10^{20} \text{ cm}^{-2} (\text{K km s}^{-1})^{-1}$ for the solar neighborhood, and the lower panel assumes $X_{\text{CO},0} = 2.0 \times 10^{20} \text{ cm}^{-2} (\text{K km s}^{-1})^{-1}$. The locus of parameters that produce $Q_{\text{th}} = 1$ (theory matches observation) is shown as black solid curves, while the gray dashed curves show regions with a discrepancy of factors of 3, 10, and 30. The vertical thin lines show the values of a recommended by Gong et al. (2020) (Gong1a) and used by Sun et al. (2020); the horizontal thin lines show the values of b from Kim et al. (2021) and Padoan et al. (2012).

If we use the simpler versions of α_{CO} that depend on only Z , there are essentially two main parameters to consider: the coefficient b in the exponent of Equation (9) and the exponent a in the Z dependence of α_{CO} (Equation (2)). Figure 4 shows the color-coded value of Q_{th} in the a - b plane; all models assume $\epsilon_{\text{cs}} = 0.3$. The upper panel is for $X_{\text{CO},0} = 1.4 \times 10^{20}$, as Gong et al. (2020) found, while the lower panel is for $X_{\text{CO},0} = 2.0 \times 10^{20}$, which corresponds to adjusting the Gong1a model to the usually assumed local $X_{\text{CO},0}$. We note that the predicted SFR depends sensitively on the scaling of $X_{\text{CO},0}$. For a cloud with $\alpha_{\text{vir}} = 2$, for example, scaling $X_{\text{CO},0}$ by a factor of 2 (0.5) results in a factor of 6.5 increase (10 decrease) in the predicted SFR. The strong dependence arises because the mass, freefall time, and virial parameter all depend on the conversion factor. Nevertheless, the plots indicate the range of values for

both parameters that fit the observational value within uncertainties.

The color gradients in Figure 4 clearly demonstrate a greater sensitivity to b in Equation (9) than to a in Equation (2) for $a \lesssim 2$. Values of $a > 2$ rapidly degrade the match to the total observed SFR. In particular, the large values inferred from studies of dwarf galaxies (e.g., Schrubba et al. 2012; Madden et al. 2020) cannot work for the Milky Way. They also lead to too much gas mass and star formation in the outer Galaxy and conflict with the dependence on R_{gal} (Lee et al. 2016). Quantitatively, we can separate the effects by comparing values in Table 1. Comparing entries 1 and 5, Q_{th} decreases by a factor of 6 when Gong4a is used versus a constant $\alpha_{\text{CO}} = 4.5$. Comparing entries 1 and 6, Q_{th} decreases by a factor of 20 when the KOF formula is used instead of the step function. In contrast, the Z dependence of α_{CO} is most notable in the dependence on R_{gal} (Figure 3). This distinction will allow a better separation of the two effects with improved knowledge of how the Galaxy’s SFR surface density depends on R_{gal} .

To conclude, we can predict within reasonable accuracy the SFR of the Galaxy by correcting molecular gas properties for the Galaxy’s metallicity gradient and including the dependence of ϵ_{ff} on α_{vir} found in calculations of the star formation efficiency per freefall time. This is a major achievement for the theory.

6. Discussion

6.1. Properties of Structures as a Function of Mass

One reason why the predicted SFR is less than the canonical calculation in Section 1 when we let α_{CO} vary with R_{gal} is that the density is lower and the freefall time higher in the more massive clouds within the mass distribution, which are the ones with lower α_{vir} (Evans et al. 2021). The median, mean, and standard deviation of the total volume density of all particles, $n = n_{\text{H}_2} + n_{\text{He}} + \dots$, and the same statistics for the freefall time are plotted versus $\log M$ in Figure 5. These plots assume the G1a-4.5 formula for α_{CO} . The massive clouds have mean densities, $n \sim 10 \text{ cm}^{-3}$, much lower than are usually assumed. The observational detection limits can be met even at these low densities, as the effective density to produce a CO $J = 1 \rightarrow 0$ line of 1 K km s^{-1} is 15 cm^{-3} (Evans et al. 2021). The freefall time increases strongly with M_{CO} up to about $3000 M_{\odot}$, where it plateaus at about 10 Myr, substantially longer than is usually assumed for a density of 100 cm^{-3} , at about 3 Myr.

6.2. Distributions of Mass and Star Formation Rate

Figure 6 shows distributions of molecular mass and SFR in each mass (top) and α_{vir} (bottom) bin, assuming the G1a-4.5 and KOF formulas. While most clouds are low mass, half the total molecular mass is contained in 490 clouds with $M_{\text{mol}} > 6.8 \times 10^5 M_{\odot}$ and half the total star formation occurs in 192 clouds with $M_{\text{mol}} > 1.3 \times 10^6 M_{\odot}$, as more massive clouds tend to have lower α_{vir} (Figure 2(a) of Evans et al. 2021). The most probable virial parameter is ~ 4 , similar to the value found for nearby galaxies in the PHANGS-ALMA survey (Sun et al. 2020). The fraction of molecular mass contained in bound clouds ($\alpha_{\text{vir}} < 2$) amounts to only 17% (see also Evans et al. 2021), but they account for 54% of the total star formation. Our model prediction that most star formation occurs in the most massive clouds (with relatively low α_{vir}) is consistent with the observational finding that half the star

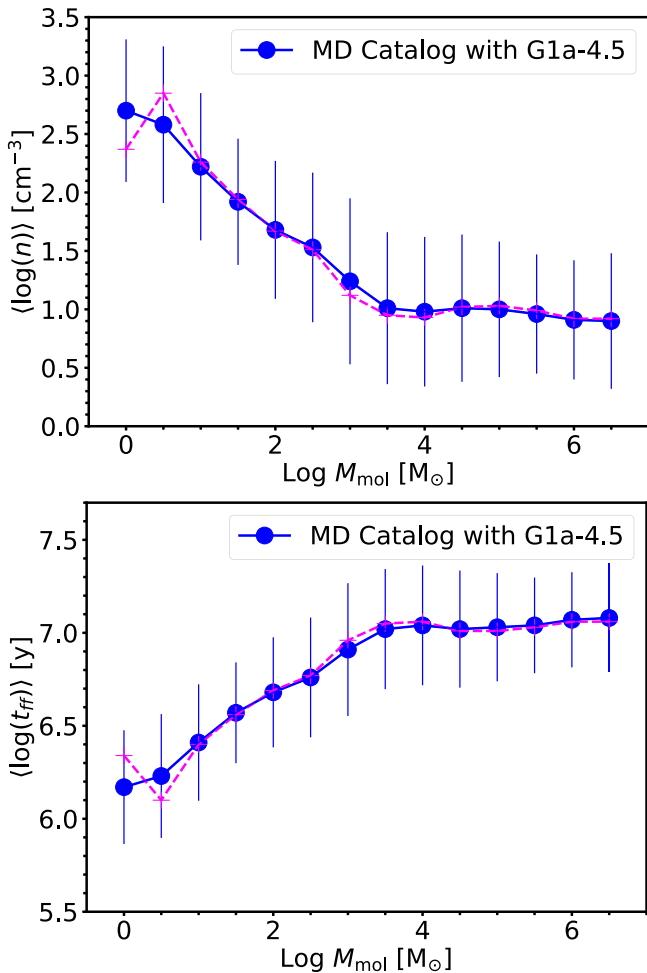


Figure 5. (Top) The mean and standard deviation of $\log n$ (blue) in bins of 0.5 in $\log M_{\text{mol}}$ for the cloud catalog of Miville-Deschênes et al. (2017). The median is plotted in magenta. (Bottom) The log of the freefall time vs. $\log M_{\text{mol}}$. The masses were computed using the G1a-4.5 formula to correct α_{CO} for Z .

formation in the Galaxy occurs in a small number of the most massive star-forming complexes (e.g., Murray & Rahman 2010).

6.3. Caveats and Further Work

Our success in predicting the observed SFR of the Galaxy rests on four pillars: the MD catalog of molecular structures, the dependence of metallicity on R_{gal} , the variation of α_{CO} with Z , and the dependence of ϵ_{ff} on α_{vir} .

The MD catalog is the only one to account for all the CO emission in the Galaxy, so it is the only one suitable for the prediction of the SFR of the Galaxy. Only a small fraction of the mass in that catalog is in bound structures ($\alpha_{\text{vir}} \leq 2$), with fractions varying from 0.07 for Gong1a to 0.39 for LD. However, other methods of structure identification (e.g., Rice et al. 2016), while also finding that most structures are unbound, find a much higher fraction of the molecular mass in bound structures. Other structure identification procedures should be attempted and compared to the observations of SFR.

Other transitions and isotopologues can also help to separate the effects of luminosity-to-mass conversions from those of efficiency. Structures defined by the $J = 1 \rightarrow 0$ or $J = 2 \rightarrow 1$ transitions of ^{13}CO were closest to the boundary between bound and unbound

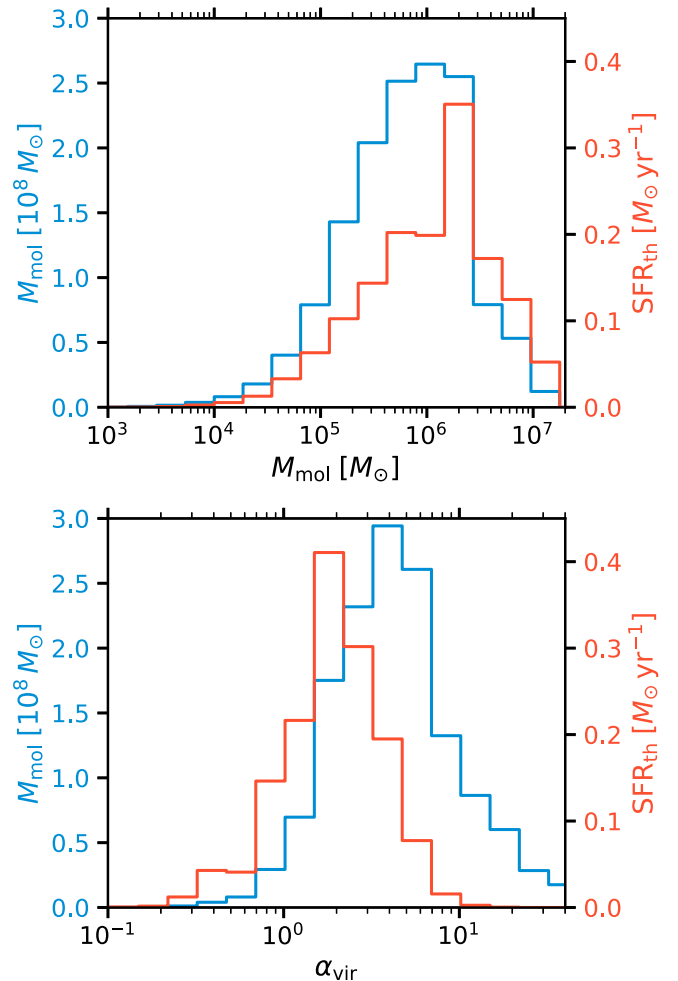


Figure 6. The total mass (red) and predicted SFR (blue) of molecular clouds in bins of M_{mol} bin (top) and α_{vir} (bottom), adopting $\alpha_{\text{CO}} = 4.50 \times Z^{-0.8}$ (G1a-4.5) and $b_{\text{KOF}} = 2.02$. The total predicted SFR is $1.46 M_{\odot} \text{ yr}^{-1}$, and the total molecular mass is $1.4 \times 10^9 M_{\odot}$.

(Evans et al. 2021), and full Galaxy surveys of these could provide new tests of theory if the appropriate simulations of their emission are available.

Alternatively, tracers that clearly favor bound structures, such as millimeter-wave continuum or HCN emission, could be used to survey the entire Galaxy. These tracers predict SFRs with lower dispersion than does CO (Vutisalchavakul et al. 2016; Jiménez-Donaire et al. 2019) and the resulting $\epsilon_{\text{ff}} \approx 0.01$ with a dispersion between studies of ≈ 0.3 dex (Krumholz et al. 2019 and references therein). These can separate the effects of varying α_{CO} from those of ϵ_{ff} , but require determinations of the HCN to dense gas mass conversion factor (α_{HCN}). This has been calculated from simulations by Onus et al. (2018), who find $\alpha_{\text{HCN}} = 14 \pm 6 M_{\odot} (\text{K km s}^{-1} \text{ pc}^2)^{-1}$, in reasonable agreement with observational constraints (Wu et al. 2005; Shimajiri et al. 2017; Evans et al. 2020). However, variations in α_{HCN} with environment (Shimajiri et al. 2017) and Z should also be considered based on a comparison to outer Galaxy clouds (S. Patra 2022, private communication), and the density “traced” by the $J = 1 \rightarrow 0$ transition of HCN may be substantially lower than usually thought when the total HCN luminosity is considered (Evans et al. 2020).

The radial dependence of the SFR should be improved using modern surveys, such as Hi-GAL (Molinari et al. 2010) for

infrared-based SFRs. Results from two lines of sight look promising (Veneziani et al. 2017). An alternative method, with the advantage of velocity information from recombination lines, would use more complete surveys of H II regions (Anderson et al. 2011, 2012, 2014). Both the inner and outer Galaxy provide strong tests of the dependence of α_{CO} on R_{gal} ; the outer Galaxy has the advantage of less confusion and deserves more attention.

The dependence of Z on R_{gal} used in our calculations is not well constrained inside about 5 kpc, where much of the molecular emission arises. Determination of gradients at smaller R_{gal} would be extremely important. There are also hints of azimuthal variations in Z (Wenger et al. 2019), which might be incorporated as knowledge of distances continues to improve. The gradient we assumed is the smallest of several choices, which range up to -0.077 dex kpc^{-1} for C/H. These steeper Z gradients produce shallower variations of Σ_{SFR} with R_{gal} , and these do not match as well the current observations. Once improved observations of both abundances and $\Sigma_{\text{SFR}}(R_{\text{gal}})$ are available, stronger tests will be possible.

The simulations of Gong et al. (2020) covered $Z = 0.5$ – 2.0 . As can be seen from Figure 1, we are mildly extrapolating those results in the very outer Galaxy and, more importantly, in the inner Galaxy. Extending the simulations over a wider range of Z would be very valuable (see, e.g., Hu et al. 2022).

The simulations that resulted in our assumed dependence of ϵ_{ff} on α_{vir} can also be extended. In addition, the issue of how to assign an observed α_{vir} to a simulation adds some uncertainty. These calculations assume that the current properties represent those at the start of the simulation, that the fit to the simulations can be used for any α_{vir} in the observations and, of course, that the simulations reflect reality. While the clouds in the Miville-Deschênes et al. (2017) sample are in a wide range of evolutionary states, the simulations suggest that the current observed values of α_{vir} will not overestimate the initial values substantially; in fact, α_{vir} decreases from the initial value over the first 4 Myr (Figure 5 of Kim et al. 2021). Those simulations cover a range of $\alpha_{\text{vir},0}$ of 1–5, and we have added a model with $\alpha_{\text{vir},0} = 10$. While the observed α_{vir} ranges from 0.1 to 100, there are few clouds with $\alpha_{\text{vir}} < 1$ but about one-third of the mass is in clouds with $\alpha_{\text{vir}} > 5$. Based on the new simulation with $\alpha_{\text{vir},0} = 10$, the expected star formation contribution of such clouds is very low (Figure 6).

We reiterate that the method used to identify and characterize molecular structures is important. In particular, the definition of the size of the structure and assignment of mass to a certain size region strongly affects the density and virial parameter. Simulations of observables from the theoretical simulations will help to identify the best method to assign sizes for comparison to the theoretical models.

7. Conclusions

Accounting for a metallicity-dependent factor to convert CO luminosity to mass and a virial-parameter-dependent star formation efficiency can bring theoretical predictions of the SFR into alignment with observed values for the Milky Way. While both play a role, the virial-parameter dependence of the star formation efficiency has a larger effect. We also predict the variation of the SFR with Galactocentric radius for different models of $\alpha_{\text{CO}}(R_{\text{gal}})$, which can be compared to improved determinations of the observed variation. These will be most

strongly affected by the metallicity dependence of the conversion from CO luminosity to mass.

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Software: `astropy` (Astropy Collaboration et al. 2013, 2018), `IPython` (Perez & Granger 2007), `matplotlib` (Hunter 2007), `NumPy` (van der Walt et al. 2011).

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