The Mass–Size Relation and the Constancy of GMC Surface Densities in the Milky Way

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Abstract

We use two existing molecular cloud catalogs derived from the same CO survey and two catalogs derived from local dust extinction surveys to investigate the nature of the giant molecular cloud (GMC) mass–size relation in the Galaxy. We find that the four surveys are well described by \(M_{\text{GMC}} \sim R^2\), implying a constant mean surface density, \(\Sigma_{\text{GMC}}\), for the cataloged clouds. However, the scaling coefficients and scatter differ significantly between the CO- and extinction-derived relations. We find that the additional scatter seen in the CO relations is due to a systematic variation in \(\Sigma_{\text{GMC}}\) with Galactic radius that is unobservable in the local extinction data. We decompose this radial variation of \(\Sigma_{\text{GMC}}\) into two components, a linear negative gradient with Galactic radius and a broad peak coincident with the molecular ring and superposed on the linear gradient. We show that the former may be due to a radial dependence of \(X_{\text{CO}}\) on metallicity, while the latter likely results from a combination of increased surface densities of individual GMCs and a systematic upward bias in the measurements of \(\Sigma_{\text{GMC}}\) due to cloud blending in the molecular ring. We attribute the difference in scaling coefficients between the CO and extinction data to an underestimate of \(X_{\text{CO}}\). We recalculate the CO observations of nearby GMCs using extinction measurements to find that locally \(X_{\text{CO}} = 3.6 \pm 0.3 \times 10^{20} \text{ cm}^{-2} \text{ (K km s}^{-1})^{-1}\). We conclude that outside the molecular ring, the GMC population of the Galaxy can be described to relatively good precision by a constant \(\Sigma_{\text{GMC}}\) of 35 \(M_\odot \text{ pc}^{-2}\).

Unified Astronomy Thesaurus concepts: Giant molecular clouds (653)

1. Introduction

Giant molecular clouds (GMCs) play a pivotal role in star formation and galaxy evolution. Stars form from such cold and massive clouds at almost every epoch of cosmic evolution. Deciphering the physical nature and evolution of GMCs is a necessary step for understanding the process of star formation and ultimately galaxy evolution. Within a decade of their discovery, Larson (1981) compiled existing CO observations of nearby GMCs and identified three basic empirical scaling relations obeyed by these objects: (1) a power-law scaling between velocity dispersion and cloud size, i.e., \(\sigma_v \sim R^{0.5}\); (2) an approximate state of virial equilibrium for the clouds, i.e., \(5\sigma_v^2 R/GM = 1\); and (3) a power-law scaling between GMC mass and size, i.e., \(M_{\text{GMC}} \sim R^2\). The latter relation implies that GMCs have constant average column densities. The scatter in all of these relations is typically large (0.4–0.5 dex; e.g., Larson 1981; Solomon et al. 1987; Falgarone et al. 2009), raising the question of how precisely the Larson relations describe the nature of GMC populations in the Milky Way. In other words, is the observed scatter in these relations largely due to experimental uncertainty inherent in the CO observations, or is much of the scatter intrinsically physical? In the first instance, individual GMCs in a population would closely conform to these relations (e.g., the GMCs would all have a very similar surface density), while in the second instance, the Larson relations are obeyed only in some average sense for the GMC population.

Using dust extinction rather than CO to measure GMC masses and sizes, Lombardi et al. (2010a) reexamined the GMC mass–size relation for a local sample of GMCs and found an extremely tight power-law scaling between these two quantities. The power-law index was found to be 2 with a measured scatter of only 11% or 0.04 dex. This scatter is significantly lower than found for any of the Larson scaling relations using CO data. Indeed, Lombardi et al.’s result indicates that local GMCs are characterized to high degree of accuracy by a constant average column or mass surface density that was directly measured to be \(\Sigma_{\text{GMC}} = 41 \pm 5 \text{ }M_\odot \text{ pc}^{-2}\). Ballesteros-Paredes et al. (2012) showed that the measurement of such a precisely constant surface density for GMCs was a natural consequence of the fact that GMCs have power-law column density probability density functions (pdfs) that decrease relatively steeply with column density (Lombardi et al. 2015) and the average column density is systematically computed for gas lying above a fixed column density threshold (typically corresponding to \(A_V \approx 1\) mag). The latter essentially guarantees that the computed average column density will be within some small factor of the value of the adopted threshold density. Indeed, Lombardi et al. (2010a) found this factor to be \(\sim 2\) for the clouds in their sample. Consequently, to the extent that GMCs in a given population have similar structure and their masses and sizes are systematically measured from the same threshold column density, their computed average surface densities should always be nearly the same. One interesting consequence of this finding is that local GMCs cannot obey a Kennicutt–Schmidt star formation scaling law (Lada et al. 2013).

Why is it, then, that reported CO measurements of cloud surface densities in the Milky Way are in the range \(\Sigma_{\text{GMC}} \sim 2–400 \text{ }M_\odot \text{ pc}^{-2}\), or, equivalently, \(A_V \sim 0.1–180\) mag (e.g., Solomon et al. 1987; Roman-Duval et al. 2010; Heyer & Dame 2015; Miville-Deschênes et al. 2017)? Such measurements clearly contradict both Larson’s and Ballesteros-Paredes et al.’s constant column density predictions. Possible explanations of this dilemma include (1) uncertainties in the determinations of cloud sizes and masses from CO data that could arise from effects such as the definition of a cloud, the use of variable surface density thresholds to define cloud boundaries, the disentangling of cloud overlap along the line of sight, variation in the CO mass conversion (\(X_{\text{CO}}\)) factor, etc.; (2) the scaling coefficient that characterizes the mass–size
relation being variable; and (3) some combination of (1) and (2).

In this paper, we reexamine the mass–size relation for GMCs in the Milky Way. We use four different GMC catalogs that employed different tracers of molecular material and differing methodologies to identify and extract the physical properties of the clouds. Two of these catalogs used CO observations to trace the molecular gas, and two used observations of dust extinction for the same purpose.

2. Data

The $^{12}$CO data were drawn from the recent molecular cloud catalogs of Rice et al. (2016; hereafter R+16) and Miville-Deschenes et al. (2017; hereafter MD+17). Both of these catalogs used the complete Galaxy-wide $^{12}$CO survey by Dame et al. (2001; hereafter DHT) to identify and measure the basic properties of GMCs across the Galaxy. The DHT survey is a composite of large-scale CO surveys obtained with a pair of 1.2 m telescopes covering the northern and southern skies with an angular resolution of 8.5′. It is the most complete and uniform CO survey of the Milky Way yet produced.

A dendrogram-based decomposition of the DHT survey was performed by R+16 to identify 1064 GMCs with masses ranging from $\sim2.5 \times 10^3$ to $10^7 M_\odot$ and sizes (radii) between $\sim2$ and 240 pc, in total recovering about 40% of the CO emission in the DHT survey. Distances to the clouds were derived from the Galactic rotation curve. For the present study, we omitted a small number of clouds for which reliable distances could not be determined, resulting in a cleaned catalog containing 1037 GMCs. A Gaussian deconvolution followed by a cluster-finding algorithm was employed by MD+17 to recover 8107 molecular clouds accounting for more than 98% of the CO emission in the DHT survey. For the present study, we filtered the MD+17 catalog by removing sources that, on independent inspection of the DHT survey, did not appear real. To identify the spurious sources, we employed the smooth-masking technique described by Dame (2011) to isolate regions of the sky with significant CO emission from those with no detectable CO emission. We then located all of the sources in the MD+17 catalog whose positions coincided with regions of null CO emission in the smoothed masks and removed them from the catalog. This resulted in a cleaned catalog containing 5577 sources with confident identifications.

The sources that were removed all had similar mass surface densities that were close to the corresponding detection limit, consistent with the suggestion that they were likely not real. The confirmed clouds ranged in mass between about 0.1 and $2 \times 10^4 M_\odot$ and in radius between roughly 0.1 and 270 pc. These ranged clearly include clouds smaller and less massive than GMCs (i.e., $R_{GMC} \gtrsim 3$ pc, $M_{GMC} \gtrsim 10^3 M_\odot$), but they represent less than 8% of the catalog clouds and have a negligible influence on our analysis.

For comparison, we also analyzed the GMC mass–size relation derived using dust extinction measurements obtained at optical and near-infrared wavelengths. For this purpose, we examined two additional published data sets. First, we used a compilation of highly resolved (FWHP $\approx 2′–3′$) Two Micron All Sky Survey (2MASS) near-infrared extinction maps of 11 GMCs located within 0.5 kpc of the Sun to define a benchmark local GMC sample (LGS; Lada et al. 2010; Lombardi et al. 2010a, and references therein). These clouds were identified from wide-field extinction maps as contiguous regions with infrared extinctions ($A_K$) in excess of 0.1 mag. The clouds in the LGS have well-known distances and range in mass from roughly $8 \times 10^2$ to $10^5 M_\odot$ and radii from about 3 to 20 pc. Second, we used the recent GMC catalog of Chen et al. (2020). This catalog contains 567 GMCs within $\sim3$ kpc of the Sun; although a few are as distant as 3 kpc or more, the majority (80%) are within 1.5 kpc of the Sun. Thus, although the Chen et al. sample occupies a significantly larger volume of the Galactic disk than the LGS, it still represents a relatively local sample of clouds compared to those in the two CO catalogs. The Chen et al. clouds were identified from a dendrogram analysis of 3D extinction maps that were presented in an earlier study (Chen et al. 2019); this study used optical data from the Gaia DR2 (Gaia Collaboration et al. 2018), together with infrared data from 2MASS (Skrutskie et al. 2006) and the Wide-field Infrared Survey Explorer (Kirkpatrick et al. 2014) to construct fully sampled optical and infrared color-excess (extinction) maps of the entire Galactic plane. The extinction maps have an angular resolution of 6″, comparable to the CO data. Distances to the extracted clouds were obtained using Gaia DR2 parallaxes and a modern variant of the Wolf (1923) method and ranged from roughly 0.36 to 3.6 kpc. The derived cloud masses ranged from 6 to $8 \times 10^5 M_\odot$, with radii between 0.2 and 86 pc. As we did for the MD+17 catalog, we have retained in the Chen et al. catalog a small fraction of the clouds that are smaller and less massive than GMCs.

3. Results and Analysis

3.1. The $^{12}$CO Mass–Size Relation for Milky Way GMCs

In Figure 1, we show the mass–size relations for the GMC populations identified in the R+16 and MD+17 catalogs. In both plots, there is a strong correlation between the two quantities. Moreover, the distribution of points is very nearly parallel to the lines of constant column density. A simple linear fit to the data finds $\log M = 1.89 \pm 0.07 + 1.98 \pm 0.05 \log R$ or $M = 78.6 R^{1.98}$ for the clouds in the R+16 catalog and $\log M = 1.76 \pm 0.02 + 2.10 \pm 0.01 \log R$ or $M = 57.5 R^{1.10}$ for the MD+17 clouds. The fact that the power-law indices of both fits are close to 2 nicely confirms Larson’s scaling relation for Milky Way GMCs, implying that these clouds are indeed characterized by a constant surface density at least within the observed scatter. The values of these characteristic GMC surface densities can be approximately derived from the scaling coefficients, that is, $\Sigma_{GMC} = 78.6/\pi$ or $25.0 M_\odot$ pc$^{-2}$ and $\Sigma_{GMC} = 57.5/\pi$ or $18.3 M_\odot$ pc$^{-2}$, respectively, and are in reasonable agreement with each other considering the difference in methods, etc. However, the scatter is large with nearly identical logarithmic dispersion in both plots of $\approx0.45$ dex.

The values of $\Sigma_{GMC}$ derived from the scaling coefficients of the fits are smaller than the respective means of the individual data points, which are $\langle \Sigma_{GMC} \rangle = 38.3 \pm 43.4$ and $40.7 \pm 44.3 M_\odot$ pc$^{-2}$, where the quoted uncertainty is the standard deviation of the measurements in the two sets of data. This is somewhat surprising, since for a power-law scaling relation with a spectral index of $\sim2$, the two measures should be similar. However, the scaling coefficients of the fits are close to the median values of the two distributions, that is, $\Sigma_{GMC}^{\text{med}} = 21.7$ and 25.9 $M_\odot$ pc$^{-2}$ for the R+16 and MD+17 catalogs, respectively. The higher values for the mean surface

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Note that for all of the data used in this study, the cloud size is defined to be $R = \sqrt{\text{Area}/\pi}$ to facilitate comparisons.
densities result from the presence of an extended high surface density tail in the observed frequency distribution of $\Sigma$. This surface density tail consists of some of the most distant GMCs, located primarily in the inner regions of the Milky Way. Such measurements are biased upward by the fact that for a fixed angular resolution and sensitivity, there is a minimum cloud radius and mass that can be detected and measured at a given distance (e.g., Appendix C in Miville-Deschênes et al. 2017). Because of this, lower-mass clouds are not detected at large distances, and only the inner, high surface density portions of the high-mass clouds are observed. Thus, these measurements can overestimate the true mean surface density of the clouds and bias the calculation of the mean value.

### 3.2. The Dust Mass–Size Relation for Milky Way GMCs

In Figure 2, we show the GMC mass–size relation derived from extinction observations of the dust within the clouds. Filled magenta squares are data from the Chen et al. (2020) survey, and filled green circles are the data from the LGS. The solid red line is a linear fit to the Chen et al. data, which returns $\log M = 2.19\pm 0.02 + 1.96\pm 0.02\log R$ or $M = 155R^{1.96}$, corresponding to a characteristic GMC surface density $\Sigma_{\text{GMC}} = 50\, M_\odot\, \text{pc}^{-2}$ for these clouds. A fit to the LGS data finds $\log M = 2.12\pm 0.04 + 1.98\pm 0.04\log R$ or $M = 131R^{1.98}$ with $\Sigma_{\text{GMC}} = 42\, M_\odot\, \text{pc}^{-2}$. Unlike the CO results, these characteristic surface densities agree well with both the means of the individual GMC surface densities in the two samples (that is, $\langle \Sigma_{\text{GMC}} \rangle = 50.4 \pm 20.9$ and $41.2 \pm 5.3\, M_\odot\, \text{pc}^{-2}$, respectively) and the median values ($\Sigma_{\text{GMC}}^{\text{med}} = 48.3$ and 39.3) of the two extinction GMC samples. Here again the quoted uncertainty is the standard deviation of the measurements. This agreement between the various estimates of $\Sigma_{\text{GMC}}$ is as expected for measurements without the distance bias mentioned above, a result of the fact that the two extinction samples occupy a smaller volume of the nearby Galactic disk.

The different scalings exhibited by the two extinction-derived mass–size relations ($\sim 50$ and $40\, M_\odot\, \text{pc}^{-2}$) are primarily a result of the different mass calibrations employed.
in the two studies. Specifically, Chen et al. (2020) use the calibration of Chen et al. (2015), \( N(H + 2H_2) = 2.41 \times 10^{21} \ A_v \ cm^{-2} \), while the LGS adopts the more standard calibration: \( N(H + 2H_2) = 1.87 \times 10^{21} \ A_v \ cm^{-2} \) (e.g., Bohlin et al. 1978; Lombardi et al. 2010b). The ratio of the two calibration factors is \( 2.41/1.87 = 1.29 \) and is comparable to the ratio of characteristic surface densities, i.e., \( \Sigma_{\text{GMC}}(\text{LGS})/\Sigma_{\text{GMC}}(\text{C+}) = 1.25 \). Once this is taken into account, the two extinction studies are in excellent agreement with each other. The scatter in both dust data sets is significantly less than that observed in the CO relations. The scatter in the Chen et al. data is 0.18 dex and the LGS only 0.04 dex, the latter an order of magnitude less than that found for the CO observations. Moreover, the two dust studies produce measurements of the characteristic cloud surface densities (\( \Sigma_{\text{GMC}} \)) about a factor of 1.7–2 higher than indicated by the CO observations.

In this paper, we will adopt the LGS gas-to-dust calibration. The reason for this is that the LGS extinctions are derived from \((JHK)\) infrared colors where the extinction law is not sensitive to variations of \( R_V \), the ratio of total to selective visual extinction (e.g., Mathis 1990). The Chen et al. extinctions, on the other hand, are primarily based on optical colors that are sensitive to variations in \( R_V \) that are not uncommon.

4. Nature of the Observed Scatter

4.1. Experimental Uncertainties or Physical Variations?

The significant difference in the size of the scatter between the \( ^{12}\text{CO} \) and extinction data is intriguing. It could be due to experimental uncertainties inherent in the \( ^{12}\text{CO} \) but not the extinction data, and/or it could result from real, intrinsic variations in \( \Sigma_{\text{GMC}} \) within the Galaxy that are not evident in the extinction data, since those clouds occupy a smaller volume of the Milky Way. Such Galactic variations would likely be systematic, perhaps environmentally driven, given the tight correspondence of the extinction data to a truly constant extinction studies are in excellent agreement with each other.

Moreover, the two dust studies produce measurements of the characteristic cloud surface densities (\( \Sigma_{\text{GMC}} \)) about a factor of 1.7–2 higher than indicated by the CO observations.

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4.2. A Radial Variation across the Galaxy

Another possible explanation for the differences between the \( ^{12}\text{CO} \)- and dust-derived mass–size scaling relations may be tied to the fact that the \( ^{12}\text{CO} \) surveys cover a much larger volume of the Milky Way than the dust extinction observations. To test this hypothesis, we examined the dependence of the mass–size relation on galactocentric radius. In Figure 3, we plot the mass–size relation for subpopulations of GMCs from the \( \text{R+16} \) catalog located in the inner and outer Galaxy. Both subpopulations clearly display independent correlations between their masses and sizes with only slightly differing slopes (2.18 and 1.95 for the inner and outer GMCs, respectively). However, there is a significant difference in the scaling between the two mass–size relations, corresponding to differing values of \( \Sigma_{\text{GMC}} \). Indeed, their mean surface densities are quite different, being 84.5 and 11.7 \( M_\odot \) pc\(^{-2} \) for the inner and outer GMCs, respectively.

The scatter (0.22 dex) in the inner Galaxy surface densities is comparable to that (0.28 dex) of the outer Galaxy GMCs. But both are significantly less than that derived for the whole Milky Way sample (0.43 dex) and closer to that of the Chen et al. extinction sample (0.18 dex). The same analysis of the \( \text{MD+17} \) sample returns very similar results. This indicates that a
significant amount of the observed scatter in the Galaxy-wide 12CO mass–size relation is due to systematic variations in $\Sigma_{\text{GMC}}$ with Galactic radius. These facts suggest that a varying scaling parameter may be needed to describe the observed mass–size relation for Milky Way GMCs. It is interesting to note here that the mean surface density of the outer Galaxy clouds, $\Sigma_{\text{GMC}} \sim 12 M_\odot \text{ pc}^{-2}$, corresponds to a visual extinction of only $\sim 0.5$ mag, very close to the value for molecular dissociation in the Milky Way, suggesting that these clouds are very tenuous objects. Although, as will be discussed later, this could also indicate issues with the adopted 12CO mass calibration. Indeed, this is suggested by the fact that when considering the whole cloud sample, there still remains a significant difference in the scaling factor (i.e., $\Sigma_{\text{GMC}}$) between the CO and dust relations, with the CO-derived $\Sigma_{\text{GMC}}$ being a factor of 2 or more lower than those derived for the dust.

To further investigate the variation of $\Sigma_{\text{GMC}}$ with location in the Milky Way, we calculated the mean of the GMC gas surface densities as a function of Galactic radius for both 12CO catalogs. The results are plotted in Figure 4. To avoid confusion, we emphasize here that our graph plots the mean of the gas surface densities of individual GMCs and not the azimuthally averaged surface density of molecular gas as a function of galactocentric radius, though the two distributions are undoubtedly related. In the outer Galaxy, the data from the two catalogs agree well, and the relation is relatively flat from 9 to 14 kpc. The GMCs in the outer Galaxy appear to be characterized by a constant $\Sigma_{\text{GMC}} \approx 13 \pm 4 M_\odot \text{ pc}^{-2}$. Inward of 9 kpc, both relations begin to rise as the radius decreases, until around 4 kpc, where the points decline with decreasing radius. The broad peak in the distributions between 4 and 7 kpc corresponds to the well-known molecular ring, which contains the inner Scutum-Centaurus and Norma spiral arms. The plot shows clear evidence for a systematic variation in $\Sigma_{\text{GMC}}$ with Galactic radius.

4.2.1. Nature of the Radial Variation: A Baseline Linear Gradient

The question we now consider is whether the observed variation with Galactic radius is intrinsic or produced by an unrecognized systematic error in the CO observations. That GMCs have power-law pdfs almost guarantees that they should have the same column density if measured from the same boundary threshold. This is because the pdfs of GMCs peak at low surface densities, near those of the boundary thresholds, and then fall off very steeply to higher column densities that occupy significantly smaller areas of the cloud. It would require significant internal changes in cloud structure for $\Sigma_{\text{GMC}}$ not to be constant (Ballesteros-Paredes et al. 2012). However, changes in the measurement threshold result directly in changes to the individually measured values of $\Sigma_{\text{GMC}}$. As mentioned earlier, Lombardi et al. (2010a) showed that for the clouds in the LGS, $\Sigma_{\text{GMC}} \approx 2 \times \Sigma_{\text{threshold}}$. The GMCs in the LGS are well separated on the sky and have relatively well-defined boundaries. The same is mostly true for clouds observed from our vantage point in the outer galaxy.

However, in the molecular ring region, the space density of clouds is much higher, resulting in significant blending of cloud emission both on the plane of the sky and in velocity. The velocity blending is caused not only by the well-known distance ambiguity in the inner Galaxy but also by the significant internal velocity dispersion of GMCs, their random and noncircular streaming motions, all coupled with a shallow gradient of velocity with distance near the tangent points in the inner Galaxy. At a typical direction in the inner galaxy, we find that a cloud at the tangent point and another 1 kpc closer along the line of sight will differ in velocity by only $\sim 5 \text{ km s}^{-1}$. 

Figure 3. Mass–size relations for Milky Way GMCs in the inner vs. outer regions of the Galaxy taken from the GMC catalog of Rice et al. (2016). The red diamonds correspond to clouds in the outer Milky Way, located between 11 and 13 kpc from the center of the Galaxy. The blue squares correspond to clouds in the inner Milky Way, between 3 and 5 kpc from the center of the Galaxy.

Figure 4. Radial dependence of mean GMC surface densities across the Milky Way disk. The blue circles are data from the Rice et al. (2016) GMC catalog, and the red diamonds are based on data from the Miville-Deschênes et al. (2017) catalog. The error bars represent the standard deviation of the values. The light dashed line is a least-squares fit to the points excluding those between 4 and 8 kpc (see text).
owing to Galactic rotation (using the universal rotation curve of Reid et al. 2014). This is comparable to the internal velocity dispersion of a $10^5 M_\odot$ GMC (Dame et al. 1986; Solomon et al. 1987), typical of the clouds studied here (e.g., Figure 1), and will result in heavy blending along the line of sight.

In this situation, finding consistent outer boundaries of the GMCs is challenging for any cloud identification algorithm. This can result in significant variations in the level of the measured boundaries and introduce a bias toward higher values of the measured $\Sigma_{\text{GMC}}$ in these directions. In addition, as mentioned earlier, sensitivity and angular resolution limits can also bias GMC measurements to higher values for the more distant clouds in these directions. This effect is difficult to quantify, and we will not attempt to do so here. However, Ballesteros-Paredes et al. (2019) modeled the effect of overlapping GMCs on the mass–size relation in CO observations and found that random variations in the degree of cloud overlap in a large cloud sample could, in addition to artificially increasing the slope of the mass–size relation, also produce much of the scatter seen in the relations.

Inward of ~4 kpc, the overall space density of clouds drops significantly, probably owing to the presence of the Galactic bar (Blitz & Spergel 1991). In this region, the clouds are again fairly well defined, as they are at and beyond the solar circle. We take advantage of this situation to produce a conservative measure of the variation of $\Sigma_{\text{GMC}}$ with Galactic radius. For this exercise, we consider only the MD+17 data, since they span a larger range of Galactic radius. We perform a least-squares fit to the MD+17 data, excluding the points between 4 and 8 kpc, to estimate the minimum (unblended) radial gradient in $\Sigma_{\text{GMC}}$. We find that

$$\Sigma_{\text{GMC}}(R_{\text{gal}}) = 54.5 - 3.7R_{\text{gal}} \, M_\odot \, \text{pc}^{-2},$$

where $R_{\text{gal}}$ is the radial distance (in kpc) from the center of the Galaxy. The fit is shown as a dashed line in Figure 4. Since the relation in Equation (1) was derived using data least likely to be biased by crowded and overlapping clouds, we suggest that it represents a baseline radial gradient in unblended GMC surface densities.

### 4.2.2. Nature of the Radial Variation: A Metallicity-dependent CO X-factor

The assumption of a constant CO mass calibration factor ($X_{\text{CO}}$) that was used in both catalogs could introduce a systematic error in the derived $\Sigma_{\text{GMC}}$. In particular, this assumption could play a role in producing the baseline radial variation in $\Sigma_{\text{GMC}}$ shown in Figure 4 and described by Equation (1). This is because the CO abundance and, consequently, $X_{\text{CO}}$ are believed to be functions of metallicity (Bolatto et al. 2013), and the Milky Way is known to have a radial metallicity gradient (Maciel & Costa 2010). The Galaxy’s metallicity decreases with Galactic radius out to about 10 kpc, where it appears to flatten (Maciel & Costa 2010 and references therein). This is very similar to the behavior of $\Sigma_{\text{GMC}}(R_{\text{gal}})$ seen in Figure 4, suggesting that $\Sigma_{\text{GMC}}(R_{\text{gal}})$ varies with metallicity and that the gradient we measure in $\Sigma_{\text{GMC}}(R_{\text{gal}})$ could reflect the use of a constant value of $X_{\text{CO}}$ in the surface density calculations rather than a value adjusted for metallicity. Indeed, studies indicate that the metallicity gradient in the Milky Way can be expressed as $\log(Z/Z_\odot) \sim -0.06 \, (R_{\text{gal}})$ (Genovali et al. 2014; Wenger et al. 2019), giving

$$Z(3 \, \text{kpc}) / Z(10 \, \text{kpc}) = 2.51,$$

which is essentially the same as the ratio of mean GMC surface densities given by Equation (1),

$$\Sigma(3 \, \text{kpc}) / \Sigma(10 \, \text{kpc}) = 2.48.$$ Apparently, the baseline gradient in $\Sigma_{\text{GMC}}$ that we observe in Figure 4 could be largely accounted for by correcting the values of the masses and surface densities by a metallicity-dependent conversion factor that approximately behaves as $X_{\text{CO}}(Z) \sim Z^{-1}$. Such a metallicity dependence of $X_{\text{CO}}$ is consistent with predictions of a recent set of simulations by Feldmann et al. (2012). Because of this dependence, the presence of the baseline gradient in $\Sigma_{\text{GMC}}$ by itself does not provide convincing evidence for the need of a variable scaling parameter in the mass–size relation, at least for those clouds outside the molecular ring.

### 4.2.3. Nature of the Radial Variation: A Peak in the Molecular Ring

The broad peak between 4 and 8 kpc in Figure 4 does suggest a significant departure from an otherwise constant GMC surface density across the Milky Way. To better understand the nature of this peak, we plot the positions of the GMCs in the MD+17 catalog on the longitude–velocity diagram in Figure 5. The clouds with the highest surface densities (red and yellow symbols) are found to lie in two regions, the first a locus between $l = \pm 30^\circ$, similar to that expected for an inner spiral arm or arms, and the second a vertical distribution near $l = 0^\circ$. The surface densities measured in this latter region are almost certainly spurious, since the X-factor in the Galactic center region is thought to be up to 10 times lower than elsewhere in the disk (Bolatto et al. 2013). The Scutum-Centaurus and Norma arms lie in the former region, which makes up the molecular ring. This suggests that perhaps the surface densities of the GMCs are enhanced by some process in the spiral arm structures. If so, this would again indicate the need for a variable (environmentally dependent) scaling parameter for the mass–size relation. However, as mentioned earlier, in this direction on the sky, we expect to observe crowding and overlap of the clouds along the line of sight where biases in the measured surface density can be introduced by cloud extraction algorithms.

How much of the observed enhancement in the molecular ring is due to a change in the physical properties of the GMCs within the inner spiral arms, and how much is a result of a bias in the measured surface densities due to significant cloud overlap and blending? The following considerations suggest that the blending of clouds could produce both increased scatter and upward bias in $\Sigma_{\text{GMC}}$ for GMCs in the molecular ring. First, when emission from a cloud is superposed on a varying background due to crowding and blending, the identification algorithms do not always measure the cloud properties to the true (or same) cloud edge or boundary. This produces an upward bias in the measured surface densities because the individual GMCs are generally stratified with power-law pdfs such that the inner regions are characterized by much higher surface densities and smaller total surface area than the outermost regions. Second, this bias would be expected to increase with distance through the molecular ring as decreasing spatial resolution increases cloud blending. This would produce an artificial increase in the measured surface densities with decreasing Galactic radius in the ring region. Third, the average scatter in the calculated mean surface density in the molecular ring GMCs ($42 \, M_\odot \, \text{pc}^{-2}$) is found to be 4.5 times higher than that in the outer Galaxy GMCs ($9 \, M_\odot \, \text{pc}^{-2}$). Random
variations in the degree of cloud overlap could account for the larger dispersions measured for \( S_{GM} \) in the molecular ring compared to other regions of the Galaxy (e.g., Ballesteros-Peredes et al. 2019). These considerations add to the surmise that surface density measurements made toward the molecular ring are much more susceptible to systematic biases that both increase the scatter in and the measured values of \( S_{GM} \) compared to other regions of the Galaxy.

Unfortunately, it is difficult to more precisely determine the magnitude of these effects from the published CO studies. Though the rise in measured GMC surface densities in the molecular ring suggests a departure from constant surface density clouds and the Larson relation in that region, the magnitude of this departure is unclear at the present time, and it could be much smaller than current measurements imply.

4.3. Comparison of Gas and Dust at 8.5 kpc: Calibration of the CO X-factor

Given the radial dependence of the CO-derived GMC surface densities, it is of interest to investigate the mass–size relations for a sample of clouds all at the same Galactic radius. In Figure 6, we plot the mass–size relations for GMCs between 8 and 9 kpc from the Galactic center derived from both CO (MD+17) and dust extinction (Chen et al. 2020). It is clear that the dust observations are characterized by considerably less scatter than the CO observations. Moreover, the characteristic GMC surface density, \( \Sigma_{GM} \), or overall scaling for the two relations is clearly different for the two data sets. The mean surface densities are \( 51.5 \pm 1.1 \) and \( 26.6 \pm 0.6 \) \( M_\odot \) pc\(^{-2}\) for the extinction- and CO-derived measurements, respectively. Here the quoted uncertainties are the standard errors in the mean values. This indicates that there is a systematic difference in the total \( (H_2) \) column density calibrations of a factor of \( \sim 1.9 \). Additionally, we tried further restricting this group of clouds to those within 3 kpc of the Sun to better match the extinction catalog. The resulting mean surface density for the CO clouds \( (\Sigma_{GM} = 26.8 \pm 0.7) \) was essentially identical to that of the more expanded sample. As mentioned earlier, the mass–size relation for the Chen et al. dust clouds is in excellent agreement with the mass–size relation of the LGS once differences in assumed gas-to-dust ratios are taken into account. In this paper, we adopt the calibration of LGS as the fiducial calibration. For the LGS calibration, \( \Sigma_{GM} = 41.2 \pm 1.6 \) \( M_\odot \) pc\(^{-2}\). Here the quoted uncertainty is the standard error in the mean. This implies a calibration difference between the GMCs in the MD+17 CO catalog and the LGS extinction-derived dust column density measurements of a factor of \( 1.55 \pm 0.07 \). Similarly for the GMCs in the R+16 catalog between 8 and 9 kpc from the Galactic center (where \( \Sigma_{GM} = 20.3 \pm 1.3 \) \( M_\odot \) pc\(^{-2}\)), we find a calibration difference of a factor of \( 2.03 \pm 0.15 \) with respect to the LGS measurements.
The difference between the CO and LGS dust mass calibrations provides a direct measure of the CO conversion factor ($X_{\text{CO}}$) for the Milky Way GMCs in the range $8 \text{ kpc} \leq R_{\text{gal}} < 9 \text{ kpc}$. Both $^{12}$CO catalogs adopted the standard $X$-factor for their mass calibration (i.e., $X_{\text{CO}} = 2 \times 10^{20} \text{ cm}^{-2} \text{ (K km s}^{-1})^{-1}$; Bolatto et al. 2013), and comparison with the extinction data indicates that this underestimates the masses by a factor of $1.55 \pm 2.03$. Correcting for this deficit using the average of the MD+17 and R+16 data, we derive a CO mass calibration factor of

$$X_{\text{CO}}(R_{\odot}) = 3.6 \pm 0.3 \times 10^{20} \text{ cm}^{-2} \text{ (K km s}^{-1})^{-1}.$$  

We emphasize that this calibration applies near the solar circle (i.e., $R_{\odot}$) and is appropriate for the two CO catalogs considered here. It may not necessarily apply to CO observations made using different data obtained on different (particularly subcloud) spatial scales and/or analyzed using different methodologies for cloud identification and extraction (e.g., Lombardi et al. 2006; Pineda et al. 2008; Kong et al. 2015; Lee et al. 2018; Lewis et al. 2020).

Earlier, we suggested that the underlying radial gradient in cloud surface densities derived from CO (i.e., Equation (1) and dashed line in Figure 4) might wholly be the result of an unaccounted-for variation of $X_{\text{CO}}$ with metallicity. If this is the case, then $X_{\text{CO}}$ must vary as the inverse of the mean cloud surface densities:

$$X_{\text{CO}}(R_{\text{gal}}) = X_{\text{CO}}(R_{\odot}) \frac{\sigma(R_{\odot})}{\sigma(R_{\text{gal}})}.$$  

The value of $X_{\text{CO}}(R_{\odot})$ derived above, together with Equation (1) for $\sigma(R_{\text{gal}})$, yields the following expression for $X_{\text{CO}}$ as a function of Galactic radius:

$$X_{\text{CO}}(R_{\text{gal}}) = \frac{83}{(54.5 - 3.7R_{\text{gal}})} \text{ for } 2 < R_{\text{gal}} \leq 10 \text{ kpc},$$  

where $R_{\text{gal}}$ is in units of kpc and $X_{\text{CO}}$ is in units of $10^{20} \text{ cm}^{-2} \text{ K km s}^{-1}$ \text{s}. For $R_{\text{gal}} > 10$ kpc, we assume a constant $X_{\text{CO}} = 6.0 \times 10^{20} \text{ cm}^{-2} \text{ K km s}^{-1}$ to reflect a constant or more slowly varying metallicity in the outer Galaxy.

We emphasize here that our determination of $X_{\text{CO}}(R_{\text{gal}})$ is an approximate one. It is based on our inference that $X_{\text{CO}}$ inversely varies with metallicity and thus with $\Sigma_{\text{GMC}}$ in order to account for the gradient in Equation (1). The fact that $\frac{\Sigma(1 \text{ kpc})}{Z(1 \text{ kpc})} \approx \frac{\Sigma(10 \text{ kpc})}{Z(10 \text{ kpc})}$ and that the inferred metallicity dependence of $X_{\text{CO}}$ is consistent with the predictions of recent simulations (Feldmann et al. 2012) provide intriguing evidence in support of the idea that a radially varying, metallicity-dependent $X$-factor might solely explain the surface density gradient of unblended clouds given by Equation (1).

5. Discussion

Our analysis shows that catalogs derived from two independent tracers of molecular gas, $^{12}$CO and dust extinction, yield mass–size scaling relations with $M_{\text{GMC}} \sim R_{\text{GMC}}^2$, which implies constant average surface densities for the corresponding cloud populations. However, the scaling coefficients of the CO- and extinction-derived relations significantly differ, implying different mean GMC surface densities for the two tracers. Moreover, the scatter characterizing the CO relations is significantly larger than that of the extinction relations. We find that the increased scatter of the CO mass–size scaling relations is a result of a radial variation in the scaling coefficient of the relations or, equivalently, in the characteristic “constant” GMC surface density implied by them. This radial variation is not apparent in the extinction observations because they do not span a sufficiently large range in Galactic radius. Calibration of the CO surface densities using the dust extinction measurements of local GMCs results in a larger $X$-factor than that used in the published CO catalogs and accounts for the different scaling coefficients found for the published CO and extinction catalogs.

We decomposed the radial variation of $\Sigma_{\text{GMC}}$ into two components: a linear gradient of decreasing $\Sigma_{\text{GMC}}$ with Galactic radius and a broad peak that coincides with the molecular ring in the inner Galaxy and is superposed on the linear gradient. We noticed that the linear decrease with radius is similar to that for metallicity in the Milky Way and posited that it results from the use of a constant, rather than metallicity-dependent, $X$-factor for computing masses from CO. In Equation (2), we derived an approximate form for the variation of $X_{\text{CO}}$ with $R_{\text{gal}}$. To provide our best estimate for the radial variation of $\Sigma_{\text{GMC}}$ in the Galaxy, we correct the mean CO-derived surface densities by the radially dependent $X$-factor derived in Equation (2) and plot the result in Figure 7. The individual data points are derived from averages of the R+16 and MD+17 catalogs. The error bars include both the intrinsic dispersions in the individual data sets and the systematic differences in the derived surface densities between the two catalogs but do not include any systematic error in $X_{\text{CO}}$.

The figure shows that a single mass surface density of $\Sigma_{\text{GMC}} = 35 M_{\odot} \text{ pc}^{-2}$ well describes the clouds outside the molecular ring. The surface densities of clouds in the molecular ring appear to significantly deviate from this otherwise Galaxy-
wide constant value. The average surface density within the molecular ring is found to be \( \Sigma_{\text{GMC}} = 82 \pm 10 \, M_\odot \, \text{pc}^{-2} \), a factor of 2.3 higher than that for clouds outside the ring \( (\Sigma_{\text{GMC}}) = 35 \pm 8 \, M_\odot \, \text{pc}^{-2} \). As discussed earlier, this difference is likely an upper limit because of a significant upward bias in the measured surface densities in the molecular ring due to cloud blending.

Although the size of the peak in GMC surface density in the molecular ring is very uncertain, it is possible that environmental conditions in this region account for at least some of the increase in the mean surface densities there. In particular, comparison of GMC mass-size relations in nearby disk galaxies suggests that the scaling coefficient of the mass-size relation can vary between galaxies and that the midplane pressure in a galactic disk is directly related to its \( \Sigma_{\text{GMC}} \) (Faesi et al. 2018). This could occur if the pressure within a GMC in equilibrium with the external midplane pressure of a galactic disk, as will be discussed in more detail below. The weight of a self-gravitating cloud gives rise to an internal pressure that only depends on its surface density, \( P_{\text{GMC}} \propto G \Sigma_{\text{GMC}}^2 \) (Bertoldi & McKee 1992). The ratio of internal pressures between GMCs in the ring and the outer galaxy is then \( \Sigma_{\text{ring}}^2 / \Sigma_{\text{outer}}^2 \). For the surface density ratio for molecular ring and outer Galaxy GMCs calculated above, the corresponding ratio of internal pressures would be \( \Sigma_{\text{ring}}^2 / \Sigma_{\text{outer}}^2 = 5.5 \pm 1.4 \). This value is likely an upper limit to the true value, given the bias embedded in the measurements of \( \Sigma_{\text{GMC}} \) in the molecular ring discussed earlier.

To estimate the external pressure of the Milky Way disk acting on the clouds, we assume that this pressure, \( P_{\text{ISM}} \), originates from two components, the stellar potential of the disk and the weight of the atomic (H I) interstellar gas. We follow the analysis of Faesi et al. (2018) and write the midplane pressure as

\[
P_{\text{ISM}} = \frac{\pi G}{2} \Sigma_{\text{H I}} \left[ \Sigma_{\text{H I}} + \sigma_{\text{H I}} \frac{\Sigma_v}{\sqrt{2 \pi G h_*}} \right],
\]

where \( \Sigma_v \) is the stellar surface density, \( \sigma_{\text{H I}} \) is the H I velocity dispersion, and \( h_* \) is the stellar scale height (see also Elmegreen 1989 and Blitz & Rosolowsky 2004). We assume \( h_* = 300 \, \text{pc} \) (Momany et al. 2006) and that \( \Sigma_{\text{H I}} = 11.0 \, M_\odot \, \text{pc}^{-2} \) (Kalberla & Dedes 2008; McEwen et al. 2015) and \( \sigma_{\text{H I}} = 9 \, \text{km s}^{-1} \) (Malhotra 1995), and both are constant between 4 and 13 kpc. We determine \( \Sigma_v \) assuming a value of \( 33 \, M_\odot \, \text{pc}^{-2} \) at the solar circle (McEwen et al. 2015) and the exponential stellar mass density profile of Kent et al. (1991). We compute the ratio of \( P_{\text{ISM}} \) between \( R_{\text{gal}} = 5 \) and 11 kpc to be \( \frac{P(5 \, \text{kpc})}{P(11 \, \text{kpc})} = 1.9 \), a factor of \( \sim 2.9 \) lower than needed to explain the increased surface densities in the molecular ring compared to those in the outer Galaxy. An independent estimate of the radial pressure profile of the Milky Way disk calculated by Wolfire et al. (2003) results in an expected ratio of \( \frac{P(5 \, \text{kpc})}{P(11 \, \text{kpc})} = 3.0 \), somewhat higher than our estimate but still below that required to explain the increased surface densities in the molecular ring. Moreover, the fact that the GMC surface densities drop inward of 4 kpc also suggests that an inwardly increasing gradient in the midplane pressure is unlikely to be solely responsible for the increased surface densities in the molecular ring. If the true \( \Sigma_{\text{GMC}} \) in the molecular ring is close to the upper limit we estimated here, then another source of pressure (e.g., spiral arm shocks) within the molecular ring would be needed to explain the observations. It is also possible that the clouds in the molecular ring are overpressured with respect to the external midplane pressure because they are strongly self-gravitating and perhaps even critically unstable. We hesitate here to speculate any further on the cause of the increased surface densities of GMCs in the molecular ring, since the actual magnitude of the increase is so uncertain at the present time. Additional modeling along the lines of the Ballesteros-Paredes et al. (2019) study might shed more light on this issue.

Finally, we note that although the radial variation in GMC surface densities can account for about half of the scatter in the Galaxy-wide mass-size relations derived from CO observations (i.e., Figure 1), the remaining scatter is still significant. One source of this scatter could be the inability of the cloud extraction and identification methods to measure consistent cloud boundaries or measurement thresholds. As we discussed earlier, the derived average surface density of a cloud scales with the choice of the outer boundary surface density threshold (Lombardi et al. 2010a). Measurements of outer boundary thresholds are only available for one of the studies considered here. Chen (2020, personal communication) has provided us with the thresholds used in the dendrogram decomposition of the Chen et al. extinction survey. These thresholds span a dynamic range of about a factor of 5 in extinction. The dispersion in the logs of these threshold boundaries is found to be 0.23 dex, comparable to the level of scatter (0.18 dex) in the corresponding mass-size relation. Thus, at least for this catalog, the measured scatter in the relation could arise from the variation in the adopted cloud boundary surface densities. Similar effects are likely in the CO data. In particular, the R +16 catalog also used a dendrogram cloud extraction methodology. The LGS measurements employed the same boundary level (\( A_K = 0.1 \, \text{mag} \)) for all clouds, and the small scatter in the corresponding measurements of \( \Sigma_{\text{GMC}} \) (0.04 dex) is likely due in part to this fact. The modest difference in scatter between the radially resolved CO and extinction relations (0.25 versus 0.18 dex) could be due to a number of factors. One possibility is intrinsic cloud-to-cloud variations in the \( X \)-factor. Such variations might arise due to environmental variation in cloud-scale properties, such as temperature structure and depletion (e.g., Kong et al. 2015; Lewis et al. 2020).

6. Summary and Conclusions

We have analyzed molecular cloud catalogs from the literature derived from both \( ^{12}\text{CO} \) and dust extinction observations to test Larson’s (1981) original finding that \( M_{\text{GMC}} \sim R_{\text{GMC}}^{-2} \) and the consequent implication of a constant average column density for individual GMCs in the Milky Way.

We find that Milky Way wide measurements of the mass-size relation using \( ^{12}\text{CO} \) observations are well described by \( M_{\text{GMC}} \sim R_{\text{GMC}}^{-2} \) or a constant column density scaling relation. Two independent studies of the DHT Galactic \( ^{12}\text{CO} \) survey return nearly identical values of slopes, scaling coefficients, and scatter characterizing the relation. The derived scaling coefficient corresponds to an average mass surface density of \( \Sigma_{\text{GMC}} = 25 \, M_\odot \, \text{pc}^{-2} \) for individual GMCs in the Milky Way. This value is considerably lower than the \( \sim 170 \, M_\odot \, \text{pc}^{-2} \)
typically found or assumed in the CO literature. In both studies, the logarithmic scatter in the mass–size relation is quite large (0.45 dex).

We find that two independent extinction-based measurements of the mass–size relation of Milky Way GMCs are also well described by \( M_{\text{GMC}} \sim R_{\text{GMC}}^2 \), or a constant column density scaling relation. The two extinction studies are in excellent agreement with each other, returning nearly identical slopes and scaling coefficients. However, both the scaling coefficient and scatter in the dust-based relations differ from those found for the CO observations. The dust-derived scaling coefficient corresponds to \( \Sigma_{\text{GMC}} = 41.2 M_\odot \text{pc}^{-2} \). The logarithmic scatter in the relations from the two extinction studies (0.04 and 0.18 dex) is significantly lower than that of the CO observations.

We show that much of the difference in the scatter between the mass–size scaling relations derived from the dust and CO catalogs is due to a significant systematic variation of \( \Sigma_{\text{GMC}} \) with Galactic radius that is only apparent in the CO data because they cover a considerably larger range in Galactic radius than the extinction surveys. We decompose this radial variation into two components. The first corresponds to an underlying linear gradient of unblended GMC surface densities that decreases with galactocentric radius. The second corresponds to a broad and strong peak in the surface density distribution above the linear gradient at the location of the well-known molecular ring between 4 and 7 kpc from the center of the Galaxy.

We find that the functional form of the linear unblended gradient is similar to that of the radial distribution of metallicity in the Milky Way. We posit that the unblended gradient in surface density is the result of the adoption of a constant rather than metallicity-dependent CO mass conversion or X-factor by the two 12CO catalogs. Our analysis of this surface density gradient suggests that \( X_{\text{CO}} \) varies inversely with metallicity. We derive an explicit expression for the radial dependence of \( X_{\text{CO}} \) in the Milky Way.

We suggest that the peak in \( \Sigma_{\text{GMC}} \) in the molecular ring may present the best evidence for a departure from a constant GMC surface density in the Milky Way. However, we find that cloud overlap and blending in the molecular ring produce an upward bias for measuring GMC surface densities in that region. The size of this observed peak in \( \Sigma_{\text{GMC}} \) and the magnitude of the departure from a constant GMC surface density in the molecular ring could be much lower than implied by the measured values.

The systematic difference in the scaling coefficients of the mass–size relation derived from CO and dust observations suggests that the X-factor adopted by the CO studies \( \left( 2 \times 10^{20} \text{cm}^{-2} (\text{K} \cdot \text{km} \cdot \text{s}^{-1})^{-1} \right) \) underestimates the GMC masses. To minimize the effect of the radial variation in \( \Sigma_{\text{GMC}} \), we compare the mass–size relations of the two tracers for clouds located between 8 and 9 kpc from the center of the Galaxy. We derive the conversion factor for these GMCs to be \( X_{\text{CO}} = 3.6 \pm 0.3 \text{ cm}^{-2} (\text{K} \cdot \text{km} \cdot \text{s}^{-1})^{-1} \).

We conclude that the bulk of the observed GMC population in the Milky Way can be described by a constant mass surface density of \( \Sigma_{\text{GMC}} = 35 \pm 8 M_\odot \text{pc}^{-2} \). The surface densities of GMCs in the molecular ring depart from this constant surface density value, but the size and nature of the departure are unclear at the present time.