Abstract. With an increased appreciation for the role of gas in galaxy evolution, there is renewed interest in measuring gas masses for galaxies. I review some of the basic concepts in using CO to determine molecular masses, and discuss some of the recent work.

1 Introduction

Observations of rotational CO transitions are the primary method used to determine molecular masses, particularly in systems outside the Milky Way. For an expanded discussion of using CO to determine masses, I refer the reader to the review by Bolatto, Wolfire, & Leroy (2013). Here I briefly introduce some of the concepts and focus on work published since the review.

The relationship between molecular column density or mass and $^{12}$CO $J = 1 \rightarrow 0$ emission is determined through two equations:

\begin{align}
N(H_2) [\text{cm}^{-2}] &= X_{\text{CO}} I_{\text{CO}} [\text{K km s}^{-1}] \\
M_{\text{mol}} [M_\odot] &= \alpha_{\text{CO}} L_{\text{CO}} [\text{K km s}^{-1} \text{pc}^2].
\end{align}

In the disk of the Milky Way the value of $X_{\text{CO}}$ is $\approx 2 \times 10^{20} \text{ cm}^{-2} (\text{K km s}^{-1})^{-1}$, which in turn implies $\alpha_{\text{CO}} = 4.36 M_\odot (\text{K km s}^{-1} \text{ pc}^2)^{-1}$ including a contribution to the mass of 36% due mostly to He according to its cosmological abundance.

2 Physics of the CO-to-H$_2$ Conversion Factor

The $^{12}$CO $J = 1 \rightarrow 0$ transition is usually very optically thick (in the Milky Way disk the typical $^{12}$CO/$^{13}$CO ratio is $\sim 10-15$, suggesting $\tau_{\text{CO}} > 5$). For gravitationally-bound clouds, its integrated intensity encodes information about mass through the line width, so the use of these equations requires that CO and H$_2$ are coextensive and that the velocity dispersion of the gas is a reflection of its self-gravity.

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DOI: (will be inserted later)
The peak temperature of the line carries information about the product of the temperature of the gas and its beam-filling fraction. It is easy to show that for self-gravitating entities \( X_{\text{CO}} \) will have mild dependencies on density and temperature, such that \( X_{\text{CO}} \sim n^{0.5} T_K^{-1} \) where \( n \) is the gas density and \( T_K \) is its kinetic temperature (see Bolatto et al. 2013 for a more detailed discussion). Note that since \( \tau_{\text{CO}} \gg 1 \), the relevant \( T_K \) is that at the \( \tau_{\text{CO}} = 1 \) surface.

The fact that CO \( J = 1 \rightarrow 0 \) is optically thick makes this method robust to changes in the CO abundance and to the details of the excitation (§3), which affect methodologies that rely on optically thin tracers. By comparison, in the optically thin regime \( X_{\text{CO}} \sim [\text{H}_2/\text{CO}] T_{\text{ex}} \exp(h\nu/(kT_{\text{ex}})) \) (a similar equation can be written for any optically thin rotation transition). Determining masses using optically thin emission requires accurate knowledge of abundances and excitation temperatures, either of which may change over a very large range (for example, \( T_{\text{ex}} \) is a very strong function of density and \( T_K \)).

Using CO to estimate molecular masses of entire galaxies requires further assumptions (Dickman, Snell, & Schloerb 1986): the CO emission must arise from an ensemble of self-gravitating clouds with a narrow range of \( n^{0.5} T_K^{-1} \). As long as the velocity dispersion in each cloud in the ensemble is a reflection of its gravity, and clouds do not shadow each other, it can be shown that the total luminosity will reflect the sum of the cloud masses.

3 Break Down of the Standard Conversion

The assumptions behind the standard proportionality between CO luminosity and molecular mass break down in three circumstances: 1) at low metallicities, 2) in environments where the gas motions do not reflect self-gravity, and 3) in places where \( n^{0.5} T_K^{-1} \) is very different from the disk of the Milky Way.

Although (3) may be important in some cases, it is probably not the dominant driver of changes. Because \( T_K \) depends on the radiation field — mostly driven by star formation — and star formation is enhanced at high density, there is likely a large degree of compensation in their ratio. Moreover, photodissociation regions (PDRs) are self-regulated to keep an approximately constant temperature for the \( \tau_{\text{CO}} = 1 \) surface; increasing the radiation field impinging on a PDR drives its surface temperature higher, but it also pushes the \( \text{C}^+ \rightarrow \text{CO} \) transition further into the cloud and into cooler regions.

Realistic simulations incorporating cloud structure and chemistry provide key insights on how \( X_{\text{CO}} \) is affected by changes in the radiation field and the distribution of column densities, velocity dispersion, and dust extinction (e.g., Clark & Glover 2015). Cloud structure has an impact on the effects of increasing the incident radiation field, but \( X_{\text{CO}} \) changes little in large, dense, and bound clouds.

3.1 Low Metallicities

At low metallicities the hypothesis of coextensivity between \( \text{H}_2 \) gas and CO emission breaks down. High CO abundance requires a minimum extinction (\( A_V \sim 1-2 \),
weakly dependent on the incident radiation field). By comparison, most of the atomic hydrogen becomes molecular at a much lower extinction \( (A_V \sim 0.2) \). Extinction is more difficult to build up at low metallicity, where the dust-to-gas ratio is lower, resulting in a increasing fraction of the \( \text{H}_2 \) gas not being associated with bright CO emission. Physical models that incorporate the relevant physics qualitatively agree on this picture (Maloney & Black 1988; Röllig et al. 2006; Wolfire, Hollenbach, & McKee 2010), as do numerical calculations incorporating cloud structure and time-dependent chemistry (Glover & Mac Low 2011).

Resolved observations of the Magellanic Clouds further validate this picture; a strong correlation between CO intensity and inferred \( A_V \) is seen (Lee et al. 2015), and global \( \alpha_{\text{CO}} \) values rapidly increase for decreasing metallicity (e.g., Jameson et al. 2015). Indeed, the CO emitting regions of clouds at low metallicity are increasingly smaller for decreasing metallicity, while the fraction of the cloud encompassed by the molecular envelope faint in CO increases (Leroy et al. 2007, 2009). This is strikingly demonstrated in the recent observations of individual molecular clouds in the very low metallicity WLM galaxy, which show very small CO emitting regions (Rubio et al. 2015).

Thus at low metallicity the amount of CO emission per \( \text{H}_2 \) molecule is set by the distribution of column densities in the cloud, mediated by the dust-to-gas ratio. It is, in fact, fairly insensitive to the gas metallicity itself, but it depends on metallicity through the dust-to-gas ratio. This highlights the importance of better understanding dust production and destruction mechanisms in galaxies. It is increasingly clear that there is not a one-to-one correspondence between gas metallicity and dust-to-gas ratio (e.g., Fisher et al. 2014), with observations finding a large dispersion in dust-to-gas ratio at fixed metallicity for low metallicity and high specific star formation rate (Remy-Ruyer et al. 2014). Understanding how the distribution of cloud column densities is established is also important, since it plays a key role at determining the fraction of the gas that reaches the critical \( A_V \) necessary for bright CO emission.

### 3.2 Increased line-widths not due to self-gravity

In very gas-rich galaxies it is possible to maintain an extended intercloud medium that is molecular and emits in CO. This medium experiences the combined gravitational potential of the stellar, gas, and dark matter components, not just its own self-gravity. In these circumstances the hypothesis that the velocity dispersion of the medium is a reflection of its mass is broken, and a “diffuse” intercloud medium may dominate the CO luminosity. A simple-minded application of the CO-to-\( \text{H}_2 \) conversion factor yields the harmonic mean between the molecular and stellar masses. This is likely the reason for the well-established observation that local ultra-luminous IR galaxies are disproportionately luminous in CO (Downes & Solomon 1998), although a dense phase could still dominate their gas mass (Papadopoulos et al. 2012).

A particularly interesting case to study is the NGC 253 starburst, close enough to observe in great detail with the Atacama Large Millimeter Telescope (ALMA).
Fig. 1. Figure 13 from Leroy et al. (2015) showing the physical state of a large sample of Giant Molecular Clouds (GMCs) in galaxies, including clouds identified in the starburst of NGC 253 (numbered circles). The curves illustrate the theoretical lines for clouds in equilibrium with external pressure (Field, Blackman, & Keto 2011). The diagonal is, essentially, the classical virial equilibrium. Using a combination of optically thin tracers the GMCs in NGC 253 are placed in this diagram. The resulting value of $\alpha_{\text{CO}}$ for these structures is somewhat uncertain but close to Galactic, with a median value of $\alpha_{\text{CO}} \sim 3 \, M_\odot \, (\text{K km s}^{-1} \, \text{pc}^2)^{-1}$.

Indeed, ALMA observations can simultaneously be used to measure the global properties and also break up the emission into clouds. Leroy et al. (2015) present observations of the nuclear region where high density tracer molecules (HCN, HCO$^+$, CS, and isotopologues) are used together to identify ten giant molecular clouds in the starburst. The authors then use six optically thin tracers (which include both molecules and dust) to determine masses for each cloud: the different tracers have a factor of 3 scatter, but a well defined mean. Using the surface densities so determined together with the size and velocity dispersion measurements, they are able to place these clouds in a virial diagram (Figure 1).

The result is that the clouds in the NGC 253 starburst are self-gravitating, in the sense that their velocity dispersion reflects the expectation for virialized clouds of their surface density. Cloud surface densities are very large, hovering around $10^4 \, M_\odot \, \text{pc}^{-2}$ (clouds in the Milky Way disk are typically $\sim 10^2 \, M_\odot \, \text{pc}^{-2}$).
Nonetheless, the derived conversion factor is $\alpha_{\text{CO}} \sim 3 \ M_\odot \ (\text{K km s}^{-1} \ \text{pc}^2)^{-1}$. The conversion factor in the large clouds is even higher, with the four largest clouds yielding $\alpha_{\text{CO}} \sim 4.5 \ M_\odot \ (\text{K km s}^{-1} \ \text{pc}^2)^{-1}$. The uncertainties are large (0.5 dex), due to the systematic uncertainties in the optically thin mass determination, and the naive application of the $n^{0.5}T^{-1}$ scaling would lead us to expect a factor $2-3$ higher conversion factor. These clouds are also embedded in an extended CO “diffuse” medium, which has most of the luminosity. The total measured $\alpha_{\text{CO}}$ is uncertain but likely $\alpha_{\text{CO}} \sim 1 \ M_\odot \ \text{pc}^{-2}$.

This same picture of a mix of phases probably accounts for the bulk of the discrepancy between $\alpha_{\text{CO}}$ estimated using the virial theorem in resolved clouds in some galaxy centers (Donovan-Meyer et al. 2013) and $\alpha_{\text{CO}}$ estimated from dust modeling in the same objects (Sandstrom et al. 2013). In summary, what matters in these circumstances is to understand what fraction of the total CO emission originates from self-gravitating complexes, and what is the source of the observed velocity dispersion. Bound, self-gravitating complexes will likely have a conversion factor that is close to the “Galactic” value (modulated by changes due to density and temperature effects), while the intercloud medium could contribute significantly to the luminosity.

4 Conclusions

In Bolatto et al. (2013) we propose the following expression to encompass the regimes of the conversion factor:

$$\alpha_{\text{CO}} \approx 2.9 \exp \left( +0.4 \frac{Z'}{Z_{\text{GMC}}} \right) \left( \Sigma_{\text{total}}^{100} \right)^{-\gamma},$$

(4.1)

with $\gamma \approx 0.5$ for $\Sigma_{\text{total}} > 100 \ M_\odot \ \text{pc}^{-2}$ and $\gamma = 0$ otherwise. The gas metallicity relative to the Milky Way, $Z'$, is used here as an “observable” proxy of the dust-to-gas ratio, but we have pointed out the shortcomings of that approximation in § 3.1. The “typical” surface density of clouds in the Milky Way disk is assumed to be $100 \ M_\odot \ \text{pc}^{-2}$, hence $\Sigma_{\text{GMC}}^{100}$ is the typical surface density of molecular clouds in the system relative to that in the Milky Way disk. Conversely, $\Sigma_{\text{total}}^{100}$ stands for the total surface density that is exerting gravitational attraction in units of $100 \ M_\odot \ \text{pc}^{-2}$.

The first factor in Equation 4.1 incorporates the physics of the HI-H$_2$ transition relative to the C$^+$-CO transition, as we understand them. In systems of lower metallicity $\alpha_{\text{CO}}$ will increase exponentially unless the decrease in metallicity is compensated by an increase in the typical surface density of clouds. The exponential character of the relation is not a fitting choice: it reflects the theoretical expectation that CO emission is rapidly confined to the highest column density regions of the cloud (Wolfire et al. 2010). In that sense, CO acts more as a column density tracer than as a bulk mass tracer at low metallicity.

The second factor in Equation 4.1 is considerably more uncertain, and reflects the expectation that the CO emitting gas, while not necessarily self-gravitating,
still has to be bound to the overall potential of the system. Therefore its velocity dispersion will be a function of the total surface density. The crucial unknown, which we repeat, is the fraction of CO emission that arises from self-gravitating clouds: a system where most CO emission originates in such clouds will likely have $\alpha_{\text{CO}}$ close to Galactic. The choice of 100 $M_\odot$ pc$^{-2}$ as the break point between purely self-gravitating gas and emission from gas bound to the overall potential is likely conservative (it could be higher), and put forward based on the results for galaxy centers. Similarly, the $\gamma = 0.5$ exponent implicitly assumes that the CO luminosity is dominated by the “diffuse” intercloud phase. Galaxy centers may be peculiar: they can have high apparent velocity dispersions due to bulk gas motions (streaming due to bars, for example) which would result in a disproportionately large fraction of “diffuse” CO emission. So it is possible that this second factor incorrectly predicts too large a correction in $\alpha_{\text{CO}}$. Conversely, it would be hard to push $\alpha_{\text{CO}}$ under the value of this prediction unless there is a large increase in the gas temperature. Undoubtedly, future observations of optically thin tracers and multi-transition excitation studies will help clarify some of these unknowns.

References

Bolatto, A. D., Wolfire, M., & Leroy, A. K. 2013, ARAA, 51, 207
Clark, P. C., & Glover, S. C. O. 2015, MNRAS, 452, 2057
Dickman, R. L., Snell, R. L., & Schilder, F. P. 1986, ApJ, 309, 326
Donovan Meyer, J., Koda, J., Momose, R., et al. 2013, ApJ, 772, 107
Downes, D., & Solomon, P. M. 1998, ApJ, 507, 615
Field, G. B., Blackman, E. G., & Keto, E. R. 2011, MNRAS, 416, 710
Fisher, D. B., Bolatto, A. D., Herrera-Camus, R., et al. 2014, Nature, 505, 186
Glover, S. C. O., & Mac Low, M.-M. 2011, MNRAS, 412, 337
Jameson, K. E., Bolatto, A. D., Leroy, A. K., et al. 2015, ApJ submitted [arXiv:1510.08084]
Lee, C., Leroy, A. K., Schnee, S., et al. 2015, MNRAS, 450, 2708
Leroy, A. K., Bolatto, A. D., Ostriker, E. C., et al. 2015, ApJ, 801, 25
Leroy, A. K., Bolatto, A., Bot, C., et al. 2009, ApJ, 702, 352
Leroy, A., Bolatto, A., Stanimirovic, S., et al. 2007, ApJ, 658, 1027
Maloney, P., & Black, J. H. 1988, ApJ, 325, 389
Papadopoulos, P. P., van der Werf, P., Xilouris, E., Isaak, K. G., & Gao, Y. 2012, ApJ, 751, 10
Rény-Ruyer, A., Madden, S. C., Galliano, F., et al. 2014, A&A, 563, A31
Röllig, M., Ossenkopf, V., Jeyakumar, S., Stutzki, J., & Sternberg, A. 2006, A&A, 451, 917
Rubio, M., Elmegreen, B. G., Hunter, D. A., et al. 2015, Nature, 525, 218
Sandstrom, K. M., Leroy, A. K., Walter, F., et al. 2013, ApJ, 777, 5
Wolfire, M. G., Hollenbach, D., & McKee, C. F. 2010, ApJ, 716, 1191