Conversion Problems: How (Not) to Determine Molecular Masses in Dwarf Galaxies

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1 Molecular Gas Masses and the Conversion Factor $X_{\rm CO}$

The determination of molecular gas masses in star forming dwarf irregular galaxies is crucial to assess the star formation process in dwarfs: Does it proceeed in the same way as in giant spiral galaxies, or are e.g. star formation efficiencies different? How large is the gas reservoir in dwarf galaxies, i.e. are dwarfs rated as 'starbursts' really undergoing a burst of activity or are they able to continue forming stars at the present rate for a significant fraction of the Hubble Time? Star formation in gas rich dwarfs also provides us with a local analogy to conditions in the high-redshift universe, since within the context of the hierarchical bottom-up scenario of galaxy formation we expect the building blocks of larger galaxies to have been small, metal-poor (low Z) systems similar to present-day dwarf galaxies.

However, the derivation of the molecular gas content of dwarf galaxies has been a long-standing problem. CO, as the only practical tracer of cold molecular gas, has been (and to some extent still is) notoriously diffucult to detect. Yet, star formation clearly takes place in many dwarf irregulars and Blue Compact Dwarf Galaxies, as is shown in detail by investigations of their stellar populations.

Taylor, Kobulnicky & Skillman (1998) have argued that there is a threshold metallicity of $12 + \log({\rm O/H}) \sim 7.9$ below which CO is not detectable. This may be understood in terms of models of the structure of low metallicity molecular clouds suggested by e.g. Madden et al. (1997) and Bolatto, Jackson & Ingalls (1999): CO is present only in the cloud core, which is surrounded by an H_2 envelope where carbon is in the form of CI or CII. In this 'hidden H_2' scenario, the CO core may vanish entirely while molecular gas still is abundant if Z is very low.

The (in)famous conversion factor $X_{\rm CO} = I({\rm CO})/N({\rm H_2})$ allows an easy estimate of the molecular gas mass based on measuring just the ^{12}CO(1–0) transition. $X_{\rm CO}$ has been calibrated in the disk of the Milky Way. Even there, values vary between $1.6 \cdot 10^{20}\,{\rm cm^{-2}(K\,km\,s^{-1})^{-1}}$ (Hunter et al. 1997) and $3 \cdot 10^{20}\,{\rm cm^{-2}(K\,km\,s^{-1})^{-1}}$ (commonly used in the 80's). While it is likely that the 'correctly' calibrated value – if it exists – is slightly below $2 \cdot 10^{20}\,{\rm cm^{-2}(K\,km\,s^{-1})^{-1}}$, a 'Standard' Conversion Factor (SCF) of $2.3 \cdot 10^{20}\,{\rm cm^{-2}(K\,km\,s^{-1})^{-1}}$ (Strong et al. 1988) is widely used.

The existence of a SCF can be motivated somewhat heuristically assuming that (a) CO counts clouds, (b) the emission is optically thick and thermalized and (c) the individual clouds are virialized, which implies a size-linewidth relation. Then, a relation of the form $X_{\rm CO} = {\rm const}\, n({\rm H_2})^{1/2}\, T_{\rm kin}^{-1}$ is obtained. If the molecular ISM is dominated by 'typical' molecular clouds with similar (average) densities and temperatures, $X_{\rm CO}$ can be expected to be constant. In the 'hidden H_2' scenario outlined above, it should, however, not be surprising if a different (larger) value of $X_{\rm CO}$ is found.

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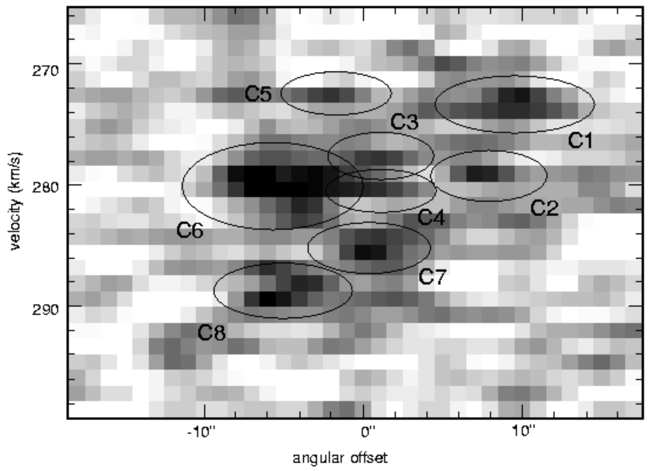

Figure 1: An example of the 'deconvolution' of a CO complex into clumps in NGC 4214, taken from Walter et al. (2001). It is obvious that the process is highly dependent on resolution and the cutoff criteria employed.

2 The Virial Method – and its Drawbacks

To determine $X_{\rm CO}$, an independent way of measuring the cloud mass (or, equivalently if the distance to the source is known, the H_2 column density) is needed. The most obvious such method is the calculation of viral masses, by using $M_{\rm vir}[{\rm M}_\odot] = 190\ \Delta v^2$ [km/s] $D/2$[pc]. The constant depends slightly on the assumed density profile of the cloud. In practice, both the cloud diameter D and the velocity width Δv can be obtained from high resolution CO observations.

It can, of course, be debated whether molecular clouds in dwarf galaxies are in fact virialized. A size-linewidth relation consistent with the one found for the Milky Way and nearby spirals seems to hold for large ($M \geq 10^5 {\rm M}_\odot$) Giant Molecular Clouds (GMCs) in nearby dwarfs, e.g. NGC 1569, IC 10 or the SMC (Taylor et al. 1999). While virialization does not necessarily follow from this (a similar relation is valid for cirrus clouds which are clearly not in virial equilibrium), the assumption is at least not obviously erroneous. The situation is more critical for more distant dwarf galaxies like NGC 4214 (Walter et al. 2001) or Haro 2 (Fritz 2000). In these cases, the resolution, even with interferometers, is too poor to resolve GMCs – the structures seen are Giant Molecular Associations (GMAs) which do not follow the size-linewidth relation and are likely not virialized. If this complication is ignored, $M_{\rm vir}$ is unlikely to be a true measure of $M_{\rm cloud}$. In addition, the linewidth can be affected by systematic streaming motions or rotation, external pressure, magnetic fields, a stellar or atomic gas component, etc.

Virial masses have been used to determine $X_{\rm CO}$ for a number of dwarf galaxies. The values found vary significantly, from (6.6 ± 1.5) SCF in NGC 1569 (which may be slightly too high, Taylor et al. 1999) to (1.2 ± 0.7) SCF in NGC 4214 (Walter et al. 2001). For Haro 2, Fritz (2000) derives (2.9 ± 0.8) SCF if the CO(1–0) line is used and (1.2 ± 0.6) SCF for the higher resolution observations in the (2–1) transition. 'Typical' values from the literature for a number of dwarfs, including IC 10, give (2...3) SCF; these form the basis of the general conclusion that $X_{\rm CO}$ in dwarfs is somewhat higher than the SCF. All galaxies for which results are given here have comparable metallicities.

Are the differences that are derived real, or due to (systematic) errors? The 'hidden H_2' should be largely included in the virial masses, at least as long as size and linewidth of the observed CO complex are dominated by the relative movement of small CO cores within a larger bound complex. Given that the typical sizes of the resolved units exceed 100 pc, this is likely.

The dependence of $M_{\rm vir}$ on the resolution is an obvious, but quite possibly decisive, problem. Fig. 1 illustrates the deconvolution of a molecular complex in NGC 4214 into subunits for which virial masses are derived. It is evident that there is a strong dependence on the velocity resolution,

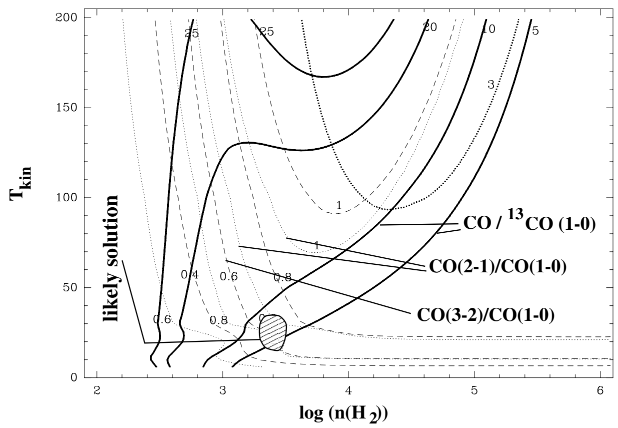

Figure 2: The principle of determining a solution for the cloud properties from CO line ratios in a non-LTE radiative transfer model. A solution is found from the intersection of curves corresponding to observed line ratios. Since ratio curves involving only ^{12}CO transitions are almost parallel, at least one ^{13}CO line needs to be measured.

which in this case is very high. Since the square of the velocity width enters $M_{\rm vir}$, a lower velocity resolution would increase the virial mass significantly and increase the low value of $X_{\rm CO}$ found for NGC 4214. The two different values given for Haro 2 clearly illustrate the influence of linear resolution on $X_{\rm CO}$.

From this, it may seem that the high values of $X_{\rm CO}$ usually derived for dwarf galaxies could be artifacts of too low a velocity or linear resolution. However, we find a high $X_{\rm CO}$ for the nearby NGC 1569, where the resolution is good. Also, some unresolved clumps in NGC 4214 yield $X_{\rm CO} <$ SCF, which is unexpected since in an unresolved clump D should be an upper limit, leading to an overestimate of the virial mass. Thus, resolution cannot explain all the variation in $X_{\rm CO}$ found in dwarfs of similar metallicity. It is, however, an issue that has to be considered carefully.

Even more basic are the varying definitions of a 'cloud' that are employed. Is it correct to always use the smallest unit that can be resolved? At some point, we will either miss the 'hidden H_2' envelopes and just regard the single CO cores, and/or we will use subunits that are moving within a larger bound entity. In the first case, we will clearly underestimate $X_{\rm CO}$, in the second case, D will be too small, while Δv may be too large, with an uncertain outcome for $M_{\rm vir}$. It is likely that with a resolution of $\sim$ 100 pc, this stage is not yet reached, but the very small values of $X_{\rm CO}$ for unresolved clumps in NGC 4214 serve as a warning. Even the methods employed for size determinations vary from using e.g. the FWHM, the 90% of flux contour or sophisticated deconvolution routines (e.g. based on information entropy, Fritz 2000).

Given the uncertainties of the virial masses, it is interesting to examine another, seemingly entirely independent, method to derive $X_{\rm CO}$.

3 The Radiative Transfer Method – and its Drawbacks

If at least three CO transitions, including at least one of a rare isotopomer like ^{13}CO, are measured, a simple radiative transfer model can be employed to derive the average properties of the emitting gas. For a given density, metallicity, isotope ratio (and velocity gradient, in the commonly used LVG approximation of radiative transfer), $X_{\rm CO}$ is obtained as $X_{\rm CO} = n({\rm H}_2)/({\rm grad}v\ T_{\rm MB})$. Fig. 2 illustrates the general principle.

The method is less independent of the virial method than it might seem since it implicitly assumes a size-linewidth relation (see Fritz 2000 for details). A major drawback is observational, however: the ^{13}CO transition(s) essential for the analysis are extremely faint and difficult to measure with present instruments, especially since the quality of the spectra should be high enough to obtain reliable line ratios. Thus, such measurements exist for only very few dwarfs, and they are confined to the molecular peak positions which may not be typical of the ISM properties in general.

The most crucial limitation of the method is the *extremely local* nature of the value of $X_{\rm CO}$ it yields. Only the CO-emitting cores are taken into account, since the (average) local properties of the CO emission itself are analysed. The envelopes (i.e. the hidden H_2) are *not* included. Since the properties within the cores can be expected to be similar to those of molecular clouds in metal rich galaxies, a value for $X_{\rm CO}$ that is close to the SCF may be expected – and is indeed found for Haro 2 ($X_{\rm CO}$ = (0.7...1.3) SCF, Fritz 2000). Note, however, that this is not inconsistent with what is derived using the virial method at high resolution.

Even simple one-component radiative transfer models show that $X_{\rm CO}$ can vary by a factor of > 10 *only depending on excitation*, without changing the metallicity at all. If Z is decreased, the local $X_{\rm CO}$ for a given n/T increases slightly, but the changing size of the CO-emitting core is likely to dominate this effect. In contrast, $X_{\rm CO}$ *drops significantly* in a low density, high temperature environment, as is qualitatively expected from the $\sim n^{1/2}/T_{\rm kin}$ relation. This situation is not likely to be relevant for low-Z dwarfs since this 'diffuse' gas component is likely to be devoid of CO or dissociated entirely. This is confirmed by the 'disk-GMC-like' properties derived for the CO emission in Haro 2, suggesting fairly low temperatures and high densities. Still, the detections of CO(3–2) emission in a number of dwarfs (see the contribution by Mühle et al. in these preceedings) show that extended, warm molecular gas is present (and detectable) in star forming dwarf galaxies. Exact densities and temperatures for this component remain to be determined.

The 'diffuse gas' scenario is very important for metal-rich starburst systems, where $X_{\rm CO}$ is found to be lower than the SCF by a factor of 3 ... 8.

4 Final Considerations

In summary, the general picture of the 'correct' way of determining molecular masses in dwarf galaxies remains somewhat clouded. Clearly, an analytical *metallicity-X_{CO}-relation* of the form $\log X_{\rm CO}/{\rm SCF} = a + b(12 + \log[{\rm O/H}])$ with $a = 5.9...9.3$ and $b = -0.65... - 1.0$ as proposed by e.g. Arimoto, Sofue & Tsojimoto (1996) is close to useless for any individual galaxy. It does describe the general trend correctly, but with a scatter > 5 for a given Z, it misses all complications and individualities.

Despite the strong possibility of systematic errors in the determination of $X_{\rm CO}$ in dwarfs, some variation is very likely to be real. Even the generally elevated value of $X_{\rm CO}$ in dwarfs compared to the SCF is not undisputed, but we need to carefully eliminate possible sources of error before drawing far-reaching conclusions. Most prominently, we need to consider how 'global' the $X_{\rm CO}$ we determine is – even with the virial method, only one molecular complex at a time is probed, and the conversion factor derived may well differ in different places in a given galaxy. Showing the dependence of $X_{\rm CO}$ on factors other than Z (e.g. the UV-field, cosmic rays, the gas morphology, pressure, magnetic fields etc.) is indeed an important goal of further studies. Clearly, $X_{\rm CO}$ can never be a 'constant' to be blindly applied to 'determine' molecular gas masses. Instead, it needs to be probed by all possible means and can then be a valuable *diagnostic* of ISM properties.

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