THE CO LUMINOSITY - H_2 MASS CONVERSION FACTOR

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ABSTRACT. The use of ^{12}CO as a mass tracer of H_2 in molecular clouds is based on three independent calibrations, all of which agree. The physical basis for an approximately constant molecular (H_2) mass to CO luminosity ratio is the origin of the CO emission from gravitationally bound molecular clouds. We discuss the size-line width and virial mass-CO luminosity relations derived from the Massachusetts-Stony Brook CO Survey. The criticisms of the size-line width relation by the Wolfendale group are wrong. Their tests were not self consistent, and were constrained by the properties of the real clouds, not independent of them, as was implied. We show that the virial masses are a reliable measure of the true cloud masses. The CO to H_2 conversion factor depends only weakly on molecular cloud parameters, and its value in other spiral galaxies should not be very different from that in the Milky Way. The H_2 masses in the centers of galaxies are not overestimated, since the CO excitation is observed to be normal there, and the brightness temperatures not much different from those in the Milky Way. The effect of metallicity on the conversion factor is also briefly discussed.

1. Three calibration techniques agree

The conversion factor to obtain molecular hydrogen mass from CO luminosity has been empirically determined by three independent techniques. Each technique is based on a different physical principle and a different set of observations. The close agreement between these independent calibration methods forms the basis for the use of CO observations as a tracer of total mass in molecular clouds.

The first technique utilizes the more optically thin ^{13}CO integrated intensities and measurements of optical extinction along the same lines of sight through nearby (dark) molecular clouds. The extinction measurements are converted to total hydrogen by a standard gas to dust ratio. This calibrates the more optically thin ^{13}CO integrated intensity $I(^{13}\mathrm{CO})$ vs. $N(\mathrm{H_2})$. The calibration of ^{12}CO is then obtained from observed average ratio of $I(^{12}\mathrm{CO})$ to $I(^{13}\mathrm{CO})$. This was the first technique used (Dickman, 1975), and led to a value of $X = 2.2 \times 10^{20}[\mathrm{cm^{-2}/K \cdot km \cdot s^{-1}}]$, where

$$N(\mathrm{H_2}) = X \cdot I(\mathrm{CO}).$$

This corresponds to a molecular mass to CO luminosity ratio

$$M(\mathrm{H_2}) = A \cdot L_{\mathrm{CO}},$$

where $A = 4.8 M_\odot/\mathrm{K \cdot km \cdot s^{-1} pc^2}$.

A second technique, applied globally to all molecular emission in the Galactic molecular ring, uses γ rays resulting from cosmic ray interaction with hydrogen molecules, and

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compares the γ ray flux to the CO flux. This completely independent technique yields $X = 2.8 \times 10^{20}$ (Bloemen *et al.* 1986) for the northern inner Galaxy, and a slightly lower value ($\sim 2.6 \times 10^{20}$) for the whole inner Galaxy.

Both the ^{13}CO-optical extinction and the γ ray calibrations use independent measures of column density, A_V and γ ray flux respectively, to independently determine X (or A). While both of these techniques provide calibrations, neither offers an explanation as to why the optically thick ^{12}CO line is a reliable mass tracer.

The ultimate test of the masses of astronomical objects must be a dynamical measurement. The third calibration technique, a measurement of the virial mass for molecular clouds in the Galactic plane, offers both a dynamical calibration and an explanation as to why optically thick ^{12}CO traces mass. Figure 3 (Solomon *et al.* 1987) shows the virial mass as a function of CO luminosity for 273 Galactic plane molecular clouds. The solid circles represent clouds whose distances are known and on which the calibration is based. The fit is

$$M_{VT} = 39(L_{CO})^{0.81},$$

which, for a typical cloud of $3 \times 10^5 M_\odot$, yields a virial mass to CO luminosity ratio of $A = 4.9$. After correcting for helium, the X factor for the H_2 column density becomes 2.3×10^{20}. Note that the virial mass-CO luminosity relation is not strictly linear, although the mass to CO luminosity ratio varies by only a factor of 1.69 for clouds with masses between 10^5 and $10^6 M_\odot$. Clouds in this range contain 90% of the mass in the sample clouds. The explanation for the existence of a virial mass-CO luminosity relation (Dickman *et al.* 1986, Solomon *et al.* 1986, 1987) is that the CO luminosity from a cloud in or near virial equilibrium is a product of the brightness temperature, cloud area and line width Δv. Since the line width for clouds of a given size is a function of the density $n(H_2)$, it can be shown (see e.g. Solomon *et al.* 1987, equations 10–15) that the ratio of virial mass to CO luminosity is proportional to the square root of the density and inversely proportional to the brightness temperature T_b (not kinetic temperature) averaged over the cloud,

$$\frac{M_{VT}}{L_{CO}} \propto \frac{n^{\frac{1}{2}}(H_2)}{T_b}.$$

Thus, if clouds are gravitationally bound, the existence of a mass to CO luminosity ratio is understood, and the parameters which effect it are cloud density and mean brightness temperature. For Galactic plane clouds, these parameters are measured, the brightness temperature directly and the density from the size-line width relation.

Maloney (1988) has incorrectly assumed that the evidence for clouds being gravitationally bound is the *existence* of the virial mass-CO luminosity relation. It is not the existence of such a relation that is proof of gravitationally bound clouds, but rather the agreement between the virial masses for individual clouds and the CO luminosity masses obtained using the totally independent calibration methods discussed above. There are no free parameters in any of the calibration techniques, yet the mass measurements or calibration factors agree to better than a factor of 2 for Galactic clouds in the molecular ring.

2. The size-line width relation

Recently Wolfendale and his collaborators have attacked the validity of the size-line width relation found from the Massachusetts-Stony Brook Galactic Plane CO Survey (MSB) by

Solomon *et al.* (1987, =SRBY), and by implication of similar results found by Scoville *et al.* (1987). In particular, they (Issa *et al.* 1990) claim to have performed a test using the MSB data which reproduces a size-line width relation from random boxes in the observed ℓ, b, v space. Here we show that the tests performed by Wolfendale and collaborators were not self consistent, used information from the real clouds while pretending to be independent of real clouds, and are just plain wrong. Wolfendale and his collaborators (Broadbent *et al.* 1989) have also used far infrared radiation to estimate the total molecular mass in the inner Galaxy, apparently not realizing that far infrared measures luminosity of dust, not the mass of dust. Use of far IR can only provide a measure of the mass of warm radiating dust, which is a lower limit to the total dust mass, particularly inside molecular clouds where there is no heating radiation field.

The SRBY size-line width relation (Figure 1) is defined by the "calibrator" clouds identified in the MSB survey data set. Calibrators are those clouds whose linear sizes can be unambiguously calculated from their angular sizes because the kinematic near-far distance ambiguity either does not exist (clouds near the tangent point), or can be resolved because the cloud is associated with an HII region whose distance is known from radio absorption line data, or because if the cloud were at its far distance it would be unrealistically far ($>$ 150 pc) out of the Galactic plane. "Non-calibrator" clouds were assigned to whichever of the two possible distances was in better agreement with that suggested by the size-line width relation determined from the calibrator clouds.

Issa *et al.* (1990) purport to show that essentially the same size-line width relation as is obtained from the real clouds can be obtained by applying the same sort of analysis to the MSB data within a set of boxes whose positions and extents in ℓ, b and v are randomly assigned. The correct way to perform this test would be to derive a size-line width relation from the calibrators among the random "clouds" and compare it to that derived from the real calibrator clouds. Instead, they present, in their Figure 4, a size-line width relation derived from *all* of their random "clouds", *after* the distance ambiguity for their non-calibrators has been resolved by choosing whichever of the two possible distances brings the cloud into best agreement with the SRBY relation derived from the real clouds, not with a size-line width relation derived from the calibrators among their random "clouds". Thus the apparent agreement between the SRBY and the Wolfendale group's random cloud size-line width relations is forced, since the SRBY relation is used in determining the other.

Issa *et al.* do not indicate which of their random "clouds" could have served as calibrators, so it is not possible to tell what size-line width relation they might indicate. Our own attempts to derive a size-line width relation from random cloud calibrators (e.g. Figure 2) give much smaller values for the exponent ($\sim$0.1, as opposed to 0.5 for the real clouds) and much greater scatter. In other words, for random "clouds", there is virtually no correlation between size and line width.

Even if one accepts the forcing of the non-calibrator random "clouds" into agreement with the SRBY relation as valid, our tests show that this results in there being little size-line width correlation among the near clouds alone, or among the far clouds alone, which is not true for the real clouds. It is also odd that most of the random "clouds" in Figure 4 from Issa *et al.* are so much larger than the real clouds.

The SRBY size-line width relation as defined is between the rms dispersions of the clouds in the the spatial and velocity coordinates, calculated over the "boxes" in ℓ-b-v space which delimit the clouds; however, the correlation is still apparent if one looks at the dimensions of the boxes, instead of at the dispersions inside them. It may be that in generating their

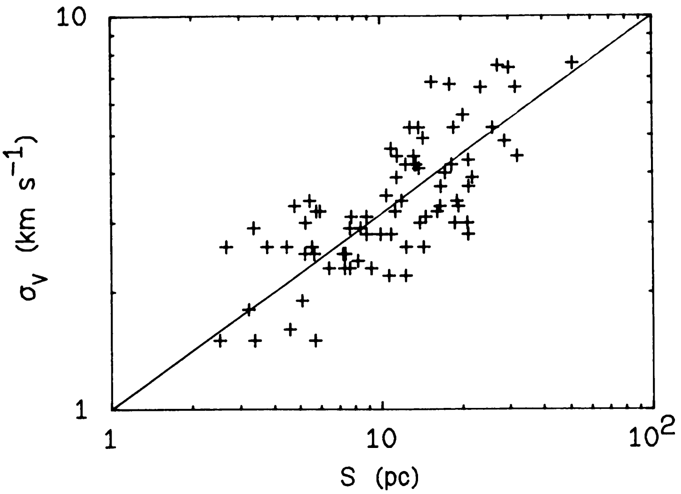

Figure 1. The size-line width relation for real molecular clouds, derived from the calibrator clouds (those for which the kinematic distance ambiguity can be resolved) identified in the MSB data set. Only the calibrator clouds (crosses) are shown. (from Solomon *et al.* , 1987) The fitted line is $\sigma_V = 1.0 S^{0.5}$.

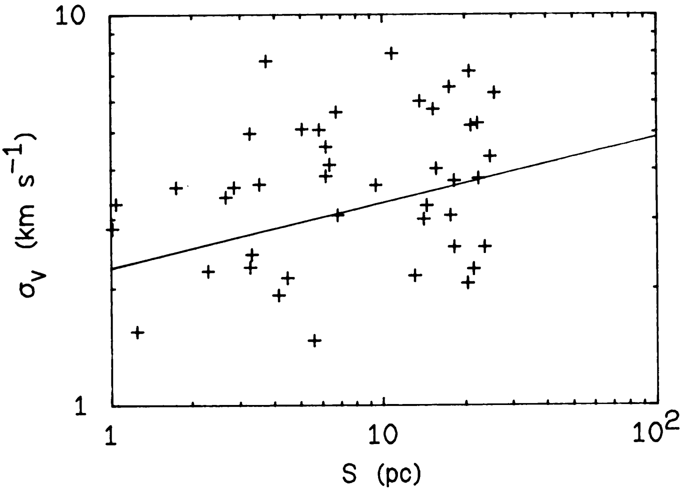

Figure 2. Line width *vs.* size for the calibrator clouds among a typical set of random "clouds". The line is the formal fit. Note that the slope is much flatter and the scatter greater than for the real clouds shown in Figure 1. There is almost no correlation.

random cloud boxes, Issa *et al.* did not treat the spatial and velocity dimensions of each box as independent random variables, but chose them from a population modeled on the real cloud boxes, and thus introduced the correlation that exists between the spatial and velocity dimensions of the real clouds into their random "clouds". Calculating dispersions over boxes chosen in this way would be expected to yield a size-line width relation whose slope is about the same as that derived from the real clouds, even if the data at the locations of the random "clouds" contained nothing but noise — but this relation will have been obtained by indirectly feeding in information about the real clouds, and so is not a valid test.

3. Test of Galactic GMC Virial Masses: Further Evidence for Virialized Clouds

An important test of the validity of virial mass measurements for Galactic plane clouds is to compare a virial mass vs. CO luminosity diagram for random "clouds" with that for the real clouds. Unfortunately, the Wolfendale group (Issa *et al.* 1990) neglected this test, which shows convincingly that the virial masses for real clouds are not artifacts of the measuring technique. Figure 4 shows the random "cloud" virial mass-CO luminosity diagram for about 300 random boxes in ℓ, b, v space in the MSB survey. The range of box sizes in angular units was similar to that of the real clouds but their locations in ℓ, b, v was assigned randomly. The solid line shows the fit to the real data (Fig. 1) from SRBY. It is immediately clear that the **random "clouds" do not give a virial mass which correlates with CO luminosity**. Almost all random "clouds" have virial masses much greater than that of real clouds with the same CO luminosity. Notice that the real virial mass-CO luminosity relation coincides with the lower boundary of the distribution of points in Figure 4. The explanation is simple: occasionally, a random location will coincide with a real cloud. The other 90 percent of random boxes have velocity dispersions too high for their CO luminosity, giving false virial masses. The fact that the lower boundary of random "clouds" in Figure 4 agrees with the real virial mass-CO luminosity relation demonstrates that the real clouds have the lowest possible virial masses for a given CO luminosity, a property which is exactly what one would expect from true clouds, but not from accidental blendings along the line of sight, which would artificially increase Δv and thus the virial mass. The random box test does **not**, as claimed by the Wolfendale group, support a lower mass to CO luminosity ratio; on the contrary, it shows that the SRBY cloud mass to luminosity ratio is systematically lower than that for any random or accidental "clouds".

Figure 4 is thus strong evidence that the real Galactic plane clouds are in or near virial equilibrium and the conversion factor X or A determined from the dynamical (virial) mass is correct.

4. Use of Milky Way Calibration for Galaxies

The existence of a CO luminosity to H_2 mass ratio is based on the origin of the CO line from gravitationally bound molecular clouds. As discussed above, the X (or A) factor should scale with average cloud density, and inversely with the brightness temperature of the cloud, $n^{\frac{1}{2}}(H_2)/T_b$. In external galaxies the clouds may have either different densities, brightness temperatures or both. Several authors (see e.g. Maloney and Black (1988)) have cautioned that in particular the temperature in the central regions of galaxies would be much higher than in Galactic plane clouds, and thus the conversion factor would be much lower. However, evidence to date obtained from measuring the CO $(2\rightarrow1)/(1\rightarrow0)$ line ratio

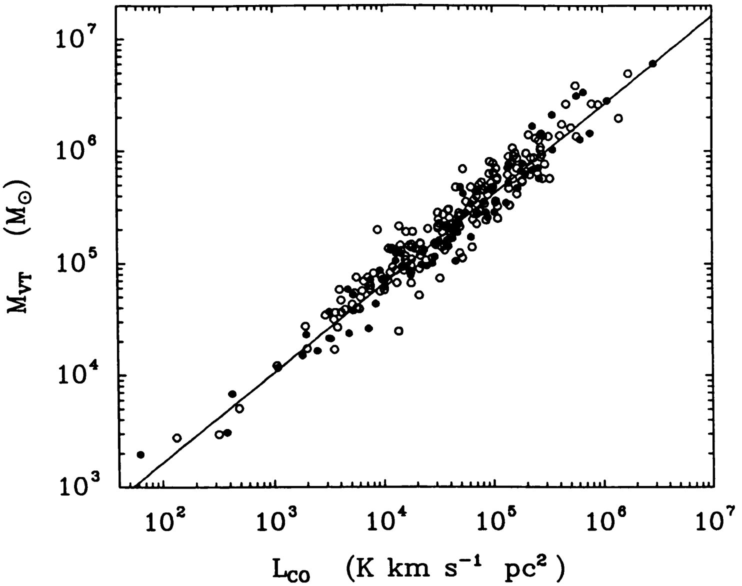

Figure 3. The virial mass–CO luminosity relation for real molecular clouds. The fit is $M_{VT} = 39(L_{CO})^{0.81}$. The closed circles are the calibrator clouds, the open circles the non-calibrators.

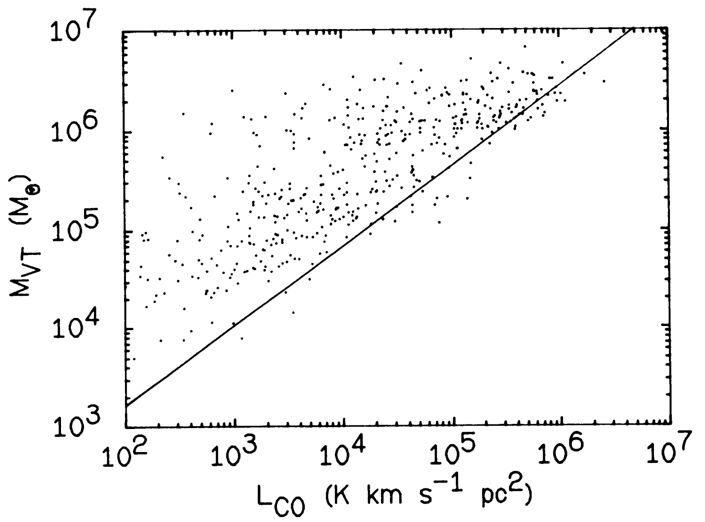

Figure 4. Virial mass *vs.* CO luminosity for a typical set of random "clouds". The line is the virial mass–CO luminosity relation for real clouds from Figure 3. Note that it delineates the lower boundary of the distribution of points in the figure (see text, section 3).

shows that with few exceptions (M82 in particular) this ratio is ≤ 1 and frequently ~ 0.5, implying a low cloud brightness temperature, $T_b \leq 10$ K, similar to that of most Galactic plane emission. Maloney and Black (1988) assumed that the excitation temperature of CO would equal the kinetic temperature, which they argued would be high near the center of galaxies, particularly infrared luminous galaxies. However, even in IR luminous galaxies such as Arp 220 or Arp 193, the brightness temperature of CO is low (see Downes *et al.* in this symposium or Radford *et al.* (1990), to be published in Ap.J.). Thus there is little evidence of the Maloney and Black effect in galaxies. Of course, there is no reason why the cloud densities $n(H_2)$ should be identical in all galaxies and clouds near the center of galaxies are likely to be more dense, just to maintain stability, raising the conversion ratio by a factor of 3 for a change in density of a factor of 10. This may be partly compensated for by a small rise in brightness temperature T_b, since increased density increases the line excitation. This partially cancelling effect means that the CO to H_2 conversion factor is fairly **robust** — robust but not perfect.

A more important worry may be differences in metallicity which effect the CO abundance. The only way to test this is by calibration measurements of virial masses for individual clouds in external galaxies. In this conference Johannson has presented virial masses for clouds in the LMC; the virial mass to CO luminosity ratio appears to be close to the Galactic value or possibly higher by a factor of 1.5. Since the LMC has a metallicity lower than the Milky Way by a factor of 5, this shows that moderate metallicity differences may not produce severe changes in the CO-H_2 conversion ratio. Note that the actual optical depth of ^{12}CO is not relevant, only the virial mass to CO luminosity ratio. For severe metal deficiencies, obviously CO luminosity must decrease relative to H_2 mass since where there is no carbon there is no CO. The SMC may be such a galaxy since it is metal deficient by a factor of about 20. Increases in metallicity above solar should make no difference, since CO is already present wherever substantial H_2 is present under Galactic conditions.

In summary, CO is a robust indicator of H_2 mass for normal spiral galaxies with metallicities roughly equal to solar or different by a modest factor. It appears to work in the center of most (probably not all) galaxies since the CO excitation is fairly normal. Most importantly there is no evidence that H_2 is being overestimated as claimed by Maloney and Black (1988) in the center of galaxies.

5. References

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Some astronomers (Nick Scoville, Nick Devereux, Judy Young, Jeff Kenney) inside the boat drifting under a famous bridge of the Seine.