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# $I_{CO}/N(H_2)$ CONVERSIONS AND MOLECULAR GAS ABUNDANCES IN SPIRAL AND IRREGULAR GALAXIES

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## ABSTRACT

Observations of emission in the $J = 1–0$ rotational transition of interstellar carbon monoxide have been used to infer column densities and masses of hydrogen on the basis of relations of the form $N(H_2)/I_{CO} = \alpha$, where $\alpha$ is a constant. Although the large-scale value of $\alpha$ appears to be accurately constant over most of the Milky Way, the underlying reason for this is not fully understood, nor is it reasonable to expect similar behavior in other galaxies. The sensitivity of the conversion factors to such cloud parameters as density, temperature, and element abundances is examined quantitatively. The conditions under which the conversion factor will be constant and equal to the Galactic value are almost certainly violated on global scales in many galaxies, with the result that substantial errors in the inferred molecular gas distributions and abundances are possible. In particular, the amounts of molecular gas in the exceptional starburst galaxies detected by *IRAS* have probably been overestimated by factors of 4–5, while the molecular contents of metal-poor systems (such as many irregular galaxies) may have been underestimated.

*Subject headings:* interstellar: abundances — interstellar: molecules — molecular processes

## I. INTRODUCTION

One of the major goals of the study of galaxies in recent years has been to determine the relationship between the molecular content of galaxies and their star formation rates. Because molecular hydrogen cannot in general be directly observed (Shull and Beckwith 1982), it is necessary to use another species as a tracer of the molecular gas. Since it is very abundant and is relatively easy to excite above the background, the CO molecule has proved to be an extremely useful probe of molecular gas in the Galaxy (e.g., Blitz, 1978). In the 11 years since the first detection of emission in the $J = 1–0$ transition of CO from other galaxies (Rickard *et al.* 1975), the number of galaxies in which CO has been observed has climbed to over 100 (see Verter 1985 for a list complete to 1984 May); for many of these, at least some data on the radial distribution of CO emission are available (Young and Scoville 1982*a*, *b*; Scoville and Young 1983; Young, Tacconi, and Scoville 1983; Scoville, Young, and Lucy 1983; Stark *et al.* 1986; Olofsson and Rydbeck 1984; Rydbeck, Hjalmarson, and Rydbeck 1985).

In order to make comparisons of the molecular gas distribution with other galaxian properties (such as H$\alpha$, infrared, and nonthermal radio emission), one must know how to convert the observed CO integrated intensity (the antenna temperature integrated over the line) to a column density of $H_2$ averaged over the antenna beam. Molecular clouds in the Galaxy (and presumably in other galaxies) are ordinarily very optically thick in the $^{12}CO$ $J = 1–0$ transition, so that it is not possible to obtain column density information directly from the observed line intensity. Indirect arguments must then be used to determine a value for $N(H_2)$ from $I_{CO}$. One approach has been extensively developed by Young and Scoville and collaborators (e.g., Young and Scoville 1982*a*), based on the following three assumptions:

1. The ensemble average of excitation temperatures and mean densities is constant across the galactic disk.
2. The peak antenna temperature is a measure of the beam filling factor, and hence of the number of clouds in the beam (Morris and Rickard 1982).
3. All clouds are in approximate virial equilibrium, in the sense that the individual cloud line widths are directly related to the cloud mass and hence to the cloud area–averaged column density.

Strictly speaking, assumption 3 is not required: it is possible to imagine clouds with similar values of $N(H_2)/I_{CO}$ which are not virialized in the above usage. This may in fact be true of dark clouds, which may be dominantly pressure-bounded rather than self-gravitating (Maloney 1987*a*). However, giant molecular clouds (GMCs) are certainly gravitationally bound objects, and it is difficult to see how they could avoid being approximately virialized (see below). There is also the philosophical point that eliminating assumption 3 removes any real physical basis from the arguments for constant conversion factors, leaving us with no alternative to blind faith as a rationale for their use.

Young and Scoville (1982*a*) argued for a mean value of $N(H_2)/I_{CO} = 4 \times 10^{20}$ cm$^{-2}$ (K km s$^{-1}$)$^{-1}$, based on observations of dark clouds, cloud cores, and GMCs in the inner plane of the Galaxy. For the dark clouds $H_2$ column densities were obtained from visual and infrared extinction measurements, while for the cloud cores they were derived from LTE analysis of CO and $^{13}CO$ observations. $H_2$ column densities in the giant molecular clouds were estimated either from the observed cloud sizes and line widths using the virial theorem or else from $^{13}CO$ data. The results for all the clouds in this sample, with the exception of the hot cloud cores, give similar values for the conversion factor, within about a factor of 2. The hot cloud cores give a value about 5 times as high; however,



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Young and Scoville argued, quite reasonably, that such actively star-forming regions would probably not constitute a significant fraction of the projected area of molecular material in a galaxy. Sanders, Solomon, and Scoville (1984) analyzed a sample of giant molecular clouds using the virial theorem, and derived a nearly identical mean conversion factor.

An alternative approach is to use an independent tracer of interstellar hydrogen for comparison with the integrated CO line emission. The intensity of diffuse gamma radiation from the Galaxy depends on the distributions of cosmic rays and of hydrogen nuclei. Careful comparisons of surveys of H I 21 cm, CO $J = 1$–0, and high-energy gamma-ray emission at angular resulutions of the order of 1° (Bloemen *et al.* 1986) show rather convincingly that $N(H_2)/I_{CO}$ is constant on a large scale (i.e., when averaged over scales of several kpc) throughout the Galaxy, with a value of $2.8 \times 10^{20}$ cm$^{-2}$ (K km s$^{-1}$)$^{-1}$, except in the central 400 pc, where the value may be as much as a factor of 10 smaller (Blitz *et al.* 1985). This method measures all of the hydrogen, distinguishes the contribution of H and $H_2$ regions, and refers to large-scale averages; it is therefore more appropriate for the interpretation of CO observations of unresolved cloud ensembles than calibrations based upon measurements of individual clouds. There is, however, no guarantee that similar results apply to any galaxy other than the Milky Way. Interpretation of the gamma-ray observations in terms of $I_{CO}$ conversion factors is also hindered by the coarse bin size required to obtain adequate signal-to-noise in the gamma-ray data, and by the as yet unresolved discrepancies between different CO surveys of the Galaxy.

Nearly all CO observations of spiral and irregular galaxies have been interpreted with a constant conversion factor very similar to the one quoted by Young and Scoville (1982*a*). *Thus all radial variations in $I_{CO}$ within a galaxy, and overall differences between galaxies, have been attributed solely to variations in the amount of molecular hydrogen gas.* What is essentially a local, semiempirical conversion (with considerable scatter) for clouds with kinetic temperature $T_k \approx 10$ K and mean density $\bar{n} \approx 200$ cm$^{-3}$ has been assumed to hold at all radii in other spiral galaxies, and in objects such as irregular galaxies where there is reason to believe the molecular clouds may be quite different from those in the Galaxy.

The first attempt to place $I_{CO}/N(H_2)$ conversion factors on a theoretical basis was that of Kutner and Leung (1985), who constructed microturbulent cloud models and compared the integrated $^{12}$CO and $^{13}$CO intensities ($I_{CO}$ and $I_{^{13}CO}$) with the actual $H_2$ column densities in the models. The model clouds were constrained to satisfy the observed correlation between turbulent velocity and cloud size, and had various kinetic temperatures, densities, and CO/$H_2$ abundance ratios. Kutner and Leung noted the sensitivity of $I_{CO}$ to variations in the kinetic temperature, and advocated a value of $N(H_2)/I_{CO} = 2 \times 10^{20}$ for giant molecular clouds. Their calculations yield emergent intensities for single lines of sight through the centers of the model clouds, and these intensities are not obviously related to the observable intensities in external galaxies, which are integrated over unresolved ensembles of clouds. As noted above, the arguments for a constant value of $\alpha$ do not rely on a direct linear relation between $I_{CO}$ and $N(H_2)$ along a single line of sight through a cloud.

Dickman, Snell, and Schloerb (1986, hereafter DSS) discussed $I_{CO}/N(H_2)$ conversion factors more specifically in the context of extragalactic CO observations. They considered an ensemble of clouds within a uniform circular antenna beam. By treating all quantities as statistical averages, they were able to calculate the integrated CO intensity from the ensemble and compare it with the actual column density (or mass surface density) of molecular material within the beam. DSS assumed that cloud-cloud shielding was negligible, and that all clouds were virialized. For a kinetic temperature $T_k = 10$ K and mean $H_2$ number density $\bar{n} = 200$ cm$^{-3}$ they obtained a value for the conversion factor about 0.7 times that of Young and Scoville (1982*a*). They also considered ensembles with power-law cloud size and velocity distributions (which did not have identical mean gas densities), and obtained conversion factors differing by only ~10% from that for the ensembles of identical clouds. They did not consider the effects of systematic variations in cloud properties as a function of galactocentric distance, although they advocated caution in the use of constant conversions factors because of such effects.

In § II we apply more sophisticated modeling techniques to examine how variations in cloud parameters will affect estimates of the amount of molecular gas based on observations of CO. In § III we will discuss the likely magnitude of such variations in real galaxies, and in § IV we will summarize our conclusions. The actual techniques for modeling systems of molecular clouds will be discussed in detail elsewhere (Maloney 1987*b*, and in preparation).

## II. MODELS OF CLOUD DISTRIBUTIONS

As part of a program to understand what observations of CO emission from other galaxies can actually reveal about the nature and properties of their molecular clouds, we have developed techniques for modeling the CO emission from galaxies in a completely general way. These methods allow us to take advantage of all the information which is available in high signal-to-noise spectra, much of which has not been utilized in previous analyses of observations. Most of this material is outside the scope of this paper; here we use these models to compare the actual distributions of molecular gas in model galaxies to those inferred from CO observations.

A model galaxy with a specified size, rotation curve, $z$-velocity dispersion, and inclination is given a molecular cloud distribution; the molecular cloud scale height is specified as a function of radius, and the radial distribution of clouds can have various forms (e.g., exponential surface density of clouds [clouds kpc$^{-2}$]). The individual clouds are assigned cylindrical ($r$, $\phi$, $z$) coordinates, sizes, line widths, excitation temperatures, and optical depths in the transition of interest: these may all be arbitrarily complicated functions of position. The convolution of a Gaussian antenna response pattern (FWHM = $\theta_{1/2}$) with the emission of the model molecular cloud distribution is performed numerically, so that no approximations are necessary. Cloud-cloud shielding is explicitly taken into account. For each "observed" position, all clouds within a distance of $1.2\theta_{1/2}$ of the beam center are included in the convolution, so that the emission from 98% of the beam area is accurately modeled. The synthetic spectrum is passed through a model "filterbank" with a given number of channels and velocity resolution. Since the distribution of molecular material is specified *a priori*, it is possible to examine directly the effect of varying cloud parameters on the observable CO integrated intensity, and compare the molecular gas abundance inferred from using constant conversion factors with the actual distribution.

The number of parameters describing a molecular cloud ensemble which may vary within a galaxy and from galaxy to

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galaxy is in principle very large. Some of these parameters are observationally relatively unimportant; for example, it is easy to show that the observed CO integrated intensity is unaltered by changes in the cloud-cloud velocity dispersion along the line of sight (the peak temperature and line width scale in such a way that $I_{CO}$ is invariant), provided that cloud-cloud shielding is negligible. We consider here three parameters, which are probably the most important parameters for the majority of galaxies: variations in the excitation temperature of the CO $J = 1$–0 transition, in the mean density of gas within clouds, and in the abundance of CO relative to $H_2$. We will also assume that all clouds are in virial equilibrium (but see § II*b*), and consider only axisymmetric galaxy models. Some of the potential difficulties in interpreting CO observations have been discussed previously by Israel (1985) and Rickard, Harvey, and Blitz (1984).

### *a*) *Variations in* CO *Excitation*

The conversion factor suggested by Young and Scoville (1982*a*) implicitly refers to clouds with $J = 1$–0 excitation temperature $T_{ex} \approx 10$ K, since it was derived from observations of clouds with area-averaged temperatures of this order. In our code the excitation temperature of the transition of interest is specified, so that the effect of variations in kinetic temperature $T_k$ is not directly modeled. However, since the $^{12}$CO $J = 1$–0 transition is believed to be very optically thick in most clouds, it is generally assumed that the lowest levels are thermalized. This is supported by the results of non–LTE models of clouds for the range of conditions which apply to most molecular clouds in the Galaxy. Thus we can expect that the excitation temperature will vary nearly linearly with the gas kinetic temperature.

For ensembles of identical unresolved clouds with $T_k = 10$ K and $\bar{n} = 200$ cm$^{-3}$ we derive a mean conversion factor from our models that is somewhat smaller than Young and Scoville's value: $I_{CO}/N(H_2) = 1.8 \times 10^{20}$. The assumption of uniform cloud size is a poor one: Galactic molecular clouds exhibit a range of about 2 orders of magnitude in size. Furthermore, in the Galaxy there is a well-defined correlation of line width with cloud size, of the form $\Delta V \propto R^{0.5}$ (Solomon *et al.* 1987). We have constructed models with power-law cloud size distributions, using the above line width–size relation with parameters appropriate to Galactic GMCs. The values of the conversion factor in these models differ by only ~20% from the uniform cloud models, in good agreement with DSS.

When attempting to derive the large-scale distribution of molecular gas in a galaxy, it is necessary to consider the effects of gas temperature gradients. Such gradients are quite likely to exist, since the intensity of the interstellar radiation field will generally increase inward, and the cosmic-ray flux may vary with galactocentric distance. In extreme environments such as starburst galaxies the characteristic temperatures of molecular clouds will almost certainly be larger than in normal galaxes as a result of the very high rates of star formation and supernovae.

A general result of our models is that the observed integrated CO intensity varies linearly with the CO excitation temperature: the ratio $I_{CO}/T_{ex}$ is a constant for ensembles of identical clouds, independent of the value of $T_{ex}$ chosen to represent the ensemble. The value of the constant depends on the fraction of the beam that is filled by the clouds and on the line widths of the clouds. A useful exercise is then to compare the radial $I_{CO}$ profiles for two model galaxies which have identical molecular cloud distributions, except that in one the excitation temperature increases with decreasing radius while in the other it is constant.

Figure 1 shows the results of such a comparison. For simplicity, the models have zero inclination (face-on), and all the clouds are identical, with radii of 10 pc. Both galaxies have exponential surface densities of molecular clouds, and a total of $10^4$ clouds. The *z*-velocity dispersion falls off exponentially with radius. The galaxy with constant excitation temperature has $T_{ex} = 10$ K, while the other has $T_{ex}(r) = 40e^{-r/7.2}$, where *r* is in kiloparsecs. Figure 1*a* shows the observed $I_{CO}$ as a function of radius for the two models. At the center position $I_{CO}$ in the galaxy with a $T_{ex}$ gradient is 4.7 times higher than in the constant $T_{ex}$ model. (Note that the ratio of *antenna temperatures* in the CO $J = 1$–0 line for $T_{ex} = 40$ K and $T_{ex} = 10$ K is 5.5) Figure 1*b* shows the molecular hydrogen distributions that would be inferred for the two models from the conversion factor appropriate for $T_{ex} = 10$ K and $\bar{n} = 200$ cm$^{-3}$, as well as the actual $H_2$ column density averaged over the beam FWHM. By using a constant α, an error of nearly an order of magnitude in the relative abundance of $H_2$ across the disk of the galaxy is made in the temperature-gradient model.

Kutner and Leung (1985) noted the sensitivity of the integrated intensity of the $J = 1$–0 line to the assumed kinetic temperature, and found the dependence of $I_{CO}$ to be nonlinear: $I_{CO} \propto T_k^{1.3}$ in their models, which they attributed to the importance of radiative cascade into the $J = 1$ level. However, the nonlinear $T_k$ dependence they found is simply due to the fact that antenna temperatures (which are *defined* as Rayleigh-Jeans temperatures) do not scale linearly with $T_{ex}$ unless $h\nu/kT_{ex} \lesssim 0.2$ (i.e., $T_{ex} \gtrsim 28$ K for the CO $J = 1$–0 line). Cloud models with $T_k$ equal to 6 or 13 K, which have been computed using a "large velocity gradient" (LVG) treatment of the radiative transfer, show the same scaling found by Kutner and Leung (1985), even though the 1–0 transition is thermalized. Thus $I_{CO}$ scales as a modest power of $T_k$, with the exponent declining to unity as $T_k$ approaches 30 K. Subthermal excitation of the CO $J = 1$–0 level makes the power-law dependence even weaker at low densities. As expected, such model computations show that $I_{CO} \propto T_k$ when $T_k \gtrsim 28$ K and when the $J = 1$–0 emission is optically thick and thermalized so that $T_{ex} \approx T_k$.

The scaling of $I_{CO}$ with kinetic temperature is a potentially very serious problem for the study of molecular gas in galaxies, as is obvious from the example above. To better estimate the true abundance of $H_2$ from $^{12}$CO observations, it is necessary to obtain information on the excitation of the CO. The best way to do this is probably by observing higher transitions of $^{12}$CO. Although observations of the $^{13}$CO isotope may be useful, the likelihood of subthermal excitation in this species, as well as uncertainties in the optical depth of the transition, will complicate the interpretation. Non–LTE models show that under a wide range of conditions, the lowest few rotational levels of $^{12}$CO are thermalized, or close to it. Thus assuming an identical excitation temperature for the $J = 1$–0 transition and another transition which is not too far above the ground state is often a reasonable approximation. The excitation temperature of the 1–0 transition may then be derived from the ratio of antenna temperatures of the two transitions, preferably from observations made with similar beam sizes. Figure 2 shows the ratio of antenna temperatures of several transitions to the $J = 1$–0 line, as a function of excitation temperature. It is evident from Figure 2 that the highest possible transition

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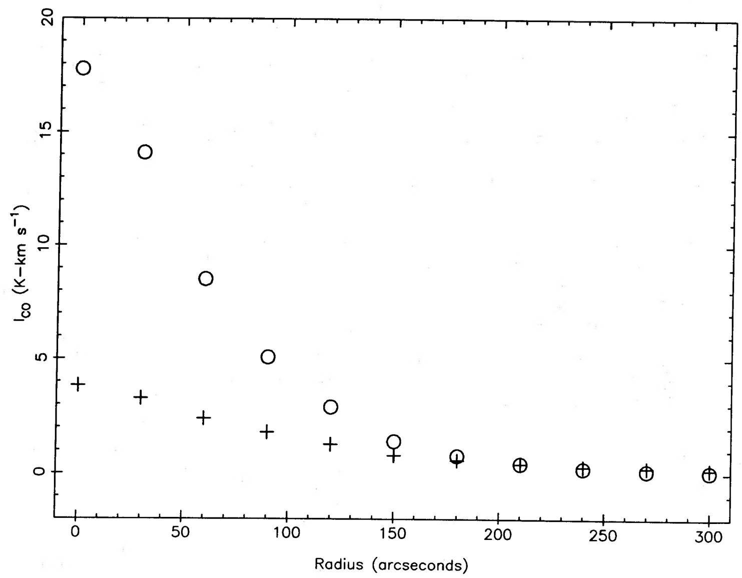


FIG. 1*a*

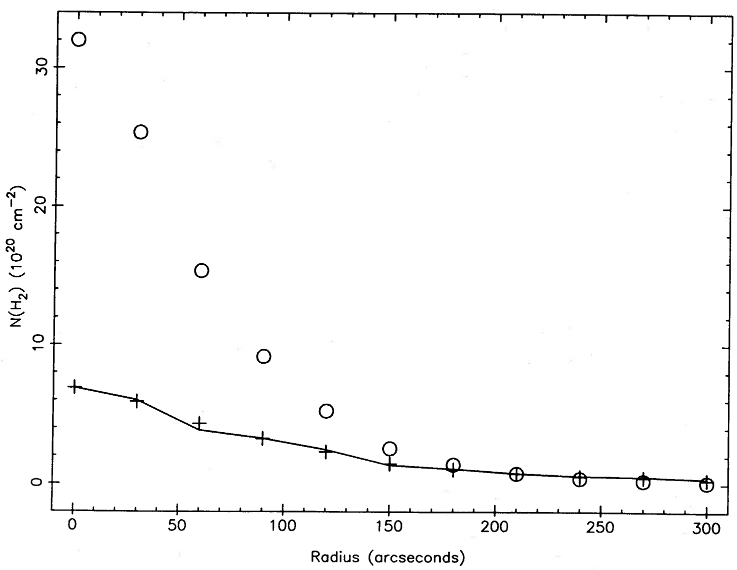


FIG. 1*b*

FIG. 1.—(*a*) Integrated CO intensity plotted against distance from the nucleus (in arcseconds) for two model galaxies at 10 Mpc. The two models are identical except for the temperature distributions of the molecular clouds. The plus signs are observable integrated intensities for a model with constant excitation temperature $T_{ex} = T_k = 10$ K. The circles are the corresponding integrated intensities for a model in which $T_{ex}$ declines exponentially from 40 K at the nucleus to 5 K at 15 kpc. The antenna FWHM for both models is 50″. (*b*) Beam-averaged column densities of $H_2$ derived from the models through use of constant conversion factors. The solid line represents the actual FWHM–averaged column density. The column densities for both models were derived using a conversion factor found to be accurate for ensembles of clouds with $T_{ex} = 10$ K and mean density $\bar{n} = 200$ cm$^{-3}$.

(within the limits of what is allowed by the necessity of $T_{ex}$ = constant) should be used for comparison with the $J = 1$–0 line. While it should be possible to distinguish regions with $T_{ex} = 10$ K from those with $T_{ex} = 40$ K using the 2–1 transition, it is probably impossible to distinguish $T_{ex} = 20$ K from $T_{ex} = 40$ K with the lowest transitions only.

As an example of the information which can be obtained in this way, the model galaxy of Figure 1 was also "observed" in the $J = 2$–1 line. Figure 3 shows the ratio of antenna temperatures as a function of radius. Superposed on these points is the curve describing $T_R^*(2\text{–}1)/T_R^*(1\text{–}0)$ for the specified variation of $T_{ex}$ with radius. Observations of such line ratios of upper transitions with sufficiently high precision should be able to identify large-scale gradients in $T_{ex}$.

### *b*) *Variations in Mean Density*

As discussed in § I, the conventional justification for constant conversion factors between $I_{CO}$ and $N(H_2)$ requires the assumption of virial equilibrium, in which the line width of a cloud is related to its gravitational potential and hence to its

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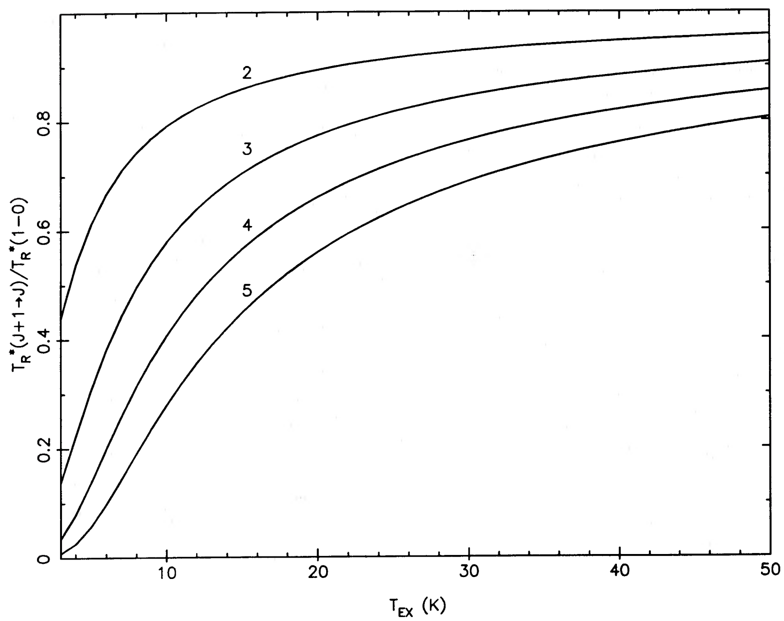


FIG. 2.—Plotted are the ratios of antenna temperatures of several rotational transitions of CO to the $J = 1$–$0$ transition, as a function of excitation temperature. It is assumed that the excitation temperatures of all the transitions are identical. Each curve is labeled with the value of $J$ for the upper level of the transition $J' + 1 \to J'$.

mass. For virialized clouds, the three-dimensional velocity dispersion is given by

$$\sigma_c = \left(\frac{\phi GM}{R}\right)^{1/2} , \tag{1}$$

where $M$ is the cloud mass, $R$ is the cloud radius, and $\phi$ is a parameter of order unity that depends on the degree of central concentration of the cloud. This can also be written as

$$\sigma_c = \left(\phi G \frac{4\pi}{3} R^2 \bar{n} \mu m_H\right)^{1/2} , \tag{2}$$

where $\bar{n}$ is the mean number density and $\mu$ is the mean mass per free particle. [If we assume the solar H/He ratio, $\mu = 2.25$ and $\bar{n} = (8/7)\bar{n}_{H_2}$.] For a homogeneous cloud the velocity dispersion can also be written in terms of the area-averaged column density, $\langle N \rangle$:

$$\sigma_c = (\phi \pi G R \langle N \rangle \mu m_H)^{1/2} . \tag{3}$$

Consider the CO emission from an individual optically thick cloud, with a specified radius and antenna temperature in the $J = 1$–$0$ transition. It is obvious that $I_{CO} \propto \sigma_c$, as long as the line width does not get so large that the line becomes optically thin. From equation (3), the average column density is pro-

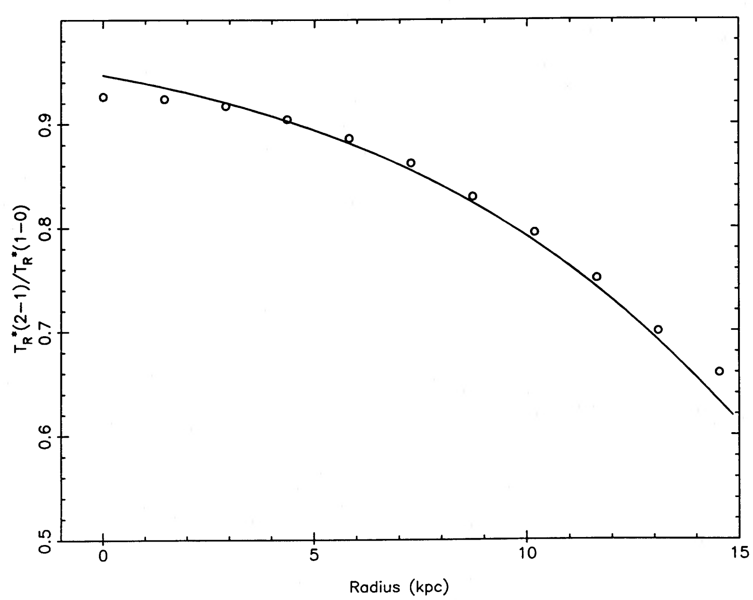


FIG. 3.—The circles are the ratios of the $J = 2$–$1$ to $J = 1$–$0$ integrated intensities for the model galaxy of Fig. 1, with an exponential excitation temperature gradient. The solid curve is the ratio of $J = 2$–$1$ to $J = 1$–$0$ antenna temperatures appropriate to the excitation temperatures at each radius.

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portional to $\sigma_c^2$; thus $N(H_2)/I_{CO} \propto \sigma_c$, and since $\sigma_c \propto \bar{n}^{1/2}$ (eq. [2]),

$$\alpha = N(H_2)/I_{CO} \propto \bar{n}^{1/2} . \quad (4)$$

The value of the conversion factor, $\alpha$, thus depends on the mean density of gas in the clouds, as noted by DSS. The effect of increasing density is opposite to that of raising the kinetic temperature: $N(H_2)/I_{CO}$ increases with $\bar{n}$.

In § I it was mentioned that Young and Scoville (1982*a*) obtained a value for $\alpha$ in hot cloud cores ~4–7 times higher than for the other molecular regions in their sample. These cloud cores [Orion-KL, M17SW, and W3(OH)] have measured antenna temperatures corresponding to $T_k \approx 30$–90 K. The analysis in § II*a* shows that this would decrease $\alpha$ by factors of 3–9 for these three regions. The large measured values of $\alpha$ imply that the mean densities in these hot cores are so high that they more than compensate for the higher gas temperatures: although these regions are evolving and not in virial equilibrium, the increased value derived for the conversion factor is undoubtedly a result of the very large densities.

The observed correlation of line-width with cloud size, of the form $\Delta V \propto R^{0.5}$, implies that virialized clouds have mean densities that scale as $R^{-1}$. Such a relation has been inferred from CO observations of isolated dark clouds, which are believed to have very simple density structures (Leung, Kutner, and Mead 1982; Myers 1983). However, these inferred densities are based on an LTE analysis of $^{13}$CO data, which probably significantly underestimates the actual densities (Maloney 1986). In addition, the infrared absorption-line observations of CO in NGC 2024 by Black and Willner (1984) show conclusively that the one-dimensional velocity dispersion of the *bulk* of the molecular gas is small, with a FWHM $\lesssim 1.4$ s$^{-1}$. This is several times smaller than the line widths measured in the millimeter-wavelength rotational transitions toward this source, even for the rarer isotopic species which presumably are less affected by line saturation effects. The millimeter observations sample much larger angular scales than the absorption-line measurements, which suggests that the velocity dispersion increases toward the cloud exterior. It is extremely important to perform these absorption-line observations in other molecular clouds, to determine whether the cloud associated with NGC 2024 is peculiar, or whether millimeter observations of CO *always* overestimate the velocity dispersions in clouds.

### *c) Variations in* CO *Abundance*

It has often been stated that $I_{CO}$ is very insensitive to changes in the abundance of CO relative to $H_2$, because the optical depth of the transition is so large. This behavior was found by Kutner and Leung (1985): varying the CO/$H_2$ ratio by a factor of 20 in their models produced only a factor of 2 change in $I_{CO}$. However, their calculated intensities refer to a single line of sight through a cloud. The abundance of CO in interstellar clouds will be high only if its column density is large enough to produce self-shielding in the dissociating transitions (see, e.g., Glassgold, Huggins, and Langer 1985); therefore, the metallicity (i.e., C/H and O/H) in a cloud will affect the size of the region where CO becomes the dominant gas-phase carbon-containing species, relative to the size of the molecular hydrogen cloud. Decreasing the metallicity will thus tend to make clouds systematically smaller, as measured in the $J = 1$–0 transition of CO, and therefore decrease the observed $I_{CO}$, since the filing factor of CO–containing gas will be smaller. In addition, lowering the CO abundance can produce a decrease in the CO excitation temperature, since photon trapping is so important in determining the excitation of the lower rotational levels at the moderate densities (~1000 cm$^{-3}$) typical of molecular clouds. The possibility that abundance gradients in spiral galaxies may have serious effects on the observed CO emission has been suggested by Blitz (e.g., Blitz 1985): in several galaxies such as M51 and M101, the radial distributions of O/H and CO are very similar. Blitz cautioned that $I_{CO}$ might be tracing the abundance of CO rather than of $H_2$.

A lower metallicity is expected to be accompanied by a smaller dust abundance. Since molecular hydrogen is formed in a grain surface reaction, this will lower the $H_2$ formation rate, which would tend to decrease the size of molecular hydrogen regions. However, at least for dust-to gas-ratios 17 times lower than the solar neighborhood value (appropriate for the SMC), this effect turns out to be very small (see below).

A smaller dust-to-gas ratio also means that the attenuation of UV radiation with depth in the cloud will be lessened. Since $H_2$ is strongly self-shielding, the higher UV flux will not drastically reduce the extent of the $H_2$ zone; however, it will contribute to the destruction of CO. It will also act to raise the cloud temperatures (see § III*a*). The smaller column densities of CO and the lessened attenuation of the incident radiation field will make it easier to destroy CO that is exposed to a strong UV background, e.g., from a nearby OB association.

To investigate the effects of such low abundances on the properties of molecular clouds, we have constructed chemical models of clouds, using parameters appropriate to the LMC, the SMC, and local Galactic molecular clouds. These models were constructed using the techniques of van Dishoeck and Black (1986) and will be discussed in greater detail elsewhere. The abundance of carbon and oxygen with respect to hydrogen and $A_V/N_H$ were lowered by factors of 4 and 17, respectively, for the LMC and SMC models, compared with the Galactic cloud values (Israel 1984; Koornneef 1984). The model clouds assume plane-parallel geometry and are exposed to incident radiation from both sides. The ambient radiation field in the LMC was increased by a factor of 2 over the standard Galactic background. All the models had number densities of total hydrogen of 1000 cm$^{-3}$, and total molecular hydrogen column densities of $10^{22}$.

Figure 4 shows the number density of molecular hydrogen plotted against distance from the cloud edge for all three models. The differences in structure of the molecular hydrogen cloud in the three models are very small: the peak abundance of molecular hydrogen declines by less than 10% when the dust-to-gas ratio is decreased by a factor of 17. Although the distance from the cloud edge where $H_2$ becomes dominant over atomic hydrogen increases by 2 orders of magnitude between the Galactic model and the SMC model (from $2.8 \times 10^{15}$ to $2.6 \times 10^{17}$), it is still less than 3% of the cloud thickness.

In marked contrast, Figure 5 shows the CO distributions for the models. The ordinate is the fraction of carbon in CO. Thus, if the same percentage of carbon as a function of depth were in the form of CO in all three models, their CO distributions would be identical on this plot. It is obvious that in terms of their CO chemistry the cloud models are very different. At the center of the Galactic cloud model 99% of the carbon is in CO, while only 5% of the carbon in the LMC and only 1% of the carbon in the SMC is tied up in carbon monoxide. Because of the importance of self-shielding in the survival of CO in molecular clouds, the decline in CO column density with decreasing

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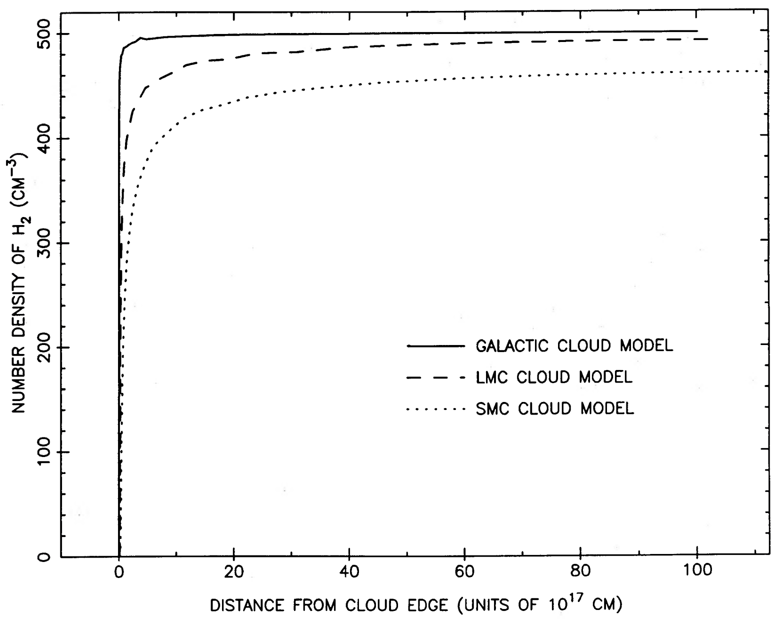


FIG. 4.—Distributions of molecular hydrogen for the three cloud models discussed in § II*c*. All models have total $H_2$ column densities of $10^{22}$ $cm^{-2}$ and total number densities of 1000 $cm^{-3}$.

metal abundances is very nonlinear. Some of the details of the photochemistry of CO are still poorly understood, but the preliminary results discussed here are based on plausible choices of the molecular parameters (van Dishoeck and Black 1987). Since these effects are essentially dependent on column density, cloud models with lower densities and therefore larger sizes will have similar profiles.

Since the model molecular clouds (as defined by the molecular hydrogen content) are very similar, whereas the CO abundances differ drastically, the use of an identical conversion factor (in particular, one that has been derived from observations of Galactic molecular clouds) will obviously give very misleading impressions of the molecular hydrogen abundances in low-metallicity systems, such as many irregular galaxies. To investigate the observational consequences, we constructed radiative transfer models of these clouds (using the Sobolev or LVG approximation) to calculate the emergent intensity in the CO lines. These models had spherical symmetry; the radial profile of CO abundance was assumed to be identical with the depth profile from the plane-parallel chemical models. Since the region where atomic hydrogen predominates is such a small percentage of the cloud volume, the density of molecular hydrogen was assumed constant and equal to 500 $cm^{-3}$; the kinetic temperature was 10 K. Figure 6 shows the emergent intensity in the $J = 1\text{–}0$ transition (given as antenna temperature) plotted against the line-of-sight offset from cloud

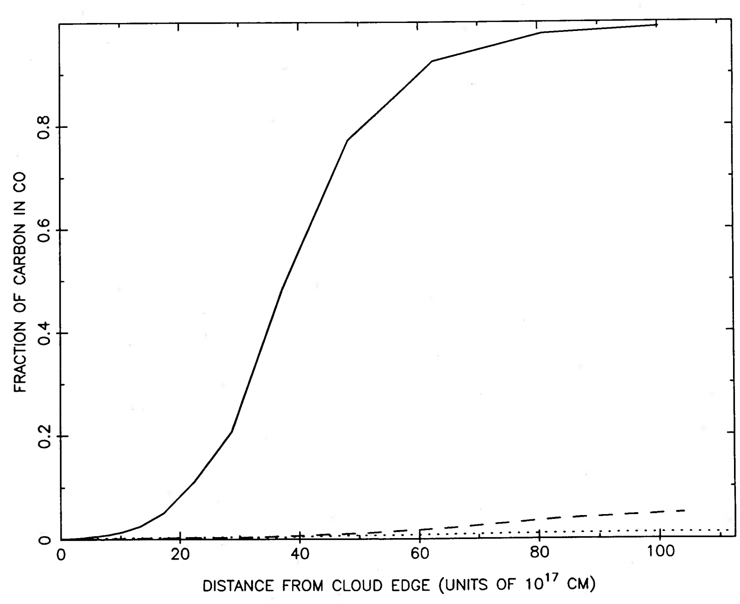


FIG. 5.—CO distributions for the three models, plotted as the fraction of carbon in CO versus distance from the cloud edge. The carbon abundance was lowered by factors of 4 and 17 compared with the Galactic cloud model for the LMC and SMC models, respectively. Legend as in Fig. 4.

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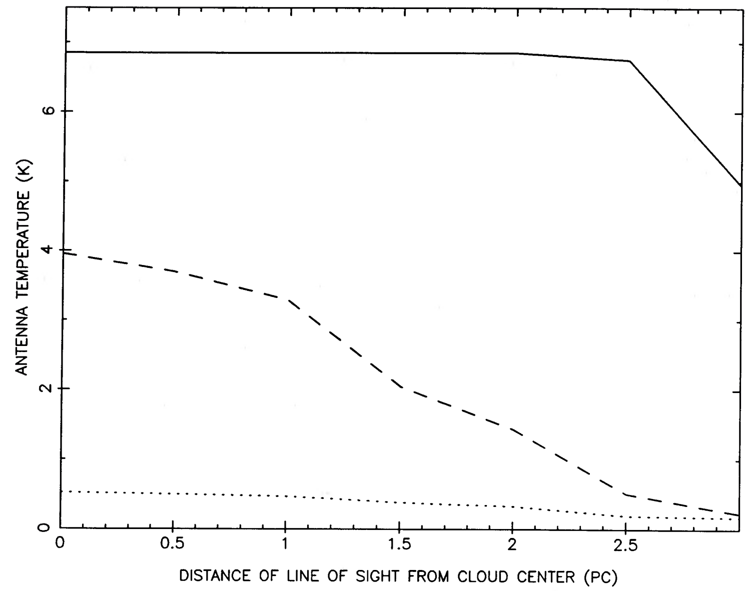


FIG. 6.—Peak antenna temperature measured for a given line of sight through a model cloud plotted against distance of the line of sight from cloud center for the three cloud models. Legend as in Fig. 4.

center (this corresponds to observing a cloud with an infinitesimal antenna beam). The 1–0 line in the Galactic cloud model is optically thick everywhere and thermalized almost throughout; the decline in intensity for lines of sight more than 2.5 pc from the cloud center is due to falloff in the excitation in the outer parts of the cloud. In contrast, in the LMC model the 1–0 line is optically thick only for lines of sight near the cloud center (the maximum optical depth is only 3.2) and is subthermally excited everywhere. The decline in both optical depth and excitation temperature away from the center produces the observed steep decline in antenna temperature with distance. CO in the SMC model is optically thin and subthermal throughout, with a peak temperature more than an order of magnitude lower than in the Galactic cloud model. The observable CO emission from low-metallicity molecular clouds can be a very poor tracer of molecular hydrogen.

Figure 6 also demonstrates that an increase of the C/H or O/H abundance above solar may not have significant effects in terms of apparent cloud size. The ratio of CO to $H_2$ sizes for the solar abundance model is not much below unity, so that only a modest increase in the observed CO intensity would be expected.

## III. VARIATIONS OF CLOUD PARAMETERS IN GALAXIES

The proper interpretation of CO emission from galaxies requires information on both the large-scale variations of cloud properties within a galaxy and systematic differences between different types of galaxies (e.g., irregular galaxies compared with late-type spirals). In this section we attempt to estimate the magnitude of such variations, from both theoretical considerations and observations.

### *a) Excitation Temperature*

The excitation temperature of a molecular transition is controlled both by the transfer of radiation through a cloud and by the coupling of the molecule to local thermal baths, principally by inelastic collisons at kinetic temperature $T_k$. The gas temperature itself is governed by heating and cooling processes that may reflect the larger environment of the cloud as well as its internal dynamical state. Thus the mean excitation temperature of a CO line can vary from cloud to cloud or from galaxy to galaxy in response to variations in many properties such as the flux of heating radiation, the abundance of grains, and the abundance of coolants.

#### i) *Effects of Dust on Gas Temperatures*

Dust grains affect cloud temperatures in several ways. At low densities, dust particles in interstellar clouds absorb and radiate approximately 100 times as much energy as the gas and attain equilibrium temperatures, $T_{\rm dust}$, established by the radiative balance. At high densities, dust can heat or cool the gas (depending on the relative magnitudes of $T_k$ and $T_{\rm dust}$) by collisional energy transfer (Goldreich and Kwan 1974; Leung 1975). Dust can also heat the gas through ultraviolet-induced photoelectric ejection (Watson 1972). The photoelectric efficiency $y$ is probably of order 0.1, so that as much as $\sim$4% of the incident UV energy can be converted into gas heating (Tielens and Hollenbach 1985*a*). At the same time, dust shields the interior of a cloud from external sources of ultraviolet radiation.

At any given location in the Galaxy, molecular clouds are exposed to the ambient interstellar radiation field. Because the dust couples more effectively to the starlight radiation field than the gas, it may be hotter than the gas. In this case the dust can serve as a heating mechanism for the gas, provided that the gas density is high enough. However, dust is also more effective at cooling itself than the gas, since the dust emission is dominantly in the far-infrared where clouds are optically thin: it is only the attenuation (by a depth corresponding to $A_V \approx 1$) of the far-ultraviolet radiation which controls heating of the gas that prevents considerably higher molecular gas temperatures.

#### ii) *Effects of Intense Radiation Fields*

For the local interstellar radiation field in the Galaxy, grain photoelectric heating is important only in the outermost ($A_V \lesssim 1$) layers of molecular clouds, as discussed above. However, in the presence of intense radiation fields this process may be important throughout molecular clouds. As an example, consider the nuclear region of M82. M82 is the

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nearest and best studied member of the class of galaxies known as starburst galaxies because of their very high current star formation rates. These objects have received intense study at millimeter wavelengths in the past three years, and virtually all of the interpretation of CO emission from these galaxies has utilized conversion factors nearly identical with that of Young and Scoville (1982*a*).

The production rate of ionizing photons in the central 450 pc of M82 can be estimated from Br$\gamma$ observations to be $\sim 2 \times 10^{53}$ s$^{-1}$. If the ionizing source is thermal, its temperature is no more than 30,000 K (Rieke *et al.* 1980). For the purposes of this estimate, assume that all the ionization is produced by B0 main-sequence stars with $T_{\rm eff} = 30{,}000$ K. This rate of Lyman continuum photon production corresponds to $5.2 \times 10^5$ B0 stars, based on the model stellar atmospheres of Kurucz (1979) and a typical stellar radius $R_* = 7.6$ $R_\odot$. Let us also assume that the central 450 pc of M82 can be modeled as a uniform mixture of stars, gas, and dust. The total extinction to the nucleus of M82 is $\sim 25$ mag (Rieke *et al.* 1980). To make a conservative estimate of the ultraviolet intensity within this region, we will assume that all of this extinction is produced between the nucleus and the edge of the source region (i.e., 25 mag/225 pc). Thus the optical depth at visible wavelengths is $\tau_V = 0.10$ pc$^{-1}$. We will take $\tau_{uv} = 2.5\tau_V$. With a uniformly random distribution of stars throughout this region, the mean intensity at 1080 Å is

$$J_\nu = 2.2 \times 10^{-17} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ Hz}^{-1} \text{ sr}^{-1} . \quad (5)$$

If we compare this with Draine's (1978) expression for the intensity of the local Galactic interstellar UV radiation field, we see that the mean UV intensity in the nuclear region of M82 is $\sim 250$ times the solar neighborhood value. This means that grain photoelectric heating will be as important at $A_V \approx 3$ in the nuclear regions of M82 as it is in the unshielded interstellar medium locally.

In reality, neither the stars nor the molecular material will be distributed uniformly. Since massive stars (at least in the Galaxy) invariably form out of molecular cloud complexes, it is expected that the molecular gas in such actively star-forming regions will see even stronger UV radiation fields. Detailed models of these photodissociation regions (the interface between molecular clouds and the H II regions around massive stars) have been calculated by Tielens and Hollenbach (1985*a*, *b*), for ultraviolet fluxes $10^3$–$10^6$ times the local Galactic value and densities of $10^3$–$10^6$ cm$^{-3}$. They found that the incident radiation has profound effects on the cloud structure and temperature to a depth of $A_V \approx 10$. Grain photoelectric emission is the dominant heat source to $A_V \approx 5$; the gas temperature considerably exceeds the dust temperature throughout most of this region. The CO emission in the lower rotational levels arises in the warm ($T \approx 50$–200 K), partially photodissociated region (containing $H_2$, O, C, and CO) at $A_V \approx 3$–5. These models also predict very strong [O I] 63 $\mu$m and [C II] 158 $\mu$m emission from the photoionized regions.

Recent observations of [C II] 158 $\mu$m emission from M82, M83, and NGC 1068 by Crawford *et al.* (1985) show very good correlations of the intensity and spatial distribution of the [C II] and CO $J = 1$–0 emission. Crawford *et al.* concluded that only photodissociation regions like those modeled by Tielens and Hollenbach could produce sufficient [C II] emission to explain their observations, so that the [C II] emission must be associated with molecular gas. A similar conclusion for [C II] 158 $\mu$m emission in the Galaxy was reached by Stacey *et al.* (1985). Since the [C II] line arises from photodissociation regions, the correlation with CO suggests that the observed CO rotational emission arises from the same regions. Since the measured [C II] 158 $\mu$m intensity from these galaxies is not very sensitive to total gas mass, density, temperature, or filling factor (Crawford *et al.* 1985), the sharp peaking of [C II] emission at the nuclei of these galaxies, *which is identical with the spatial distribution of* CO *emission*, can be attributed primarily to the intense UV radiation fields rather than to increasing molecular abundance. This strongly suggests that CO observations are also affected by excitation temperature variations in galactic nuclei (Crawford *et al.* 1985). Note that the models of Tielens and Hollenbach predict that the brightness temperatures of the CO rotational transitions will increase with increasing $J$, since the increase in optical depth with $J$ means that the higher $J$ lines will be formed at shallower depths into the cloud, where the temperature is higher. Anomalously large $J = 2$–$1/J = 1$–0 antenna temperature ratios have been observed in the nuclei of M82, Maffei 2, and NGC 253 (Sutton, Mason, and Phillips 1983; Sargent *et al.* 1985; L. J Rickard 1986, personal communication). For M82 this high value has been widely interpreted in terms of small, optically thin CO–emitting clouds (Olofsson and Rydbeck 1984; Crawford *et al.* 1985; but see Young and Scoville 1984). CO emission from photodissociation regions provides a somewhat more plausible explanation (Maloney 1987*b*).

Additional evidence for high gas temperatures in the nuclear regions of galaxies is supplied by ammonia observations of the Galactic center (Morris *et al.* 1983) and the nucleus of IC 342 (Ho and Martin 1983; Martin and Ho 1986). In both cases the inferred gas temperatures (on size scales of hundreds of parsecs) are $T_k \approx 50$ K. As mentioned in § I, Blitz *et al.* (1985) concluded that the $N(H_2)/I_{\rm CO}$ conversion factor in the central 400 pc of the Galaxy is as much as a factor of 10 lower than it is elsewhere in the Galaxy. They attributed this to an increase in the CO/$H_2$ abundance ratio. However, a large part of this variation may simply be due to the increased temperature in the Galactic center. Rickard and Harvey (1983) found evidence for variation in dust temperatures near the nucleus in Maffei 2 that correlated extremely well with the variations in $I_{\rm CO}$. Since many galaxies show evidence for at least moderately enhanced star-forming activity in their nuclei, in the absence of information on the excitation of CO across Galactic disks one must be extremely cautious in deriving molecular gas distributions from CO $J = 1$–0 emission, especially in the nuclear regions.

Of particular interest in regard to large-scale variations in excitation temperature are the very infrared-luminous galaxies discovered by *IRAS*. Sanders and Mirabel (1985) observed a sample of these galaxies which also had radio-bright nuclei. They concluded that the galaxies with the highest infrared luminosities possess unusually large molecular components; this overabundance of molecular material compared with normal galaxies allows these galaxies to form very large numbers of early-type stars in a "burst" of star formation, which in turn powers the infrared luminosity. However, the molecular clouds in these very luminous objects are almost certainly affected by the intense radiation field that must be generated by such activity. Of the luminous *IRAS* galaxies observed by Sanders and Mirabel (1985), those with the largest measured CO intensities also have *IRAS* 100 $\mu$m/60 $\mu$m color temperatures of $\sim 40$–50 K, considerably in excess of typical far-IR color temperatures ($\sim 25$–30 K) for galactic disks. Deutsch and Willner (1986) also found this to be the case for

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their sample of Markarian galaxies observed by *IRAS*. Since most of these galaxies are only a few arcminutes in diameter, the *IRAS* observations measure emission from nearly the whole extent of each galaxy. Thus the global far-IR emission from these galaxies is dominated by warm dust.

The temperature of dust in the interstellar medium is not very sensitive to the intensity of the interstellar radiation field. Assuming that the dust does most of its radiating in the infrared, with emissivity $\epsilon_\lambda = \epsilon_{IR} \approx 10^{-2}$, the temperature of a grain in equilibrium with the solar neighborhood radiation field integrated between 0.1 and 8 $\mu$m, $F_{sn}$, is given by

$$F_{sn} \approx \epsilon_{IR} \sigma T_d^4 . \quad (6)$$

With $F_{sn} = 0.025$ ergs cm$^{-2}$ s$^{-1}$ (Black 1987), $T_d = 14$ K. Increasing the intensity of the radiation field by 2 orders of magnitude to a value appropriate for the nuclear regions of M82 would only increase the dust temperature to 45 K. Since the dust temperature is so insensitive to the radiation field, the large color temperatures inferred from *IRAS* imply that either (1) emission from dust associated with actively star-forming regions dominates the *IRAS* observations of these galaxies, or (2) the interstellar radiation field throughout much of the dust-containing volume of these galaxies is $\gtrsim 10^2$ times the local interstellar radiation field in the Galaxy.

Either of these alternatives implies that the gas responsible for the observed CO emission is likely to have excitation temperatures on the order of 40–50 K or more, for the reasons discussed above. This means that use of the standard conversion factor will tend to overestimate the amount of molecular gas by factors of 4–5, unless the molecular clouds in these galaxies have characteristic densities $\bar{n} \gtrsim 3000$ cm$^{-3}$ (§ II*b*).

At the other end of the scale are the S0 and Sa galaxies, which as a class have very low star formation rates as measured by *IRAS* (S. Pompea 1987, personal communication). The lower limit to molecular cloud temperatures in a galaxy is believed to be determined by the energy input from cosmic rays (Dalgarno 1976). In the Milky Way this limit seems to be about 8 K. Since the cosmic-ray flux is believed to be supplied largely by Population I objects, galaxies with very low rates of star formation will presumably have lower rates of heating by cosmic rays, so that the molecular gas will be colder and therefore harder to detect. Thus use of a Galactic conversion factor for S0 and Sa galaxies may underestimate the amount of molecular gas.

### *b) Variations in Mean Density*

Molecular clouds in the Milky Way show variations of several orders of magnitude in mean density on scales of $\lesssim 10$ pc. The clumpy nature of molecular clouds means that the mean densities of large cloud complexes (with sizes $\sim 100$ pc) are quite low ($\sim 100$ cm$^{-3}$); as one looks at smaller scales, one finds molecular condensations with higher densities, reaching $10^4$ cm$^{-3}$ or more on scales of $\lesssim 0.1$ pc (see Scalo 1985, and references therein). Isolated dark clouds also show a range of mean densities, and the mean density appears to decrease with cloud size (Leung, Kutner, and Mead 1982; Meyers 1983); the actual scaling of density with cloud size remains somewhat uncertain (Maloney 1986). Whether there are any trends in mean density with radius in the Galaxy has not been established.

There are some reasons for supposing that large-scale variations in mean density *might* exist in galaxies. The tidal gravitational fields of galaxies place lower limits on the density of stable molecular clouds (Stark and Blitz 1978; Blitz and Glassgold 1982). Define the tidal acceleration by

$$T \equiv -\frac{d}{dR}\left(\frac{\theta^2}{R}\right) + \frac{\theta^2}{R^2} = -R\frac{d}{dR}[\omega^2(R)] \quad (7)$$

(Stark and Blitz 1978), where $\theta$ is the circular velocity at distance $R$ from the galactic center and $\omega$ is the angular velocity at distance $R$. The minimum tidally stable mass of a cloud at distance $R$ is then given by

$$M_t = \frac{T(R)r_c^3}{G} = 22\left[\frac{T(R)}{10^{-31}\ \mathrm{s}^{-2}}\right]\left(\frac{r_c}{10\ \mathrm{pc}}\right)^3 M_\odot , \quad (8)$$

where $r_c$ is the cloud radius (for the case of zero velocity dispersion at the cloud boundary; Blitz and Glassgold 1982). The minimum average density in a stable cloud is

$$\bar{\rho}_{min} = \frac{3T}{4\pi G} = 3.6 \times 10^{-25}\left(\frac{T}{10^{-31}\ \mathrm{s}^{-2}}\right) \mathrm{g\ cm}^{-3} \quad (9)$$

for spherical clouds; $\bar{\rho}_{min}$ may be a few times higher for other cloud geometries.

Consider the two extreme cases of (1) solid-body rotation ($\omega$ = constant) and (2) a flat rotation curve ($\theta$ = constant). In case 1, we have the simple result that $T = 0$: there is no tidal acceleration, and consequently no tidal constraint on the densities of stable molecular clouds. In case 2, assuming that $\theta$ is constant throughout the whole disk,

$$T = 2\frac{\theta^2}{R^2} = 8.4 \times 10^{-31}\left(\frac{\theta}{200\ \mathrm{km\ s}^{-1}}\right)^2\left(\frac{10\ \mathrm{kpc}}{R}\right)^2 \mathrm{s}^{-2} . \quad (10)$$

Throughout most of a galactic disk ($R \gtrsim 1$ kpc) the minimum density for stable clouds implied by equation (9) will not be an important constraint; however, near galactic centers the strong dependence of $\bar{\rho}_{min}$ on radius may have interesting consequences.

If we assume that typical disk molecular clouds in the Galaxy have mean number densities $\bar{n} \approx 200$ cm$^{-3}$ and $\mu = 2.25$, then $\theta = 220$ km s$^{-1}$ gives $\bar{\rho}_{min} = \bar{\rho}_{disk}$ at $R = 700$ pc. The minimum tidally stable number density is then

$$\bar{n}_t = 2.0 \times 10^3 f\frac{\theta^2}{R^2}\ \mathrm{cm}^{-3} , \quad (11)$$

where $\theta$ is in kilometers per second and $R$ in in parsecs and $f$ is a geometrical factor ($\sim V_{sphere}/V_{cloud}$, with $r_{sphere}$ equal to the cloud semimajor axis). Equation (11) indicates that $\bar{n}_t \gtrsim 10^4$ for $R \lesssim 100$ pc, suggesting that clouds near the Galactic center may have densities high enough to excite molecules such as CS. Stark *et al.* (1986) have reported detection of very widespread CS $J$ = 2–1 emission from the Galactic center. Since the CS emission is very intense on scales of hundreds of parsecs in this region, completely unlike what is observed throughout the rest of the disk, Stark *et al.* concluded that Galactic center clouds must have much higher mean densities than typical disk clouds, a result which they explained in terms of the tidal stability criterion. (See § III*d*.) Although the measurements will be difficult, it would be very interesting to search for CS emission from the centers of other galaxies, and to compare those with approximate solid-body rotation (such as NGC 6946, NGC 300) in their nuclear regions to those with very flat rota-

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tion curves (such as M51, NGC 2841). CS $J = 2$–1 emission has been detected from the nuclei of M82 and IC 342 (Henkel and Bally 1984).

Another effect which may be important in some galaxies is that of variations in the pressure of the interstellar medium (ISM). Although a molecular cloud that is gravitationally bound will be more or less unaffected by the ISM pressure, this may not be true in galaxies with very high star formation rates (Maloney 1987*b*). The large energy input from supernovae in such galaxies could raise the average pressure considerably, possibly to the point where it would affect the sizes of molecular clouds.

If molecular clouds are long-lived objects, then they probably are in approximate hydrostatic equilibrium and perhaps in virial equilibrium as well. However, there are certainly reasons for thinking that molecular clouds in certain environments may not be virialized. In molecular clouds associated with the formation of early-type stars, the energy input from radiation and stellar winds will significantly disturb some fraction of the molecular material. Similarly, the extremely large line widths observed in systems such as Arp 220 and NGC 6240 may result in part from the dynamic interaction of the galaxies. Increased line widths resulting from external perturbations of the molecular material will result in overestimates of the molecular mass.

### *c*) *Variations in* CO *Abundance*

Determinations of abundances in spiral galaxies (Pagel and Edmunds 1981; Dufour, Shields, and Talbot 1982) show that C/H and O/H typically increase by factors of 4–5 from the edge of the visible disk to the nucleus. Since the abundance ratios measured in the outer regions of the disk are usually close to solar, this increase will probably not cause major systematic effects in $I_{CO}/N(H_2)$ conversions, at least not as a result of CO cloud size variations. The observed similarity of the CO and abundance distributions in spirals may have some more subtle underlying cause.

The case in irregular galaxies is often quite different, and the models discussed in § II*c* demonstrate that abundances affect CO emission in irregular galaxies. Molecular clouds in such systems must be very different from those in the Galaxy, in terms of their observable properties, as a consequence of the decrease in cloud size as measured in CO with decreasing abundance.

The Large and Small Magellanic Clouds are the prototypical examples of the class of irregular galaxies, and have C/H ratios that are 1/6 and 1/31 of the solar value respectively (Dufour, Shields and Talbot 1982). Israel *et al.* (1986) searched for CO emission from the LMC and SMC using the ESO 3.6 m telescope, with a beam size of 2'.0 at the CO $J = 2$–1 frequency. They found peak antenna temperatures $T_R^* \approx 1$ K, which is about a factor of 4 lower than one would obtain by placing typical Galactic giant molecular clouds (with kinetic temperatures of 10 K and mean projected surface areas of 2300 pc$^2$; Blitz 1978) at Magellanic Cloud distances. The peak antenna temperature measured for a single cloud is given roughly by

$$T_{mb} \approx T_R \frac{\Omega_c}{\Omega_A}, \tag{12}$$

where $T_{mb}$ is the antenna temperature for a perfect antenna with a Gaussian diffraction pattern and no sidelobes ($T_{mb} =$ $T_R^*$ for an antenna with negligible error pattern), $T_R$ is the Rayleigh-Jeans radiation temperature of the line, $\Omega_c$ is the solid angle subtended by the cloud, and $\Omega_A$ is the antenna beam solid angle. If the CO emission is optically thick and thermalized at $T_{ex} = 10$ K, then $T_R = 5.3$ K for the CO $J = 2$–1 transition. We can now calculate the mean radius in CO of the clouds that will give the observed value of $T_R^*$ (assuming a perfect Gaussian beam for the observations of Israel *et al.* 1986): it is given by

$$R_{CO} = \left(\frac{T_{mb}}{T_R} \Omega_A 4d^2\right)^{1/2}. \tag{13}$$

Recent determinations of the distance modulus of the LMC imply a distance of 44–53 kpc, which gives $R_{CO} \approx 15$–18 pc. The mean radii of dark clouds observed in the LMC are $\sim$26–32 pc (Hodge 1972), so that decreasing the CO cloud radius by only about a factor of 2 below the total cloud radius will produce the necessary dilution of CO emission and lead to an underestimate of the amount of molecular gas present if a conversion factor derived from observations of Galactic molecular clouds is used.

Our models of low-metallicity clouds suggest that the amount of molecular hydrogen in the Magellanic Clouds has been significantly underestimated by the use of standard $I_{CO}/N(H_2)$ conversion factors, a conclusion also reached by Israel *et al.* (1986) on the basis of similar arguments. However, we do not need to confine ourselves to theoretical considerations: if we assume that molecular clouds are in virial equilibrium, it can be shown observationally that the existing molecular clouds in the Large and Small Magellanic Clouds are scarcely less massive than those in the Galaxy.

An estimate of Magellanic GMC sizes can be obtained from the dark cloud studies of Hodge (1972, 1974): these yield $\int dS = (2.2$–$3.3) \times 10^3$ pc$^2$ for the LMC and $\int dS = (0.9$–$1.2) \times 10^3$ pc$^2$ for the SMC; the range in values represents the uncertainty in the distance modulus of the Magellanic Clouds. Thus GMCs in the Magellanic clouds are not significantly smaller than Galactic GMCs. The line widths measured by Israel *et al.* (1986) in the Clouds are typically 7 km s$^{-1}$, for both the LMC and the SMC. Assuming that these clouds are in virial equilibrium, then from the measured sizes and line widths we can calculate masses using equation (1). This calculation yields $M = 3 \times 10^5\ M_\odot$ for the LMC and $2 \times 10^5\ M_\odot$ for the SMC, using the smaller values for the distance moduli of the clouds. Since hydrogen must be in molecular form in any clouds where there is enough CO to be detectable, these masses indicate that molecular cloud complexes in the Magellanic Clouds are comparable in mass to their counterparts.

While it is quite probable that real variations in molecular hydrogen content exist in irregular galaxies, it is not safe to conclude from weak CO lines and a Galactic $I_{CO}/N(H_2)$ conversion that stars must be forming from atomic hydrogen clouds in the LMC and SMC.

### *d*) *Molecular Clouds in the Galactic Center*

The prominence of the Galactic center relative to the disk in the lines of molecules requiring high densities for excitation (Stark *et al.* 1986; Güsten and Henkel 1983) suggests that cloud mean densities must be much higher in the Galactic center than elsewhere. As discussed in § III*b*, Stark *et al.* attribute this to tidal forces in the Galaxy: near the Galactic center, clouds must have densities roughly more than a few times $10^4$

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to survive. Such high densities imply large line widths for virialized clouds, and in fact the observed line widths are $\sim 20$–50 km $s^{-1}$, much larger than for typical clouds in the disk (Stark and Bania 1986).

If Galactic center clouds are in virial equilibrium and have densities $\sim 3000$–$10^4$ $cm^{-3}$, then the analysis of § II*b* indicates that $\alpha \approx 4$–7 times the disk value; from equation (5), $\alpha \propto \bar{n}^{1/2}$. However, the gamma-ray analysis of Blitz *et al.* (1985) indicates that $\alpha(R \leq 400 \text{ pc})/\alpha(\text{disk}) < 0.15$, unless the gamma-ray emissivities [photon (H atom)$^{-1}$ $s^{-1}$ $sr^{-1}$] are very different in the disk and the Galactic center region. Since the inferred increase in mean density raises $\alpha$, the analysis of Blitz *et al.* indicates that some other factor must decrease $\alpha$ by $\gtrsim 25$–45. The possible mechanisms for increasing $I_{CO}/N(H_2)$ are (1) increased gas temperature, (2) line widths greater than virial line widths, and (3) enhanced $CO/H_2$ ratio.

1. Since $T_{ex}$ scales roughly as $T_k$ in optically thick clouds, explaining the decrease in $\alpha$ by an increase in cloud temperature would require Galactic center clouds to have kinetic temperatures of 250–450 K, which are unreasonably high. Although molecular emission from gas with temperatures as high as $\sim 300$ K has been observed from Galactic center clouds (Harris *et al.* 1985; Genzel *et al.* 1985), this gas probably does not constitute a large fraction of the molecular material in this region; furthermore, gas at 300 K would be optically thin in the $J = 1$–0 line of CO unless the $CO/H_2$ ratio were very much higher than in the disk. A more reasonable upper limit on the CO excitation temperature for the inner few hundred parsecs of the Galaxy is probably 50–60 K (Morris *et al.* 1983). This still leaves a factor of 5–8 in $I_{CO}/N(H_2)$ to be explained.

2. Suppose that the velocity dispersion in a cloud is equal to some constant $\beta$ times the velocity dispersion it would have in virial equilibrium. Then from equation (3) we have

$$\sigma_c \propto \beta \langle N \rangle^{1/2} . \quad (14)$$

Then $\langle N \rangle \propto \sigma_c^2/\beta^2$, and so

$$\frac{N(H_2)}{I_{CO}} \propto \frac{\sigma_c^2}{\beta^2} \frac{1}{\sigma_c} \propto \frac{\sigma_c}{\beta^2} . \quad (15)$$

If we denote the conversion factor for $\beta = 1$ (virialized clouds) by $\alpha_1$, then the correct value of the conversion factor in the nonvirialized line width case will be

$$\alpha = \frac{1}{\beta^2} \alpha_1 , \quad (16)$$

and use of a conversion factor for virialized clouds will overestimate $N(H_2)$ by a factor of $\beta^2$. Line widths that are 2–3 times the virial line widths would then produce the necessary scaling of $I_{CO}/N(H_2)$. Considering the very turbulent nature of Galactic center clouds and the widespread noncircular motion evident from observations (Bally *et al.* 1986), it would not be surprising if $\sigma_c > \sigma_{virial}$.

3. An enhancement in the $CO/H_2$ ratio was suggested by Blitz *et al.* (1985) to explain the Galactic center gamma-ray deficit. The oxygen abundance in the Galactic center is probably $\sim 5$ times the solar neighborhood value (Shaver *et al.* 1983). Note that if the CS abundance increases to the point where the optical depth in the observed $J = 2$–1 line is significantly greater than unity, the density required to excite CS will be lower than the canonical value of $\sim 10^4$.

## IV. SUMMARY

Consideration of the effects of variations in molecular cloud parameters on conversion factors between integrated CO intensity and molecular hydrogen column density show that these conversion factors are very sensitive to the kinetic temperature of the emitting gas. Theory and observation suggest that the gas temperatures in systems with high star formation rates can be quite high, so that use of a standard (e.g., Young and Scoville 1982*a*) conversion factor will lead to serious systematic overestimates of the amount of molecular gas. This conclusion probably applies not only to galaxies with unusually high global rates of star formation, such as the infrared-luminous galaxies discovered by *IRAS*, but also to the nuclear regions of many less extreme galaxies (such as IC 342 and the Galactic center). Galaxies with very low rates of star formation such as Sa galaxies may have quite low cloud temperatures. Observations of higher level rotational transitions are crucial to obtain estimates of the CO excitation temperatures. In addition, very small abundances of carbon and oxygen, such as are observed in the LMC and the SMC, will result in significantly smaller clouds as measured in CO compared with the molecular hydrogen size, and hence to greatly reduced cloud-averaged CO emission; the use of a conversion factor appropriate for the Galaxy in interpreting observations of metal-deficient irregular galaxies will significantly underestimate the amount of molecular gas.

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