GIANT MOLECULAR CLOUDS IN THE GALAXY: DISTRIBUTION, MASS, SIZE and AGE

P. M. Solomon†, D. B. Sanders†, and N. Z. Scoville††

†Astronomy Program, State University of New York, Stony Brook, N.Y.
††Astronomy Dept., University of Massachusetts, Amherst, Mass.

1. INTRODUCTION

Millimeter wave observations of emission from the CO molecule have become, over the past eight years, the dominant method for determining the physical properties of dense interstellar clouds, composed primarily of molecular hydrogen and for exploring the structure and kinematics of the galactic disk. In this paper we briefly review the CO survey results in the literature (Section 2) and then present new results (Section 3-7) of an extensive ^{13}CO and ^{12}CO survey of the galactic distribution, size, mass and age of molecular clouds. The interpretation of this survey leads to a new picture of the interstellar medium dominated by very massive stable long-lived clouds which we refer to as Giant Molecular Clouds. We find that Giant Molecular Clouds (GMC's) with $M = 10^5 - 3 \times 10^6 M_{\odot}$ are a major constituent of the galactic disk, the dominant component of the interstellar medium in the galaxy interior to the sun and the most massive objects in the galaxy. We find that the interstellar medium and star formation are dominated by massive gravitationally bound clouds in which stars and associations are forming but at a very low rate in comparison to the free fall time. The galactic distribution of the molecules as traced by CO emission is interpreted as the distribution of GMC's. As the most massive objects in the galaxy they are also basic to the dynamics of the disk.

2. SUMMARY OF PREVIOUS RESULTS ON RADIAL DISTRIBUTION OF CO EMISSION

The most striking large scale characteristic of molecular clouds in the galaxy is their concentration in the galactic center region and in a ring at a galactocentric distance (R) extending from 4-8kpc. Both of these features are in sharp contrast to the flat atomic hydrogen distribution. The shape (see Figure 1) and magnitude of the effect have remained unchanged since the original CO survey by Scoville and Solomon (1975) of 90 points in the galactic plane, carried out with the NRAO 36-foot antenna (beamwidth of 1!1 at the CO wavelength of 2.6mm). The observations included a sampling every 1° in longitude from $\ell = 0°$ to $\ell = 90°$.

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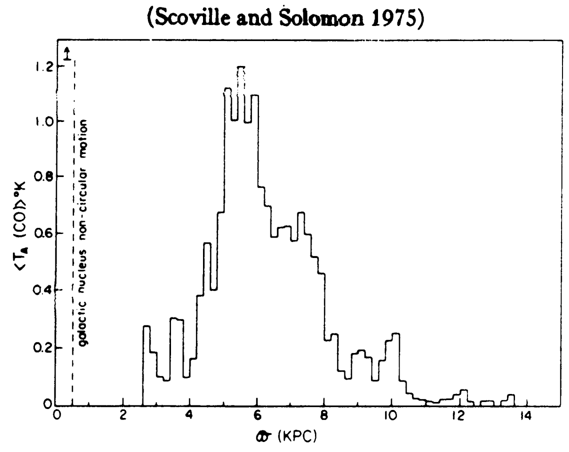

Figure 1.
Distribution of CO emission as a function of galactocentric distance showing the 5.5kpc peak and ring like structure between 4-8kpc (Reproduced from Scoville and Solomon, 1975, Ap. J. 199 L105)

The use of the small beam combined with the large cloud sizes made it possible to truly sample the cloud distribution rather than just the distribution of emission from confused sources. The interpretation of the well defined features in the line profiles was in terms of emission from discrete clouds. Estimates of the total mass were based on counting clouds to obtain the number of clouds per unit length, using 3 observations of ^{13}CO emission in the plane combined with radiative transfer calculations to estimate the H_2 density within each cloud and adopting a standard path length of 20pc through each cloud. The necessity for more ^{13}CO observations to obtain better quantitative densities was stressed; however the ratio of the total number of clouds at the 5kpc peak compared to 10kpc, the essential feature of the distribution, can be deduced just from the counting of emission lines and the galactic rotation law. The main results are summarized in Table 1.

A subsequent ^{12}CO survey was carried out by Burton and Gordon (see Table 1) with higher sensitivity and containing about 5 times as many points, all at $b = 0^o$. Gordon and Burton quoted a mass and H_2 density based on an assumed ^{13}CO intensity ratio of 1/3 for all emission, but ^{13}CO was not observed. Burton (1976) has reviewed this work. Cohen and Thaddeus have presented ^{12}CO survey results, including data taken out of the plane, obtained with a 4 foot antenna. The scale height was observed to increase between 5 and 8kpc. The general shape of the radial distribution was similar to that found by the earlier surveys except for a total absence of emission between 2 and 4kpc. These results however are not confirmed by the new observations reported here.

3. OUTLINE OF FOUR PART SURVEY

In the following we present the principal results of a new four part survey (Solomon, Sanders and Scoville, 1979) designed to determine the distribution and total mass of molecular clouds and consequently star formation regions in the galaxy as well as the properties of the

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TABLE 1.

SUMMARY OF GALACTIC CO SURVEY RESULTS (Prior to 1978)

AUTHORS	RADIAL DISTRIBUTION	H_2 DENSITY	Z (FWHM)	COMMENTS
SCOVILLE & SOLOMON ApJ 199 L105, 1975	"RING" AT 4-7kpc PEAK AT 5.5kpc AND AT <400pc MIN. AT 2-4kpc	1-5cm^{-3} 5cm^{-3} AT PEAK	130pc (FWHM) 2 ℓ's	TOTAL MASS 1-3x10^{9}M$_\odot$ MASS PER CLOUD ~10^{5}M$_\odot$,MOLECULES IN CLOUDS STRONG CLUMPING MORE H_2 THAN H
BURTON et al. ApJ 202, 30 1975	4-8kpc	NOT GIVEN	70pc	CONSIDERABLE STRUCTURE
GORDON & BURTON ApJ 208,346 1976	4-8kpc RING MAX. at 5.7kpc MIN. at 2-4kpc	2cm^{-3} AT PEAK	117pc 1 ℓ	CLOUD DIAMETER 5-17pc 10^6 CLOUDS TOTAL STOCHASTIC MODELS TOTAL GAS INCREASING TO CENTER
COHEN & THADDEUS ApJ 217 L155	4-8kpc RING NO EMISSION AT <4kpc	NOT GIVEN	90-170 pc	SCALE HEIGHT INCREASES BETWEEN 5-8kpc CENTER BELOW b=0^o

individual clouds in terms of size, mass, temperature, stability and age. The first three parts containing about 1500 separate observations have been carried out at the NRAO[1] 36-foot antenna with some additional data from the FCRAO 45-foot antenna. The purpose and type of observations are:

I. H_2 Densities from ^{13}CO Observations.

II. Size and Mass of Molecular Clouds from High Spatial Resolution ^{12}CO Strips in ℓ and b.

III. Galactic Distribution in Radius, R and Height Above the Plane Z, Total Mass and Possible Spiral Structure (if any) from ^{12}CO Observations every 1^o in ℓ, every 12'in b.

IV. Two Dimensional Maps of Selected Clouds to determine individual cloud Size, Shape and Mass.

4. ^{13}CO OBSERVATIONS

The use of CO as a tracer of molecular hydrogen within molecular clouds and of molecular clouds throughout the galaxy, is based on two related premises. First the CO to H_2 abundance ratio is assumed to be reasonably constant and therefore a measure of the CO column density will

[1] Operated by Associated Universities, Inc., under contract with the NSF.

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yield a measure of the hydrogen column density, and secondly the photons emitted by CO, and consequently the line intensity, result from collisions between H_2 and CO.

However, the high intensity and ubiquity of the ^{12}CO emission, which allows extensive observations of otherwise unknown molecular clouds, is due to a high opacity and therefore is not easily interpreted in quantitative terms. At moderately high densities the ^{12}CO intensity reflects primarily the cloud temperature. In order to quantitatively interpret the CO survey of the galaxy and test the validity of the molecular distribution derived from ^{12}CO, we have observed the much less abundant isotope ^{13}CO at even galactic longitudes with $b = 0^o$ and $10^o \leq \ell \leq 44^o$ and $\ell = 0^o$.

4.1 Radial distribution of ^{13}CO

A sample spectra of ^{13}CO and ^{12}CO is presented in figure 2; the close correspondence between them is evident but the intensity ratio T^{13}/T^{12} is different in each feature. In our total sample the observed ratio varies from less than 1/20 to 1/3 with an average value of 1/5.5. In figure 3 we compare the ^{13}CO and ^{12}CO emissivity, $J = T^* dv/dr$, from the same data set, as a function of distance from the galactic center. The extremely good agreement of the radial distribution between ^{13}CO and ^{12}CO establishes the reality of the high concentration of molecules between 4-8kpc as deduced from ^{12}CO. Thus ^{12}CO emission is a good indication of the relative mass distribution in the galaxy even though it is saturated. This can be explained if the total emission depends on the number of clouds rather than the intensity of each cloud.

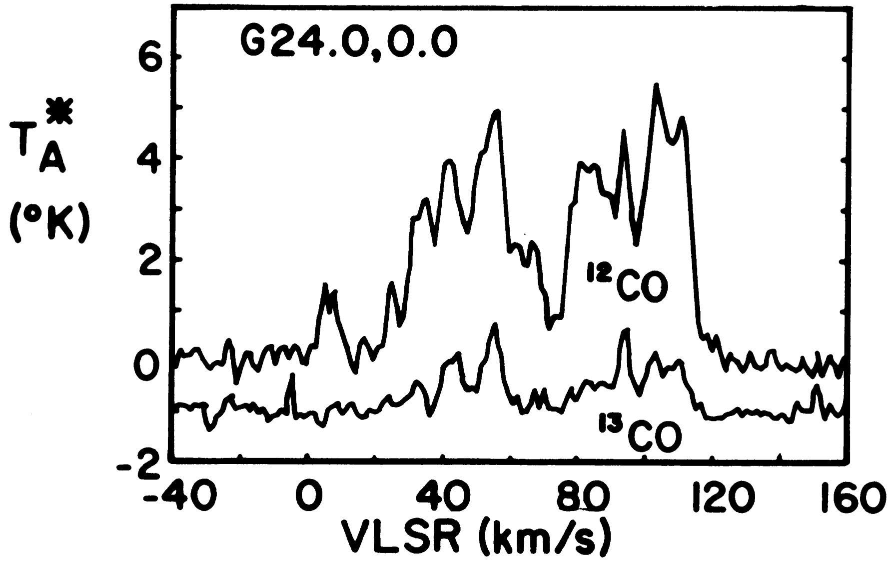

Figure 2. Sample spectra of ^{12}CO and ^{13}CO. The intensity is in units of T_A^*. $T_A^*/\eta = 1.6\ T_A^*$.

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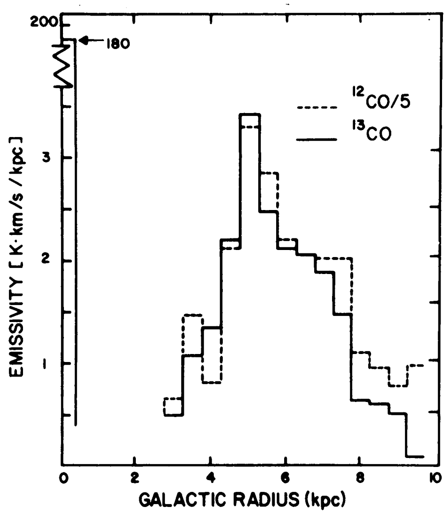

Figure 3. The ^{13}CO and ^{12}CO emissivity, J, as a function of galactic radius.

4.2 Calibration of H_2 densities

We have analyzed the ^{13}CO data and relative intensities T^{13}/T^{12} using the escape probability approximation for radiative transfer (Scoville and Solomon 1974). Assuming $^{12}CO/^{13}CO = 40$, we find that a good value for $^{13}CO/H_2$ is 5×10^{-7} corresponding to $CO/H_2 = 2 \times 10^{-5}$ or about 3% of C in CO. As can be seen from figure 3, there is no systematic variation of T^{13}/T^{12} with galactic radius and we therefore assume that $^{13}CO/H_2$ and $^{13}CO/^{12}CO$ are constant, in interpreting the data. There is insufficient sampling at $R \geq 9$kpc to judge the reality of the apparent decrease in T^{13}/T^{12}. The one observation of the galactic center shows $T^{13}/T^{12} = 1/7$, very similar to the rest of the galaxy. Using the above values and a typical observed ^{12}CO intensity ($T_A^* = 9$-13K) which determine the stimulated emission factor and partition function, the H_2 column density can be shown to be

$$N(H_2) = 3.6 \times 10^{21} \int T\,(^{13}CO)\,dv \ \mathrm{cm}^{-2} \quad ,$$

or

$$\frac{N(H_2)}{\Delta r} = \bar{n}_{H_2} = 1.2\ J\,(^{13}CO)\ \mathrm{cm}^{-3} \quad ,$$

where J [K·km/s/kpc] is the ^{13}CO emissivity. Since the observed mean value at $3 < R < 9$ kpc of J^{12}/J^{13} is 5-6, we adopt $\bar{n}_{H_2} = 0.2\ J\,(^{12}CO)$ in order to derive molecular hydrogen densities and total mass from the large scale ^{12}CO survey which samples emission from a full range of b and ℓ (see section 6). The mean H_2 density at 5.5kpc is therefore $n_{H_2} \sim 5\ \mathrm{cm}^{-3}$. This result is however sensitive to the true ratio $^{13}CO/H_2$.

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5. CLOUD SIZE AND MASS DISTRIBUTION FROM HIGH SPATIAL RESOLUTION DATA

The goal of these observations is to determine the nature of the objects containing interstellar molecules. This project is designed specifically to obtain the cloud properties from a random sample.

Two strips in galactic longitude have been observed at $b = 0.^{\circ}0$, $23.^{\circ}0 \leq \ell \leq 30.^{\circ}5$ with 2' spacing and at $b = -0.^{\circ}6$, $11.^{\circ}5 \leq \ell \leq 16.^{\circ}0$ with 4' spacing. In addition a few strips perpendicular to the plane have been observed at $\ell = 12^{\circ}$, 24° and 30°. The complete data can be found in Solomon et al. (1979) and Solomon and Sanders (1979). The emission in the velocity-longitude plane (Figure 4), summarizing 215 separate observations, shows a very clear breakup into clouds. The approximate galactocentric distance of the features is indicated on the top axis; the concentration in the 4-7kpc region is very striking. The large number of features near the maximum permitted velocity is due to the small radial velocity gradient near the tangential point.

5.1 Cloud size distribution

In order to display the observations in a form convenient for measuring cloud sizes, they have been divided into sections of about 2 1/2 degrees in ℓ; the distance to a feature is calculated assuming it is on the near side of the tangential point, and the displacement in longitude is then converted to apparent displacement parallel to the galactic plane. The result is a drawing showing the projected size versus velocity as in figure 5.

Typical spacing between observations ($R \sim 5.5$kpc, $\ell \sim 27^{\circ}$, $\Delta\ell = 2'$) corresponds to about 3pc and the determination of cloud dimensions has a lower limit of about 10pc. The contour levels in Figures 4 and 5 are in units of $T_A^* = 1$K or $T_A^*/\eta \sim 1.6$K. Cloud sizes at the level of $T_A^* = 3$, 4 and 5K were measured for all high resolution observations along the galactic plane. Clouds were counted only if the size > 10pc at the 4K contour level with at least one contour at $T_A^* = 5$K. Measurement of size was obtained at a constant velocity; the velocity of maximum emission was restricted to a full range of only 3km/s in order for a feature to be designated as a single cloud. As can be seen from the figures, there is significant overlap at $T_A^* \leq 2$K both in velocity and space. The observed sizes are lower limits to the true sizes since the near distance has been assumed, the emission is traced only to the level $T_A^* = 3$K and the size represents a random slice through the cloud. Figure 6 shows the distribution of cloud sizes at the $T_A^* = 3$K ($T_A^*/\eta = 5$K) level. The average cloud size in the sample is 40 pc, a factor of 4 above the minimum detectable size. There are no emission holes inside these regions, although there may be several local maxima. These objects can best be described as Giant Molecular Clouds or possibly GMC Complexes and represent a class of objects which are the most massive in the galaxy.

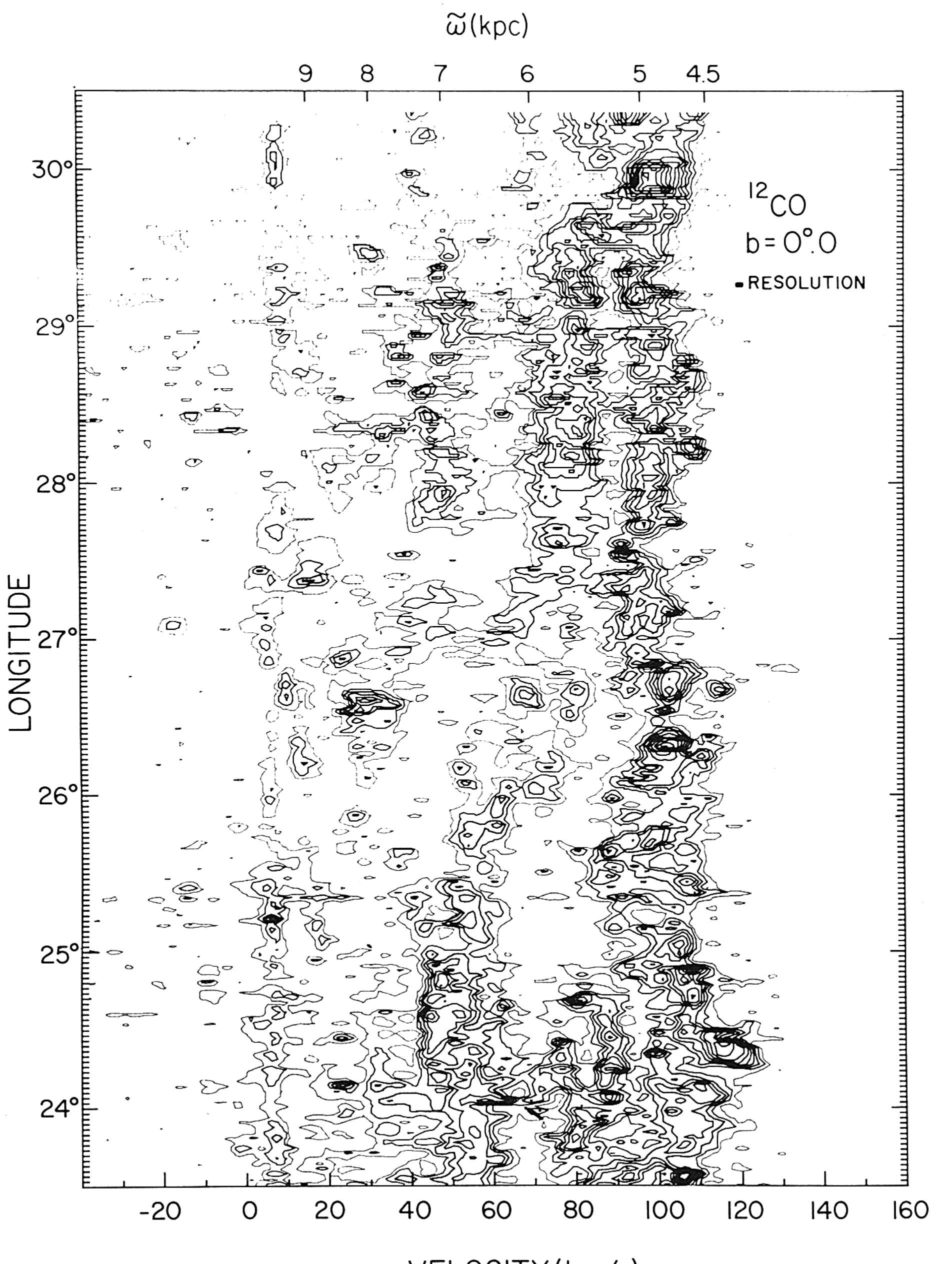

Figure 4. CO emission from data taken every 2' displayed in the longitude-velocity plane. Contour intervals are in steps of $T_A^* = 1K (T_A^*/\eta = 1.65)$. The diagram is a synthesis of 215 separate observations. The resolution is indicated by the black rectangle. The breakup into Giant Molecular Clouds is very striking above the third contour.

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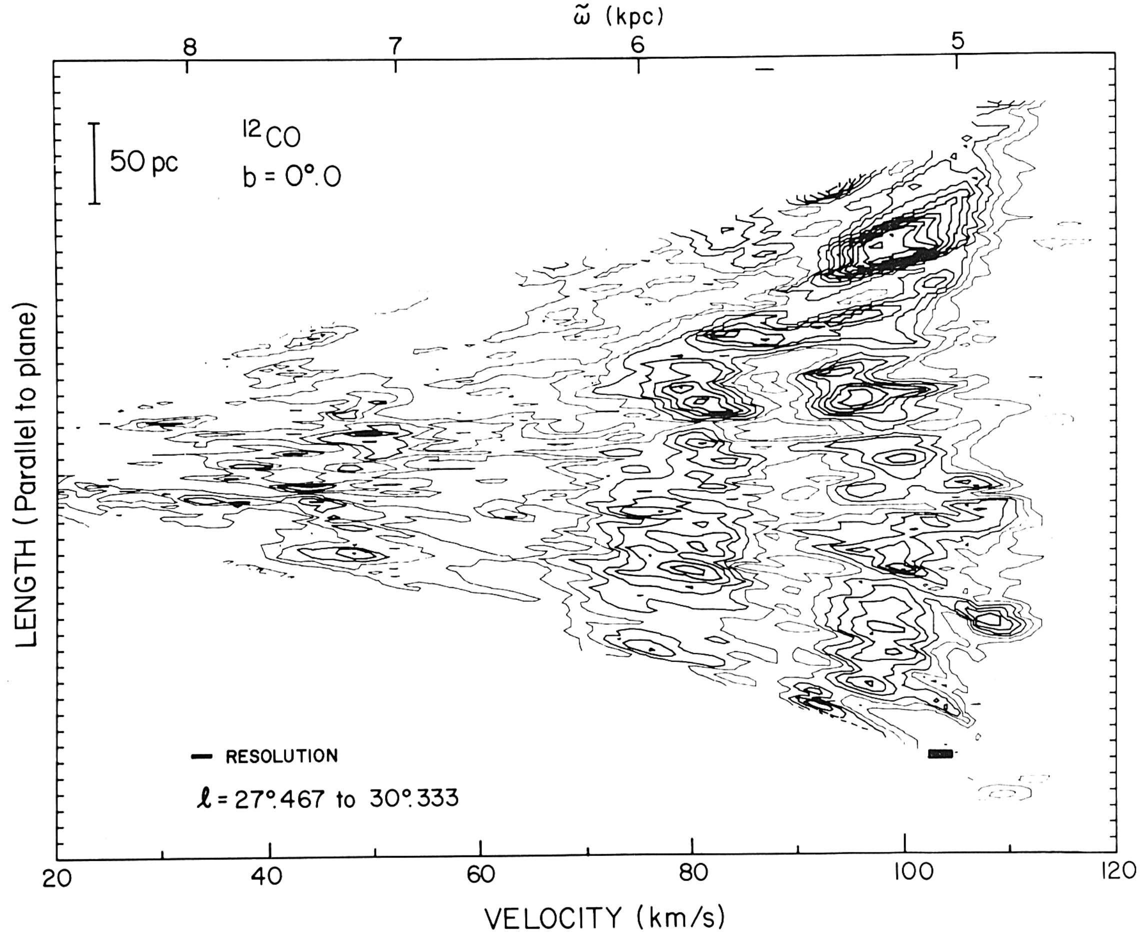

Figure 5. A sample of CO emission showing the sizes of the clouds along the galactic plane. In deriving the sizes, the near distance has been assumed. The resolution is indicated by the black rectangles. Lowest contour unit is $T_A^* = 1K$ ($T_A^*/\eta = 1.6K$) with intervals of 1K.

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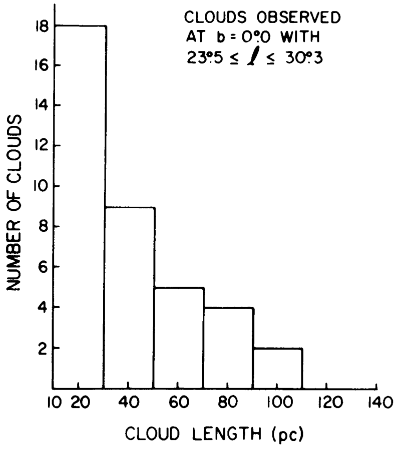
Fig. 6. The distribution of length parallel to the galactic plane for a typical chord intersecting a GMC, (size) determined from 2' resolution mapping parallel to the galactic plane between $\ell=23\overset{\circ}{.}5$ and $30\overset{\circ}{.}5$ at $b=0^{o}$. See text for a description of criteria used for measurement.



With a typical dimension of 40pc and a mean H_2 density of 300 cm^{-3} the mass per GMC in the sample is about $5 \times 10^5 M_\odot$. The density of 300 cm^{-3} is consistent with the observed ^{12}CO and ^{13}CO intensities. Radiative transfer calculations show that $T^{13}/T^{12} = 1/6$ for these conditions. A small fraction of the mass is in condensed cores within the clouds, which are the actual sites of star formation.

The observed distribution of cloud length (Fig. 6) has been obtained from a sample along a line parallel to the galactic plane. This represents a fair sampling of cloud area. In order to obtain the true distribution of cloud lengths a correction must be employed allowing for the fraction of clouds of length Λ in the sample which is $\propto 1/\Lambda$. The total number of clouds in the 4-8kpc ring meeting the selection criteria described above is

$$N(\Lambda)d\Lambda = \frac{N'(\Lambda)}{\varepsilon} \quad \frac{2.55\ Z_{\frac{1}{2}}}{\Lambda} \quad d\Lambda \qquad (1)$$

where N' is the number of clouds counted in the sample (Fig. 6), ε is the fraction of the galactic ring in ℓ and r sampled and $2.55\ Z_{\frac{1}{2}}/\Lambda$ is the ratio of the total number in the disk to the number sampled at $b=0^{o}$. $Z_{\frac{1}{2}}$ is the HWHP height of the cloud distribution from Section 6. We estimate that $\varepsilon \approx 0.05$ for the data at $23\overset{\circ}{.}5 < \ell < 30\overset{\circ}{.}5$, using the radial distribution of Section 6. (See Solomon et al. 1979 for further discussion.

The sample between $\ell = 23\overset{\circ}{.}5$ and $30\overset{\circ}{.}5$ at $b = 0\overset{\circ}{.}0$ contains 38 GMC's. Using the scale height and radial distribution from Section 6, we estimate that this represents approximately 0.75 percent of all clouds, leading to a total of 4000 Giant Molecular Clouds in the Galaxy. The lower limit for counting in this estimate is clouds with a chord larger than 10pc with some CO emission at $T_A^*/\eta > 8K$, ($T_{kinetic} > 11K$) in a random slice through the region.

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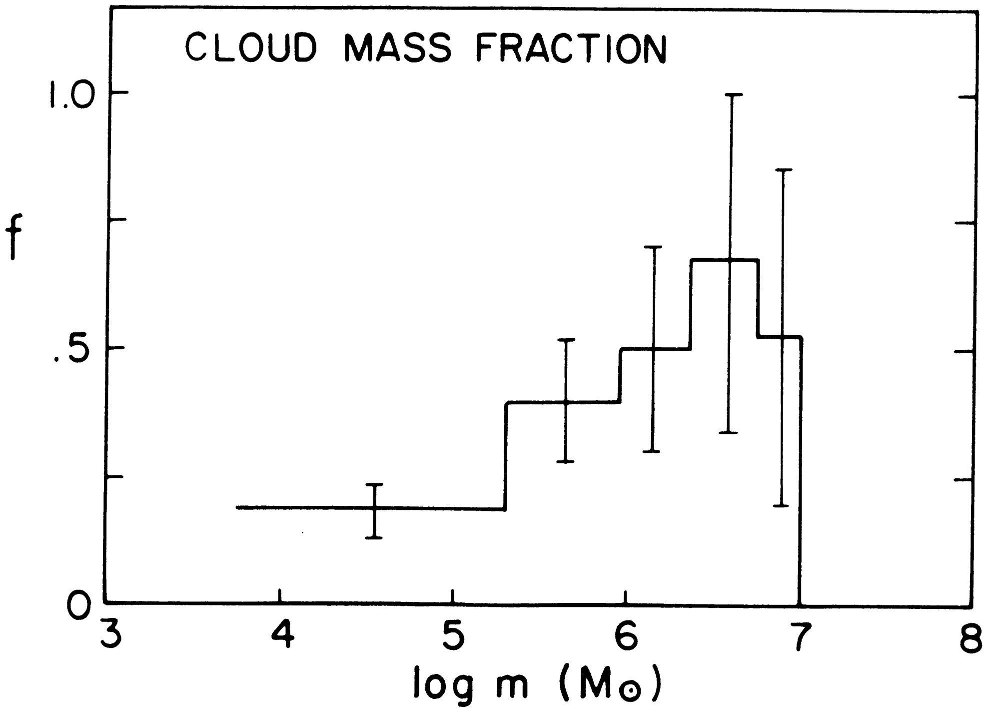

Fig. 7. The fraction of total mass contained in Giant Molecular Cloud Complexes of mass m, per logarithmic interval. Observational selection of Fig. 6 has been corrected by equation (1). The error bars are determined by the sample size. The greatest uncertainty in m stems from the uncertainty in $^{13}CO/H_2$.

5.2 Cloud mass function

The most important parameter in determining the origin and evolution of the clouds is the mass distribution. From our sample of 38 clouds corrected by equation (1) we can derive the fraction of total mass per logarithmic cloud mass interval. In order to proceed from linear size measurements, we assume that the measured length represents a random slice through an irregular cloud and that the true cloud mass can be approximated by a sphere of this dimension with a density $n(H_2) \sim 300\ cm^{-3}$. The effect of elongation along the galactic plane introduces a small error; however the greatest uncertainty comes from the very high mass end of the spectrum where the sampling becomes insufficient since a few GMC's may contain a large fraction of the mass. We have observed no GMC's in this sample with a length (as defined above) > 100pc, and the statistics give large uncertainties in the mass fraction in GMC's > 60pc with $m > 10^6 M_\odot$. Figure 7 shows the observed mass fraction per logarithmic mass interval

$$f = \frac{1}{M}\frac{dM}{d\log m}$$

where M is the total mass in clouds and m is the GMC mass. The total mass of the 38 GMC's is about $4 \times 10^7 M_\odot$. The 4000 GMC's in the galactic ring have a total mass $\approx 2 \times 10^9 M_\odot$. J. Kwan (private communication) has considered theoretical mass distributions for colliding molecular clouds which give reasonable agreement with Fig. 7. From our sample corrected by equation (1) we find $f \propto m^{0.2}$.

The formal gravitational collapse time (free fall time) for these objects is $t_c \approx 3 \times 10^6$ yrs and yet most of the mass in clouds is contained in them. They are clearly not systematically collapsing to form stars since the galactic star formation rate of about $3\ M_\odot$/yr is only a small fraction of the total formal collapse rate. The efficiency of star formation can be defined as the ratio of the observed rate to the formal mass collapse rate in GMC's,

$$\varepsilon = \frac{\left(\frac{dM}{dt}\right)_{\text{observed}}}{\left(\frac{dM}{dt}\right)_{\text{GMC}}}$$

Using $(dM/dt)_{GMC} \approx 3 \times 10^9/3 \times 10^6 = 10^3\ M_\odot$/yr yields $\varepsilon \approx .003$. We thus find that star formation is inhibited by a factor of ≈ 300 compared with the formal free fall time.

6. GALACTIC DISTRIBUTION IN R AND Z.

In the section of the galaxy $-4^\circ < \ell < 70^\circ$ we have obtained about 730 observations of ^{12}CO emission with full velocity coverage, spaced every 1° in longitude and every 12' in latitude out to positions where the total integrated intensity has dropped at least to 1/4 of the maximum ($|b| \sim 2.^\circ0$) and no features other than local clouds are apparent.

The large number of line profiles, showing emission from molecular clouds along the entire line of sight, can be viewed more comprehensively in the form of latitude-velocity contour diagrams; each latitude velocity drawing is a composite of all observations at a single galactic longitude. In figure 8 we present a sample b-v diagram which demonstrates some of the salient features of the distribution. The emission is discrete in both the velocity and spatial dimensions indicating that only a small fraction of the volume is occupied by molecular clouds. The clouds are often centered below $b = 0^\circ$ and there are irregular bumps in the location of the center. Observations confined only to $b = 0^\circ$ will therefore miss significant emission.

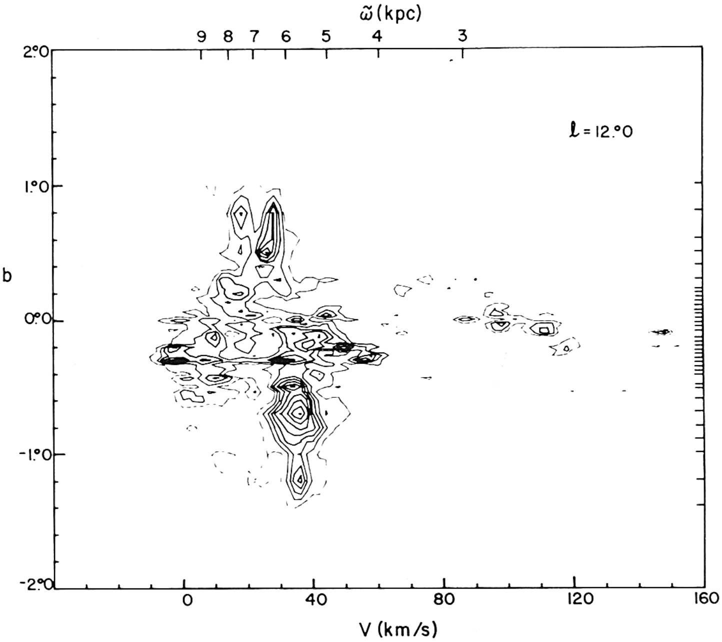

Figure 8. A sample latitude velocity diagram of CO emission from the survey at $\ell = 12^{o}$. The righthand vertical axis tick marks indicate points observed. Each contour interval is $T_A^* = 1K$ ($T_A^*/\eta = 1.6K$)

The intensity is typically $T_A^* = 3\text{-}5K$ or $T_A^*/\eta = 5\text{-}8K$ which translates to Planck brightness temperatures and therefore kinetic temperatures $T_{kinetic} = 8\text{-}11K$. This represents a typical kinetic temperature in a random region of a molecular cloud. Cloud cores with $T_k >> 10K$ are sampled only a small fraction of the time.

The survey data has been analyzed on the assumption of cylindrical symmetry to derive the radial,R,and height,Z,dependence of molecular clouds in the galaxy, the center of the distribution, Z_c, and the total surface emission of CO perpendicular to the galactic plane. The mean molecular hydrogen density and mass has been determined using the ^{13}CO calibration of Section 4.

For the purposes of our analysis the inner galaxy, $R < R_{\odot}$, has been divided into annuli $\Delta R = 0.5$kpc. The emissivity $J = T\, dv/dr$ was computed for all line segments passing through a given annulus determined from our samping in longitude $0^{o} < \ell < 70^{o}$. The appropriate fitting function (assuming cylindrical symmetry) is a double Gaussian which allows for contributions from the "near" and "far" segments along the line of sight with identical galactocentric distance R. Such points at distances r_1 and r_2 from the sun are equidistant from and on opposite sides of the subcentral point. The three variable parameters in the expression for J are the emissivity at the center of the distribution J_o, displacement of the center (from b = 0^o) Z_c, and scale height (half width at half maximum) $Z_{1/2}$.

$$J(R,b) = J_o \exp -\left[\frac{(Z_1-Z_c)}{1.2\ Z_{1/2}}\right]^2 + J_o \exp -\left[\frac{(Z_2-Z_c)}{1.2\ Z_{1/2}}\right]^2 \quad K\cdot km/s/kpc$$

The distance perpendicular to the plane for near and far points contributing to J(R,b) is given simply by $Z_1 = r_1 b$ and $Z_2 = r_2 b$.

The scale height of the molecular cloud distribution $Z_{1/2}$ and the center of the "plane" Z_c are presented in Figure 9. A displacement of Z_c below the b = 0^o plane is found for the entire region 2.5<R<8.5kpc with Z_c = -26pc in the ring. The region $4.5 \leq R < 8.5$kpc shows a relatively constant value of $Z_{1/2} = 60 \pm 9$pc. The HI scale height in this region determined primarily from emission near the loci of subcentral points has an average value of 130pc, about twice that for molecular clouds. (Jackson and Kellman, 1974).

The radial distribution in emissivity $J_o(R)$ over the range 2.5 - 9.5kpc and at the galactic center is presented in Figure 10. We have not included regions exterior to the sun which are inadequately sampled over this longitude range. At the peak of the distribution where $\bar{n}(H_2) \sim 5\ cm^{-3}$, there is a factor of 30 more H nucleons in molecular hydrogen than atomic hydrogen. Even if we assume that the calibration of section 4 has overestimated by a factor of three the ratio of emissivity to $n(H_2)$, by using too low a value of $^{13}CO/H_2$, we still find 10 times more nucleons in H_2 than H.

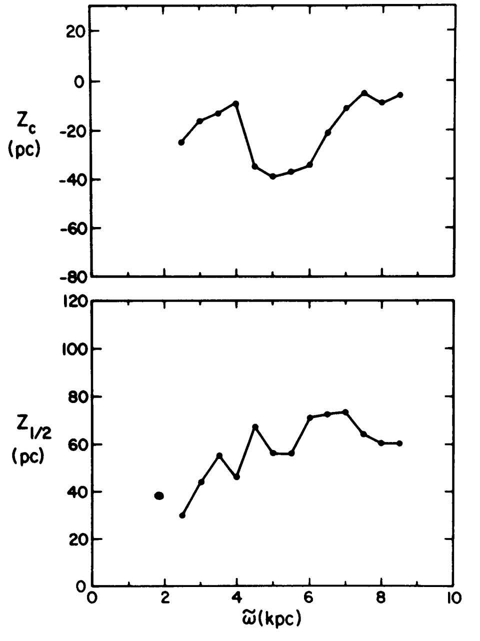

Figure 9. The scale height of molecular clouds in the galaxy $Z_{1/2}$ and the displacement from b = 0^o represented by Z_c as a function of galactic radius.

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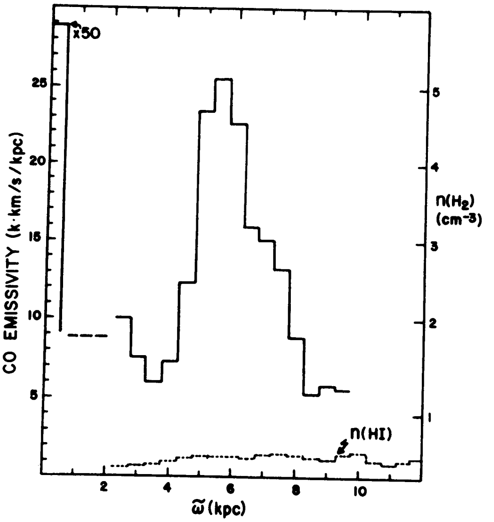

Figure 10. The CO emissivity J_o at the center of the distribution and the mean H_2 density. The transfer from emissivity to H_2 density has employed the ^{13}CO data. (see text). The $^{13}CO/H_2$ ratio is the largest uncertainty in the calibration.

The ring has half intensity at b = - 0°.8 and b = + 0°.3. The total surface density of molecular clouds perpendicular to the galactic plane is presented in figure 11. Integrating between 2 and 9.5kpc, we find a total mass in molecular clouds of 4 x $10^9 M_\odot$. Only approximately 1/15 of the total surface density in the interstellar medium is in atomic hydrogen at the peak of the ring. Again allowing for as much as 10% of available ^{13}C in ^{13}CO the ratio is still only 1/5.

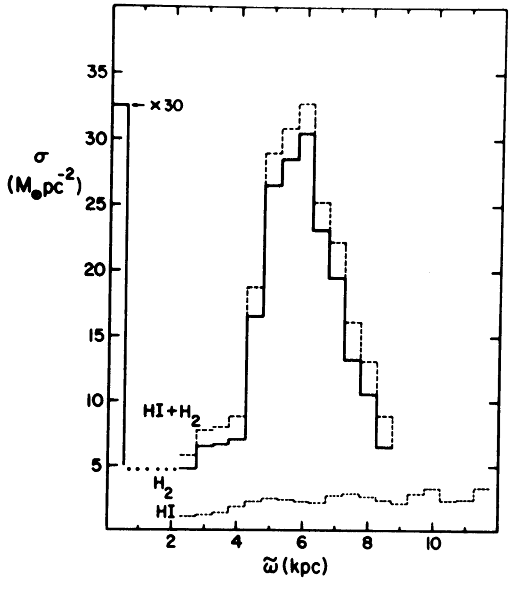

Figure 11. The mass surface density of molecular clouds in the galaxy. The total mass is about $4x10^9 M_\odot$.

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7. TWO DIMENSIONAL ^{12}CO MAPS OF SELECTED CLOUDS

In order to explore the structure of individual clouds in greater detail, a set of 15 cloud features was chosen at random from the initial large scale ^{12}CO survey. The objective was to determine cloud sizes in ℓ and b, orientation with respect to the galactic plane, peak temperatures and the presence of core regions as well as kinematic information on the internal structure of the clouds.

Data for seven objects has been reduced and is summarized in Table 2. All clouds were mapped at 3' resolution. Sizes have been measured to a level $T_A^* = 4K$ and, where sufficient data exists, to $T_A^* = 3K$. The ℓ/b ratio in Table 2 indicates that there is some tendency for elongation along the galactic plane. The average size in ℓ is 34pc at $T_A^* = 4K$ using all 7 clouds and 45pc at $T_A^* = 3K$, using 4 of 7 clouds where sufficient data exists. The ℓ sizes are in good agreement with the high resolution longitude strip results of Section 5. ^{13}CO observations of each cloud have allowed the determination of column densities. Using the measured cloud cross sections and column densities, mass estimates for each cloud were also determined. The average mass is 6.2 x $10^5 M_\odot$ similar to the mass found for a mean cloud size in the high resolution survey.

TABLE 2.

AVERAGE CLOUD SIZES† AT INTENSITY $T_A^*(^{12}CO) = 4K$

ℓ	34pc
b	26pc
maximum	49pc
ℓ/b	1.3
angle††	30°
mass	6.2 x $10^5 M_\odot$

†Sample of 7 clouds in the region $10^\circ \leq \ell \leq 40^\circ, 4 < R < 8$kpc
††Angle of maximum chord from galactic plane

8. SUMMARY: AGE AND ORIGIN OF GMC'S

Although interstellar clouds are generally regarded as extremely young objects ($\leq 10^7$yrs) we show below that the large mass of individual clouds and the large fraction of the ISM in molecular clouds necessitates an age of at least 3 x 10^8yrs. We first summarize the cloud properties, based on the high resolution data (Section 5), in Table 3. The clouds have several small cores with much higher densities and in this sense should be regarded as complexes.

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TABLE 3

AVERAGE PARAMETERS FOR GIANT MOLECULAR CLOUDS

Length $<\text{Area}>^{\frac{1}{2}}$	40 pc
Kinetic Temperature	10K
Density, n_{H_2}	300 cm^{-3}
Mass	$5 \times 10^5 M_\odot$
Number in the Galaxy $4<R<8$kpc	4000

On a galactic scale we have deduced the smoothed out properties for the molecules including all CO emission without considering individual cloud masses. These are summarized from Sections 4 and 6 in Table 4. The largest uncertainty in the mean densities is the $^{13}CO/H_2$ ratio.

TABLE 4

MOLECULE DENSITIES AND SCALE HEIGHT AT 4-8kpc

Mean Density at 4-8kpc, $\bar{n}_{H_2}$	3 cm^{-3}
Scale Height, $Z_{\frac{1}{2}}$	60pc
Center, Z_c	- 26pc
Mass Surface Density, σ	20 $M_\odot/pc^2$
$2\ n(H_2)/n_{HI}$	20
Mass Ratio $\sigma(H_2)/\sigma_{HI}$	10

The age of GMC's, τ(GMC) can be simply determined from the observations by considering the relationship between the total mass in a form available for their formation, M_i, the time scale for formation by a particular mechanism τ_i and the total mass in GMC's M(GMC). In a steady state the total mass in a form is proportional to the lifetime. If form i is the dominant source for GMC's, then

$$\frac{M_i}{\tau_i} = \frac{M(GMC)}{\tau(GMC)} \qquad \text{or} \;, \tag{2}$$

$$\tau(GMC) = \tau_i \; \frac{M(GMC)}{M_i}$$

In the most general case we have

$$\frac{1}{\tau(GMC)} = \frac{1}{M(GMC)} \sum_i \frac{M_i}{\tau_i} \tag{3}$$

The generally accepted mechanism for formation of dense clouds is the compression of the diffuse interstellar medium or low density clouds by a spiral density wave. The time scale for this mechanism is the phase rotation period for the spiral density wave $\tau_R \approx 2 \cdot 10^8$yrs. If all of the interstellar medium represented by HI is available to be compressed, then

$$\tau_{GMC} \geq 2 \times 10^8 \text{yrs} \; \frac{M_{GMC}}{M_{HI}}$$

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From the survey data we have $M_{GMC}/M_{HI} = 2\ \bar{n}_{HI} = 30$ if 3% of C is in the form of CO, and $2\ \bar{n}(H_2)/\bar{n}_{HI} = 10$ if 10% of C is in CO, giving $2 \times 10^9 < \tau_{GMC} < 6 \times 10^9$ yrs a significant fraction of the age of the galaxy. If the compression is viewed as working on the intercloud medium, the time scale is greater than the age of the universe. We conclude that GMC's do not form by compression of diffuse clouds in a spiral density wave.

The largest pool of mass available to form GMC are molecular clouds themselves. Cloud collisions, a mechanism considered for much smaller masses by Field and Saslaw (1965) are therefore an obvious candidate. In this case M_i, from (2) is the total mass in clouds available for collision with the GMC. What is clear from the mass distribution of clouds is that at least half of the total mass is in GMC's.We therefore take $M(GMC)/M_i = 1$ for this case and τ_i becomes τ_c, the growth time for a GMC by collisions. We have for a GMC of mass m ,

$$\tau_c \sum_j n_j\ \sigma\ v_j\ m_j = m(GMC) \tag{4}$$

with n_j clouds of mass m_j; σ is the GMC crossection πr^2. Substituting $\sum n_j m_j = \bar{n}_{H_2}\ m_{H_2}$ and $m = 4/3\ \pi\ r^3 n_{H_2}$ gives

$$\tau(GMC) = \frac{n_{H_2}}{\bar{n}_{H_2}} \quad \frac{4/3\ r}{v} \tag{5}$$

when v is the weighted velocity of the clouds represented by $\bar{n}_{H_2}$. For our current estimate we merely adopted $\bar{n}_{H_2}$ from Table 4 using all available mass, n_{H_2} and r from Table 3 and set v = 10 km/sec giving

$\tau(GMC) = 3 \times 10^8$ yrs.

This age which is 100 times the collapse time may be a lower limit, since we have assumed an equal mass in small cold clouds to that observed in GMC's.The problem of star formation in GMC is then one of an overabundance of opportunities and the question is not how do stars form but rather, why is star formation so inefficient in the current stage of galactic evolution.

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DISCUSSION

Stark: In the bulk of your data, what is the antenna temperature of the noise and of the baseline ripple?

Cohen: The 1σ noise level is always less than 0.3 K in a 500 kHz bandwidth spectrum. The baseline curvature is generally about 0.1 K and is always less than the 1σ noise.

Solomon: $\Delta T_{rms} \simeq 0.3$ K. The baselines in our earliest data have some ripples of order 0.5 K but the recent data have negligible ripples. Some of our data (including ^{13}CO) has $\Delta T_{rms} \sim 0.1$ K.

Strom: Optical photographs of M33 reveal dust clouds with $\tau_V \geq 1$ of sizes ≥ 10 arc sec (linear size $\gtrsim 30$ pc). Many of the clouds lie outside the spiral arms, in the disk of M33. Hence, optical observations of M33 suggest the presence of clouds, comparable in dimension with those Solomon reports for our own Galaxy, outside the arms.

Stecker: Concerning the important question of the absolute amount of H_2 in the 5-kpc annulus, have you made any assumptions to account for possible large-scale radial abundance gradients of [C]/[H] and [O]/[H] between R = 5 and 10 kpc?

Solomon: No. Our observations of the $^{13}CO/^{12}CO$ intensity ratio as a function of galactic radius do not show an increase with decreasing R. If $^{13}CO/H_2$ and $^{12}CO/H_2$ were both increasing inward we would expect to observe increasing saturation of ^{13}CO. The stronger emissivity at 5 kpc results primarily from a larger number of clouds and not from differences in the emissivity of individual clouds.

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