STAR FORMATION IN OUTER GALAXY MOLECULAR CLOUDS

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ABSTRACT. A variety of observations of molecular clouds outside the solar circle (mostly around R = 14 kpc) are reported. Maps of CO, ^{13}CO ($J = 1 \rightarrow 0$) and CO ($J = 2 \rightarrow 1$) emission are discussed. Cloud sizes and masses range up to the GMC class. However, envelope kinetic temperatures are lower than those in GMCs in the molecular ring. Continuum observations, using the VLA at 6 cm and 20 cm, and far infrared observations, taken on the Kuiper Airborne Observatory, suggest the presence of newly formed late O and early B stars.

1. INTRODUCTION

With the observation of a significant amount of CO emission from clouds well outside the solar circle (Kutner and Mead, 1981), it became clear that there is much to be learned by studying the outer galaxy.

One intriguing possibility is to use the outer galaxy in comparison with the inner galaxy (molecular "ring"). By comparing star formation in two different environments, we can see which features are important in determining the efficiency of star formation and the initial mass function. The outer galaxy environment might be expected to be different from that in the inner galaxy for a number of reasons: (1) The clouds in the outer galaxy may receive less cosmic ray heating. (2) With a lower density of clouds in the outer galaxy, the frequency of cloud-cloud collisions is lower. (3) The time between passages through a spiral arm is greater in the outer galaxy.

An advantage of studying the outer galaxy is that there is no distance ambiguity. (All kinematic distances in this paper are calculated on the assumption of a flat rotation curve, and $R_o = 10$ kpc and $v_o = 250$ km/s, Blitz 1979). With distances known, we can address a number of large-scale and small-scale questions:

(1) What is the radial distribution of molecular hydrogen, $M_{H2}(R)$? In studying this, we must worry about variations with R in the conversion factor from CO luminosity to cloud mass with R (e.g. Kutner and Leung 1984).

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(2) What is the z-distribution (perpendicular to the galactic plane) of molecular material in the outer galaxy? We are interested in both the thickness of the disk and the location of the midplane. In particular, we would like to know if the H_2 distribution follows the warp and flare evidenced in the H I.

(3) Is there evidence for spiral arms in the distribution of CO emission? An additional reason for the outer galaxy being a good place to study this is that the arms in other galaxies appear to become more distinct as they get farther from the center.

(4) What is the cloud size distribution in the outer galaxy? How does it compare with that in the inner galaxy?

(5) What are the cloud physical conditions? How do they compare with those in the inner galaxy?

(6) Is there evidence for massive star formation in the outer galaxy? How does its efficiency compare with that in the inner galaxy?

(7) How do isotopic abundances vary from the inner to the outer galaxy?

In order to pursue the answers to these, questions we have undertaken two sets of CO observations, a large-scale, very undersampled, survey, and more detailed observations of individual clouds.

The results of the large-scale mapping have been presented, in part, in Kutner (1983) and Kutner and Mead (1984). The data consist of a series of strips in ℓ and b. Generally, the spacing along the strips is 0.1° (or about 5 times our beamwidth). Most of the data is in the first quadrant, but there is some in the second and third quadrants. To summarize those results: (1) The mass of H_2 outside the solar circle is estimated to be 5 x 10^8 $M_\odot$, as compared with 1 - 2 x 10^9 $M_\odot$ inside the solar circle. (For comparison, the corresponding numbers for H I are 2 x 10^9 $M_\odot$ outside and 1 x 10^9 $M_\odot$ inside [Henderson *et al.*. 1982]. (2) There is evidence for an armlike feature, some 14 to 15 kpc from the galactic center in the first quadrant, possibly extending over at least 90° in galactic azimuth. (3) The molecular material follows the H I warp in the outer galaxy. (4) The galactic plane flares in H_2, as it does in H I. The thickness of the CO emitting layer is about 3 times as great at R = 15 kpc as it is at R = 7 kpc.

The survey data was used to select some 50 clouds for further study. Some were chosen because they appeared interesting on the survey data, and others were selected randomly. The locations of the selected clouds are shown in Figures 1 and 2. In Figure 1, the clouds are depicted as they would be viewed from above the galactic plane. It can be seen that most of the clouds are associated with the 14 - 15 kpc armlike feature, mentioned above. In Figure 2, the height above or below the plane, z, is shown as a function of ℓ The warp is clearly seen. The rest of this paper will be devoted to individual cloud properties.

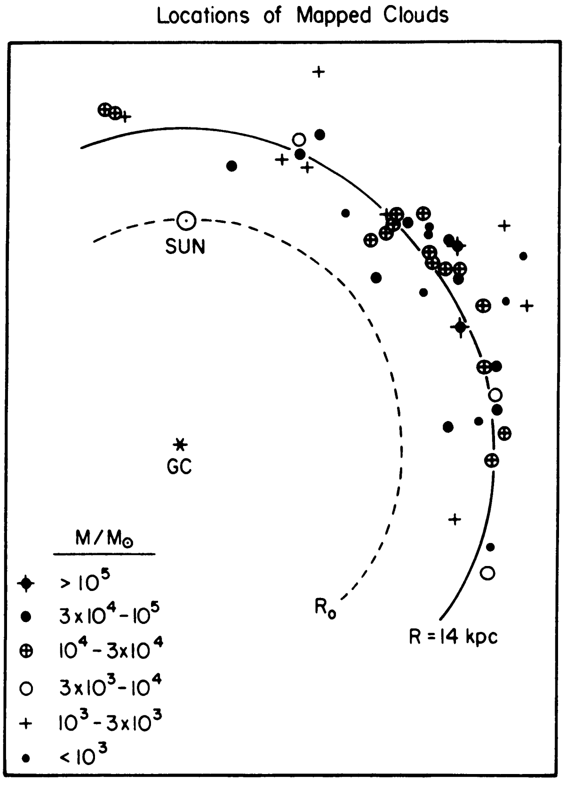

Figure 1 -

Locations of mapped clouds. Kinematic distances are based on a flat rotation curve, with R_o = 10 kpc and v_o = 250 km/s. Symbols represent cloud masses, as indicated. Masses are derived from CO integrated intensities, as described in the text. The dashed curve represents the solar circle, and the solid curve is a circle 14 kpc from the Galactic Center.

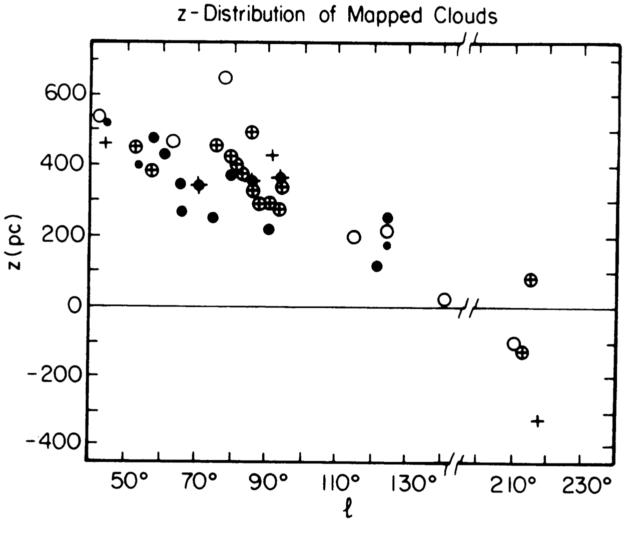

Figure 2 -

Height of clouds in Figure 1 above or below the Galactic plane. z values are based on galactic latitude, b, and kinematic distances. The effect of the warp is clearly seen. The figure also gives a feeling for the thickness of the plane.

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2. MOLECULAR OBSERVATIONS

Observations were made with the NRAO[1] 11m (amd, subsequently, 12m) telescope. CO ($J = 1 \rightarrow 0$) maps, with 70" resolution, were made of 35 clouds, and ^{13}CO maps were made of parts of 10 clouds. Following the resurfacing of the 12m telescope, CO ($J = 2 \rightarrow 1$) maps, with 35" resolution, were made of parts of 11 clouds. Samples of the spectra are shown in Figure 3. In this Figure, it is important to note that the angular size of each box (approximately one beamwidth), translates into a few parsecs at the large distances of the clouds. Therefore, though the clouds do not subtend large angles, their linear dimensions are many of parsecs, typical of giant molecular clouds (GMCs) in the inner galaxy.

However, it is apparent from these spectra that the CO ($J = 1 \rightarrow 0$) lines are weaker than those in inner galaxy GMCs. This statement applies to both the peak line temperatures in the cloud cores, and the envelope, or more uniform, regions. These weaker lines may result from beam dilution, or from emission which is inherently weaker. The higher resolution of the CO ($J = 2 \rightarrow 1$) lines give us information on the question of beam dilution. A comparison of Figures 3c and 3d shows that the $J = 2 \rightarrow 1$ lines are stronger, and more strongly peaked than the $J = 1 \rightarrow 0$ lines in the indicated cloud core. Also, Kutner and Mead (1984) showed that, for clouds at a common distance from the galactic center, there is a falloff in peak line temperatures with distance from the sun. We therefore conclude that the CO temperatures in the cloud cores are beam diluted.

The same is not likely to be true of the cloud envelopes. In the envelopes, we see extended regions of approximately constant line intensity from position to position, with approximately equal line intensities in both the $J = 1 \rightarrow 0$ and $J = 2 \rightarrow 1$ lines. One possibility is that the CO optical depths are much lower in these clouds than in inner galaxy GMCs. However, this is ruled out by two lines of reasoning: (1) The ^{13}CO lines are a factor of about 3 weaker than the CO lines. This is essentially the same ratio as found in the inner galaxy clouds. If the CO optical depths were low in the outer galaxy clouds, the ^{13}CO lines would be much weaker than we observe. (2) If the CO lines were not optically thick, one wouldn't expect the approximate equality between the $J = 1 \rightarrow 0$ and $J = 2 \rightarrow 1$ lines. Therefore, the CO optical depths in the outer galaxy clouds must be comparable to those in inner galaxy clouds.

We must therefore explain the weaker CO emission by saying that the excitation temperature, T_x, is lower. The lower T_x may result either from subthermal excitation, or from a lower kinetic temperature, T_k. We first consider the possibility of subthermal excitation. Such excitation would result from a combination of insufficient H_2 density, n_{H2}, and CO column density, N_{CO}. The N_{CO} is important, because trapping of radiation can contribute to the thermalization of a transition. We have already argued, above, that the CO optical depths (and, therefore, column densities) must be normal in these clouds. Therefore, if the excitation is subthermal, it must result from a low n_{H2}. However, if the rate of collisional excitations is low, then differences in trapping will result in large excitation temperature differences between CO and ^{13}CO. This would result in a very large $CO/^{13}CO$ intensity ratio, which we do not observe. We must therefore conclude that the

[1] The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under contract with the National Science Foundation.

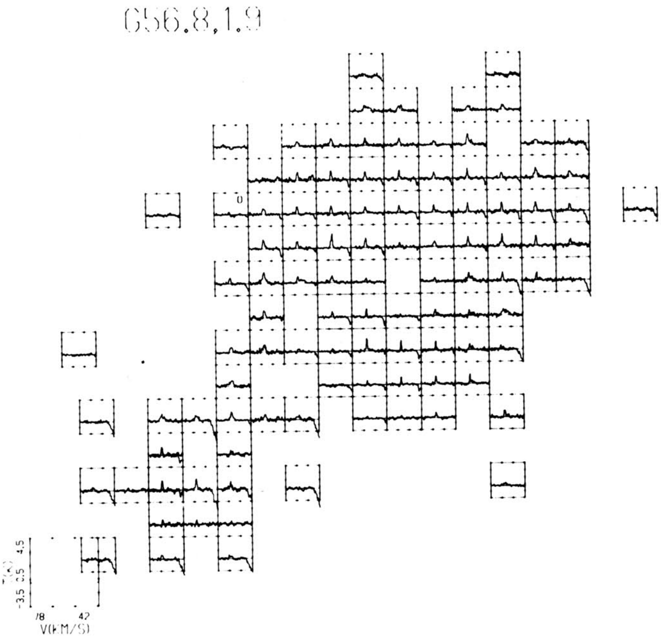
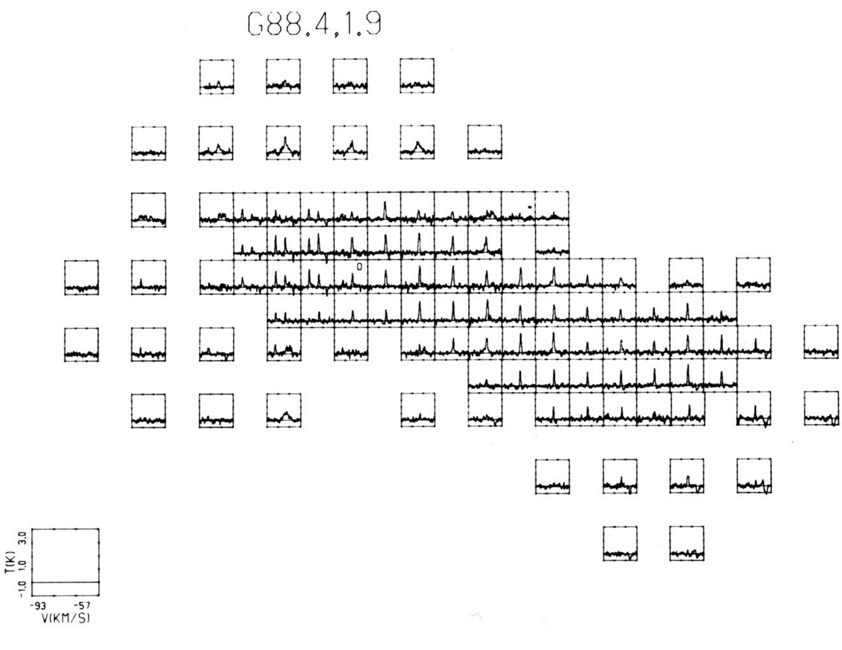


Figure 3a

Figure 3b



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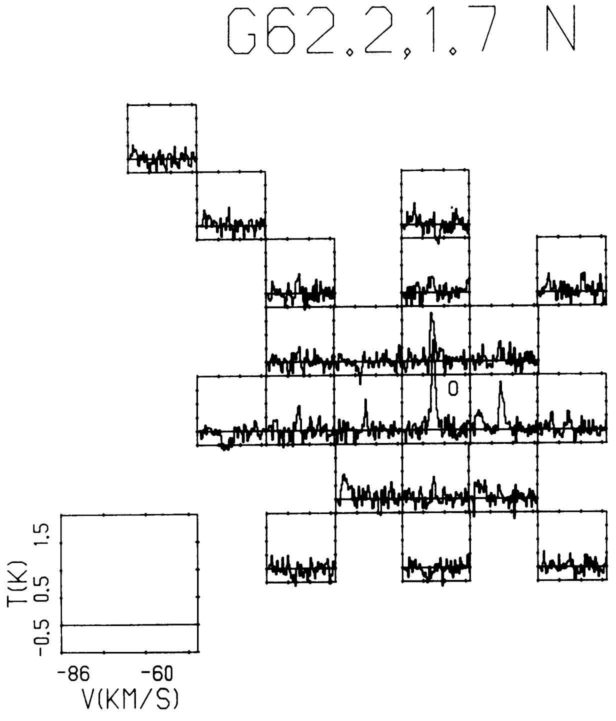

Figure 3c

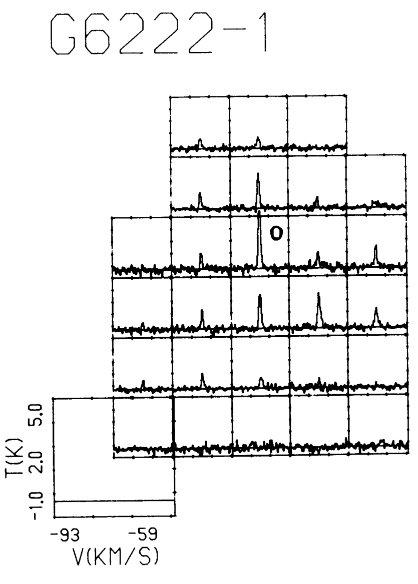

Figure 3d

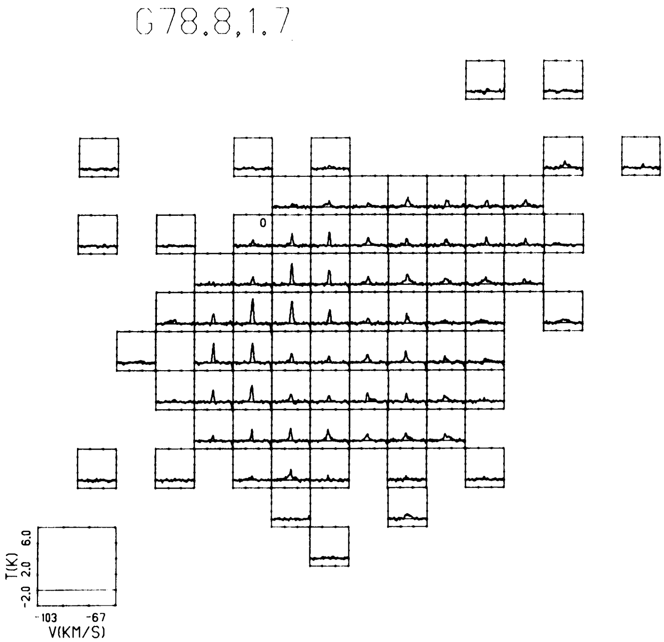

Figure 3e

Figure 3f

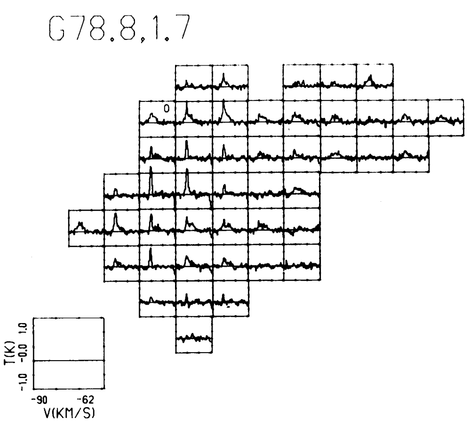

Figure 3g

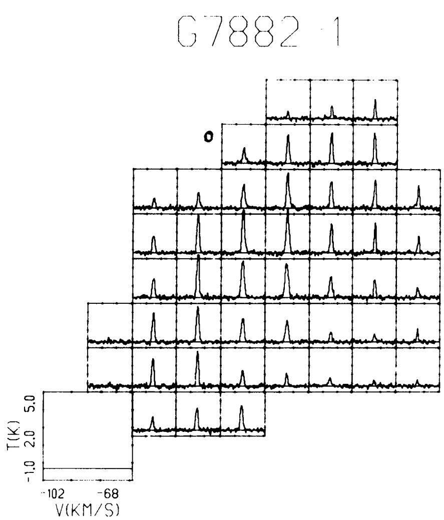

Figure 3 - Representative spectra. In each map, one box represents one beamwidth, 60" for the CO and ^{13}CO (J=1-0) and 30" for the CO (J=2-1). Maps were made in RA and DEC offsets, with north up and east to the left. A larger box at the lower left of each map gives the line temperature (expressed as T_R^*) and velocity scales for all of the boxes in that map. Each map has one reference position, marked with a "O". This can be used for lining up maps of different species within the same cloud.

a - G56.8+1.9. At d = 16.0 kpc and R = 13.5 kpc, each box corresponds to 4.7 pc. This is the CO (J=1-0) map.

b - G88.4+1.9. For the nearer component (v_{lsr} = -63 km/s), d = 9.2 kpc and R = 13.4 kpc, so each box corresonds to 2.7 pc. For the other component (-79 km/s), d = 11.0 and R = 14.6 kpc, so each box corresponds to 3.2 kpc. This is the CO (J=1-0) map.

c - G62.2+1.7. This is the CO (J=1-0) map. For this cloud, R = 14.3 kpc and d = 15.8 kpc, so each box represents 4.6 pc.

d - G62.2+1.7. This is the CO (J=2-1) map. Each box is 2.3 pc. A comparison of Figures 3c and 3d shows the effects of beam dilution, as the J=2-1 line is stronger and more sharply peaked, a result of the better angular resolution at the higher frequency.

e - G78.8+1.7. This is the CO (J=1-0) map. For this cloud, R = 14.5 kpc and d = 15.8 kpc, so each box represents 3.7 pc. A 6cm continuum source, with approximately a 1' extent, has been found 1.5' south and 0.5' west of the "O" position.

f - G78.8+1.7. This is the ^{13}CO (J=1-0) map. The linear scale is as in 3e.

g - G78.8+1.7. This is the CO (J=2-1) map. Each box represents 1.9 pc.

Table 1

Far Infrared Results and Source Properties

Source	α(1950) h	m	s	δ(1950) °	'	"	Sv(100μm)[a] (Jy)	Sv(50μm)[a] (Jy)	d (kpc)	R (kpc)	T_D[b] (K)	L[c] ($L_\odot$)	Spectral[d] Type
G65A	19	49	25.1	29	10	26	12±2	< 6	15.5	14.5	< 41	~2x10³	B3-B2
G69B	19	59	03.3	32	54	03	< 35	50	13.4	13.6	---	< 1x10⁴	< B0.5
G69C	19	59	15.7	33	02	50	865±200	775±200	13.4	13.6	50±3	2x10⁵	07
G84A	20	42	18.9	45	20	27	< 20	< 30	12.1	15.0	---	< 6x10³	< B1
G84C	20	42	47.8	45	15	53	65±3	< 16	12.1	15.0	< 34	~ 6x10³	B1-B2
G88C	20	56	56.0	48	22	58	< 15	< 25	9.4	13.5	---	< 3x10³	< B2
G89A	20	59	54.6	48	43	13	95±10	118±4	9.8	14.0	56±3	1.5x10⁴	B0.5
G89B	21	00	53.1	48	48	21	< 20	< 30	9.8	14.0	---	< 4x10³	< B2
G93A	21	16	42.1	51	37	12	< 15	< 30	9.8	14.0	---	< 3x10³	< B2

[a] Errors are statistical only; calibration uncertainty is ±30%; for G69C, the errors include estimates of uncertainties in integrating map.
[b] A λ^{-1} emissivity law was assumed.
[c] Includes only ~ 40-150 μm flux; for G65A and G84B, only ~ 70-150 μm flux.
[d] Uncertain to ~ 2 subclasses in B1-B5 range; upper limits imply "later than".

CO is thermalized (or very close to it), and that the T_K is low, probably of the order of 7 K. We have already suggested that this lower T_K could arise from a lower cosmic ray flux in the outer galaxy.

We now look at the cloud masses. In their analysis of CO as a tracer for H_2 column density, Kutner and Leung (1984) show that, for low T_k, the ^{13}CO column density, calculated on the assumption of equal excitation temperatures, greatly underestimates the true column density, and is not a reliable tracer. The integrated CO intensity, I_{12}, is a much better tracer under those circumstances. However, they show that the conversion factor, NH_2/I_{12}, is a strong function of T_k, varying approximately as $T_k^{-1.3}$. Therefore, while a factor of 2×10^{20} cm^{-2}/K-km/s may be appropriate for the warm GMCs in the molecular ring, we have adopted a value of 4×10^{20} cm^{-2}/K-km/s for the outer galaxy clouds. Using this conversion factor, we have derived the cloud masses indicated in Figure 4. We see that, for the clouds mapped, most of the mass is in clouds with GMC range masses, $\sim 10^5$ $M_\odot$. We also have found at least one complex (whose individual clouds have not all been mapped, so they don't show up in Figure 4) whose mass is about 10^6 $M_\odot$, comparable to the GMC complexes in the inner galaxy.

3. EVIDENCE FOR STAR FORMATION

Many of the CO maps show peaking and broadening of the lines that is typical around regions of massive star formation in inner galaxy GMCs. It is therefore natural to search for other indicators of massive star formation in the outer galaxy clouds. Two such indicators are thermal radio sources, indicating the presence of H II regions, and far infrared sources, indicating dust being heated by embedded stars.

The search for radio sources was carried out at the NRAO Very Large Array (VLA). The smallest (D) configuration was used for 6cm observations, and the next larger (C) was used to obtain 20cm data at the same resolution. The observations at two wavelengths were necessary to separate thermal from non-thermal sources. The commensurate configurations were used so that a structure of a given angular size would have the same fraction of missing flux at each wavelength, giving an accurate spectral index. The 20cm data were taken more recently and are still being analyzed, so we present mostly the results of 6cm observations. The full data set will appear in Mead, Kutner, and Evans (1986).

So far, 19 clouds have been searched for radio emission, and we find extended (with a 15" beam) 6cm sources near the CO peaks of all but 3. Of course, the 20cm data will be needed before we can say, with some certainty, that they are H II regions. In addition, the definite association of a source with a cloud would be more secure with the observation of a recombination line close to the CO velocity. Figure 5 shows some samples of 6cm continuum contours, superimposed on the CO contours for the given clouds.

We have also searched for far infrared emission from clouds with circumstantial evidence for star formation activity. These observations were carried out from the NASA Kuiper Airborne Observatory (KAO). The observations are described in more detail by Mead, Kutner and Evans (1985) and Mead *et al.* (1986). Observations were made at 50 and 100 μm, with an angular resolution of 40" at 100 μm. The results of the observations are presented in Table 1. Eleven regions in six clouds were searched, and 100 μm emission was found from four. All four are coincident with 6cm continuum sources. In Figure 5 we show the placement of infrared and radio sources on a CO map.

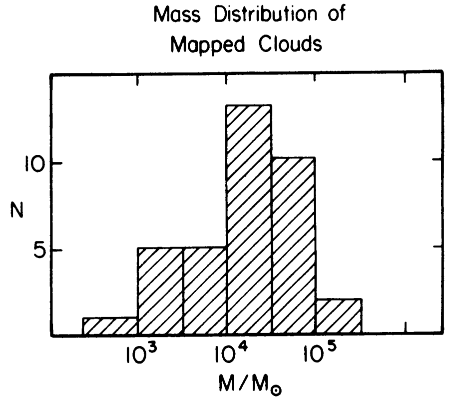

Figure 4 - Distribution of the masses of mapped clouds. Masses are determined from integrated CO intensities, and a conversion factor of 4×10^{20} $cm^{-2}/K\text{-}km\text{-}s^{-1}$. The choice of this value is discussed in the text.

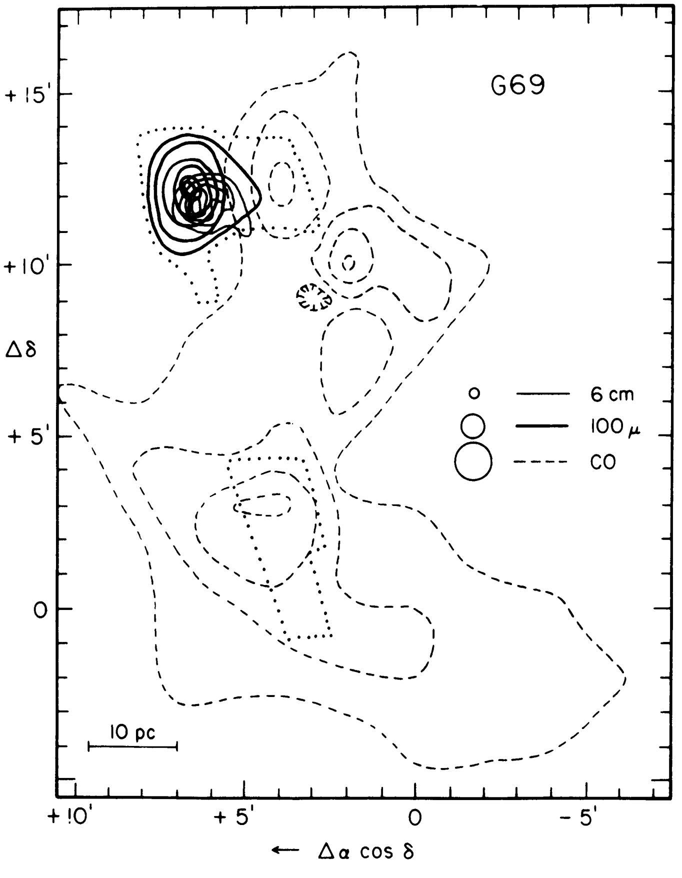

Figure 5 - A comparison of CO, far infrared, and 6cm continuum emission for one cloud. The cloud is 13.6 kpc from the GC and 13.4 kpc from the sun. Contours of each type of emission are coded, as indicated in the legend. The circles represent the beam sizes for the various studies. The dotted lines are boundaries of regions searched for far infrared emission.

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One advantage of the far infrared observations is that they allow us to estimate the luminosity of any embedded stars. It is assumed that most of the radiation from the star is absorbed by the dust, and reradiated in the far infrared. Based on our 100 μm fluxes, and the model calculations of Panagia (1973), we have estimated the spectral types for main sequence stars needed to produce the observed luminosities. These are also given in Table 1. The spectral types range from O7 to B2, clearly showing that massive star formation is taking place in these clouds.

4. SUMMARY

We have presented observations on the nature of the molecular clouds outside the solar circle. These conclusions are based on mapped clouds selected from an initial undersampled survey. The findings to date are:

(1) The clouds sizes and masses range up to those typical of inner galaxy GMCs, lengths of several tens of parsecs, and masses up to a few x 10^5 $M_\odot$. If the mapped sample is typical, most of the mass is in the GMCs, as opposed to a large number of small clouds.

(2) The cloud envelope kinetic temperatures are about 7 K, significantly lower than for GMCs in the inner galaxy. This could be explained by a lower cosmic ray heating rate in the outer galaxy.

(3) There is evidence, both from radio and far infrared observations, for massive star formation in some of the outer galaxy clouds.

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TERZIAN: From your work does the galaxy of CO clouds stop at about 15 kpc?

KUTNER: It does seem to have a "luminosity" edge. However, if the cloud temperature goes down with R, there could be cold clouds beyond 15 kpc that we do not see at our current sensitivity levels.

WILSON: Beam dilution would make your measured T_R^* less than the T_K of clouds. How sure are you that these distant clouds are not beam diluted?

KUTNER: We are most worried about beam dilution for the peaks. For the envelopes of the large clouds, we see the same T_R^* at several adjacent positions, ruling out beam dilution of a single core. However, if we are always looking at many diluted clumps when we look at a GMC envelope, then there might be some problem. (However, if we look at a cloud with a uniform projected surface density of clumps, then moving a cloud farther away dilutes the clumps, but brings more into the beam).

SANDERS: 1) Our CO survey of the Milky Way shows that $\sim$ 8-10% of the total CO luminosity originates at $R > R_\odot$, and assuming $L_{CO} \propto M(H_2)$ we would argue that 8-10% of the total H_2 mass is outside the solar circle. You estimate that $\sim$25% of $M(H_2)$ is at $R > R_\odot$. Since your survey covers similar regions of the galaxy as our survey, why the discrepancy. 2) OB star formation is plentiful in the "Perseus arm" clouds of the second quadrant (e.g. Cep A, NGC 7538, ...). Do you see similar OB star forming complexes in the first quadrant?

KUTNER: 1) I think that most of the discrepancy comes from the fact that you have assumed a scale height, while we have measured the z distribution. 2) We see similar complexes along this 14 kpc "arm"-like feature in the first quadrant.

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