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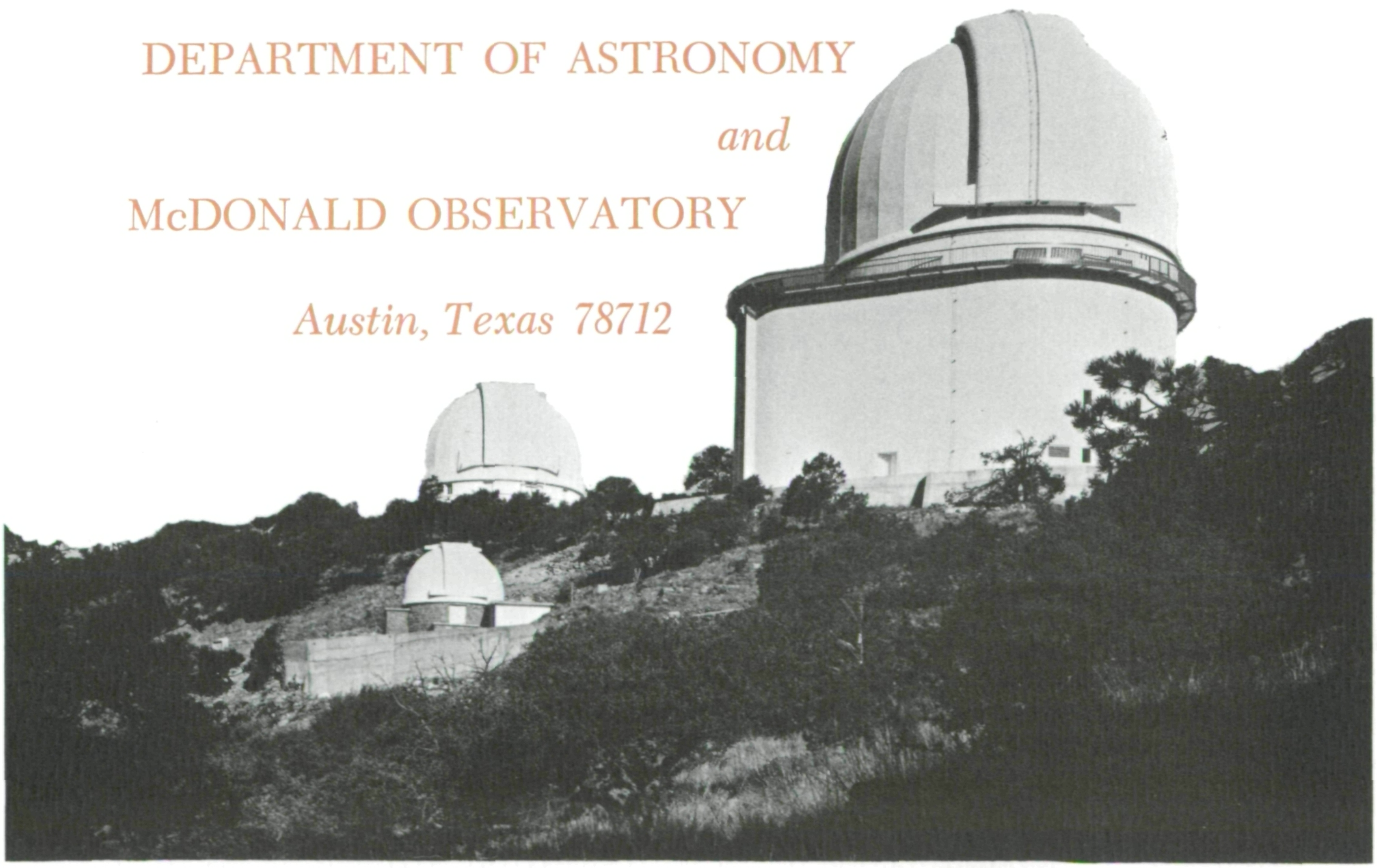

MOLECULAR CLOUDS IN THE OUTER GALAXY
I. FAR INFRARED OBSERVATIONS

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ABSTRACT

From the Kuiper Airborne Observatory, we have detected far infrared emission from 4 molecular clouds in the outer galaxy. Eleven areas in 6 clouds were observed at 50 and 100μm. The far-infrared luminosities indicate the presence of stars with spectral types ranging from B3 to O7. Therefore, despite the fact that these clouds have lower CO line temperatures than comparable clouds in the inner galaxy, they are giving birth to massive stars.

Subject Headings: infrared: sources - interstellar: molecules

I. INTRODUCTION

The outer galaxy offers a new perspective on various problems in star formation and galactic structure. First, there is no distance ambiguity in the outer galaxy. Given a rotation curve, a unique distance can be calculated from a radial velocity. Second, we expect the spiral arms in the outer galaxy to be less tightly wound and better defined than in the inner galaxy. This is the case in other spirals. Hence, we have a clearer view of galactic structure in the outer galaxy. Third, because the environment for clouds is different in the inner and outer galaxy, we can observe the effects of environment on star formation. For example, the time between arm passages is longer in the outer galaxy, and cloud-cloud collisions should be less frequent in the outer galaxy. Depending on whether such collisions tend to shred clouds or make them grow, the clouds may have shorter or longer lifetimes than those in the inner galaxy. Also, if the cosmic ray flux decreases with increasing galactocentric radius, we would expect to see cooler cloud envelopes in the outer galaxy.

The atomic gas in both the inner and outer parts of the galaxy was surveyed via H I by Weaver and Williams (1973) and Henderson, Jackson, and Kerr (1982). Many surveys of the molecular material in the inner galaxy have been made. Burton and Gordon (1978), Cohen (1978), Solomon, Sanders, and Scoville (1977) and Dame (1983) have all observed CO as a tracer for H_2. The outer galaxy has been less thoroughly scrutinized. Blitz, Fich, and Stark (1982) observed CO toward 242 H II regions over the entire northern galaxy. They observed H II regions in the outer galaxy in the 2nd and 3rd quadrants and one in the outer part of the 1st quadrant. Kutner and Mead (1981) reported an under-sampled search of the first quadrant of the outer galaxy whose purpose was to locate clouds for more detailed study. The search has since been extended to cover the galactic longitude ranges 45°-160° and 200°-225° (Kutner 1983; Kutner and Mead 1985; Kutner 1986). Maps of CO emission have now been made of 36 clouds, with 10 being mapped in $^{13}CO(J=1\rightarrow0)$ and $^{12}CO(J=2\rightarrow1)$(Mead 1986; Mead and Kutner 1986). Radio continuum maps have been made of 17 clouds (Mead, Kutner, and Evans 1986).

From the studies of individual clouds, it was found that outer galaxy clouds have lower CO line temperatures than their inner galaxy counterparts (Mead 1986; Mead and Kutner 1986). These lower line temperatures are interpreted as arising, at least in part, from lower kinetic temperatures. Since the outer galaxy clouds have sizes and masses comparable to the inner galaxy clouds, it is interesting to compare star formation in the two types of clouds. As a first step, we ask whether the cooler outer galaxy clouds are forming massive stars. Infrared observations can answer this question, and that is the goal of this study. Assuming all the star's radiated energy is absorbed by the dust in the surrounding cloud and then reradiated in the infrared, the integrated infrared flux is directly related to the star's luminosity. By converting the infrared luminosities to spectral types, we can estimate the masses of the stars being born in the outer galaxy clouds.

II. OBSERVATIONS

Observations were made aboard the Kuiper Airborne Observatory in 1983 August. A far infrared photometer (see Wilking *et al.* 1984) was attached to the 0.9m telescope. Data were taken simultaneously in two wavelength bands, centered at roughly 50μm (~ 40-70μm) and 100μm (~ 70-150μm), at each of 3 spatial positions separated by 1 arc minute in azimuth. Each beam was 40 arc seconds in diameter. The chopper throw was 5 arc minutes in azimuth. Because the water vapor radiometer wasn't working, the zenith water vapor columns were estimated (P. Kuhn, private communication). The data were calibrated by observing IRC+10420 at the start of each of two flights and S140 at the end. The three channels' relative gains were set from the S140 observations (Harvey, Wilking and Joy 1984). Overall calibration was established by averaging center channel sensitivities on each calibration source. We estimate a ±30% uncertainty in the intensity calibration caused mostly by uncertainties in estimating the water vapor opacity.

Six clouds were searched for far infrared emission. Clouds were chosen from a set for which CO and 6cm radio continuum maps were available. Mead (1986) and Kutner (1986) give brief descriptions of these observations. A complete description of the CO and 6cm observations will appear in, respectively, Mead and Kutner (1986) and Mead, Kutner, and Evans (1986). The whole extent of the CO cloud was not mapped in the infrared. Instead, regions around molecular or radio continuum peaks were searched initially for emission. There were 11 initial search areas. If emission was seen, a map was made.

III. RESULTS

Infrared emission was detected from 4 of 6 clouds searched. Criteria for detections and upper limits were conservative. Source detection required a signal of 5σ at some position in the map. Once the source was detected, detection of another position required a 3σ signal. Upper limits are the maximum, over the region searched, of the quantity $2\sigma+|S_\nu|$, where S_ν is the nominal flux density and σ is the standard deviation at a given position.

Our results are presented in Table 1. A source name which corresponds to an approximate galactic longitude and latitude appears in the first column. Short names, used in the text and figure titles, appear in the second column. The A, B, and C's refer to different molecular peaks in a cloud. The third and fourth columns contain positions of our infrared sources. For a detection, the right ascension and declination of the strongest position are tabulated. For an upper limit, the coordinates of a position near the center of the searched region are tabulated. We have determined 100μm flux densities for 4 search areas and upper limits to the flux density for the remaining 7. At 50μm we have 2 definite detections and 9 upper limits. For detections, the size of the area with emission $\geq 3\sigma$ is indicated in the column labeled size. For upper limits, the size refers to the area searched. A flat rotation curve with $R_\odot$ = 8.5 kpc and $v_\odot$ = 220 km/s was used to derive $d_\odot$ and R (distances from the sun and galactic center) from the CO velocity.

Maps of our detected sources comprise figures 1-5; the far infrared data are shown on top of the CO (Kutner and Mead 1981; Mead and Kutner 1986) and radio continuum (Mead, Kutner and Evans 1986) maps. The coordinates of the reference position in each map are indicated in the figure caption. In all maps, the region searched in the far infrared is indicated by a dotted outline. (Three positions, arranged in a line, were observed at a time. As the observatory moved, the line of beams rotated on the sky, producing an irregularly shaped search region.) In G69 and G89, enough positions were detected to draw contours of 100μm emission. In G84 and G65 however, only two positions were detected; boxes indicate the detected positions and pluses indicate the position of the strongest 100μm emission.

We have examined the IRAS point source catalogue for sources at positions observed with the KAO. At 10 of 11 positions, we found an IRAS point source. The 10 IRAS positions include the 4 positions detected with the KAO and 6 positions for which we have upper limits. The IRAS flux densities range from about 1.5 to 4 times the flux densities or upper limits obtained with the KAO. We attribute this to our chopper throw being too small to get completely off the source. This hypothesis is confirmed by preliminary inspection of the IRAS images. IRAS emission typically extends far beyond that seen from the KAO. Insufficient chopper throw may also explain why infrared emission wasn't observed near all the molecular peaks that we searched. Further inspection of the images will reveal whether there is extended infrared emission over the whole cloud seen in CO.

IV. DISCUSSION

The most striking and interesting feature of the maps is that the infrared source is always at or near a radio continuum source and a molecular peak. All of the radio continuum sources associated with infrared sources have spectral indices which indicate that the sources are thermal (Mead, Kutner, and Evans 1986). These facts strongly suggest that the stars responsible for the ionization of the radio continuum sources are also responsible for heating the dust and gas. This situation is often seen in the inner galaxy and explained by such a scenario. In cases where the three peaks are along nearly the same line of sight, we assume that all the emission is emanating from sources at the same distance. We have considered the possibility of chance coincidence on the sky, but believe it to be very unlikely. A more definite association of H II region with the molecular peak will require measurement of the velocity of the H II region by observing a recombination line. This would also rule out the possibility of a foreground H II region, perhaps in the Perseus arm or its extension into the first quadrant.

The dust temperatures listed in Table 1 were calculated by assuming that grain absorption efficiency (Spitzer 1978) varies as λ^{-1} and using the equation given by Evans (1980). In the luminosity calculation, only the 40 to 150μm flux is included. (In other words, no correction has been made for emission outside our bandpass.) For G65A and G84B, only the 70 to 150 μm flux is included because there was no detection at 50μm. Spectral types were estimated from the luminosities using calculations of Panagia (1973) and Avedisova (1979) for main sequence stars. These two sets of models agree for O stars, but differ by about 2 subclasses for stars in the B1 to B5 range. In six clouds searched, we found four stars with spectral types between 07 and B3 indicating that massive stars (M ~ 5-30 $M_{\odot}$) are forming in the outer galaxy.

A single star was assumed to be the heat source in each case. If a cluster of stars is responsible for the heating and ionizing, each star will obviously be of later type than we calculated. However, the number of ionizing photons radiated drops off sharply for spectral types later than about B3. Therefore, a group of stars of types later than mid to late B will barely be able to ionize the gas at all, independent of quantity. Radio continuum data provide a measure of the number of ionizing photons being generated by the stars. Spectral types and luminosities can then be derived. Mead, Kutner, and Evans (1986) derive spectral types of O5 for G69 and B0 for G65, G84, and G89; all these are slightly earlier than those derived from far infrared data. The luminosities inferred from the radio data for G89, G84, G69, and G65 respectively are a factor of 2, 5, 5, and 10 higher than those inferred from the far infrared data. Two possible explanations for this "radio excess" are 1) that the sources are, for some reason, significantly underluminous in the infrared, and 2) that the far infrared observations did not measure all of the flux. We suggested the latter possibility earlier, in connection with the IRAS data. Further analysis of the IRAS data with regard to this question will appear in a future paper.

Despite the sparseness of our sample, we would like to compare, at least preliminarily, our clouds to inner galaxy clouds. 1) Even though outer galaxy CO peaks are weaker than those in the inner galaxy, it appears that they still trace star formation (as is the case in the inner galaxy). We have seen that infrared emission is associated with many, though not all, of the CO peaks in our search. 2) The derived dust temperatures are all higher than the derived (from CO) kinetic temperatures, about 15K at the peaks (Mead and Kutner 1986). Thus, the usual explanation for

CO peaks in inner galaxy clouds (i.e. the star heats the dust which heats the gas) is plausible for outer galaxy clouds as well. 3) Lester *et al.* (1985) have studied, in detail, two H II regions in the inner galaxy, G30.8-0.0 and G25.4-0.2. They found luminosities in the 10^5 to $10^6 L_\odot$ range, consistent with other bright, well-studied H II regions in the inner galaxy. The far infrared luminosities of the outer galaxy clouds are generally less by a factor of 10^3. Only G69's luminosity is comparable to that of inner galaxy clouds.

V. CONCLUSION

In this paper, we have presented far infrared observations which provide evidence that there is massive star formation (inferred spectral types range from B3 to O7) in outer galaxy molecular clouds. This is in spite of the lower CO line temperature of the outer galaxy clouds, relative to comparable sized inner galaxy clouds. These lower line temperatures have caused the importance of star formation in the outer galaxy to be overlooked. Extensions of this study can be used to extend the range of galactocentric radii over which massive star formation can be studied. This may tell us about the importance of galactic environment in massive star formation. Moreover if the physical conditions, especially temperature, are different in outer and inner galaxy clouds, then we have the basis for comparisons that will allow us to assess the effects of these differences on massive star formation.

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Table 1

Far Infrared Results and Source Properties

Source	Short Name	α(1950)	δ(1950)	Sv(100μm)[a] (Jy)	Sv(50μm)[a] (Jy)	Size[b]	d[c] (kpc)	R[c] (kpc)	T_D[d] (K)	L[e] ($L_\odot$)	Spectral Type
G65.5+1.3	G65A	19^h 49^m 25.1^s	29° 10' 26"	12±2	< 6	≲1'	14.2	13.2	< 41	~$2x10^3$	B3-B2
G69.7+1.5	G69B	19 59 03.3	32 54 03	< 35	50	2'x2'	12.2	12.2	—	< $1x10^4$	< B0.5
	G69C	19 59 15.7	33 02 50	865±200	775±200	3'x3'	12.2	12.2	50±3	$2x10^5$	O7
G84.7+1.7	G84A	20 42 18.9	45 20 27	< 20	< 30	2'x2'	11.6	13.7	—	< $6x10^3$	< B1
	G84B	20 42 34.0	45 15 32	< 35[g]	< 50[g]	1'x2'	11.6	13.7	—	< $9x10^3$	< B0.5
	G84C	20 42 47.8	45 15 53	65±3	< 16	≲1'	11.6	13.7	< 34	~ $6x10^3$	B1-B2
G88.8+1.9	G88C	20 56 41.0	48 20 02	<15	<25	2'x2'	8.3	11.8	—	< $3x10^3$	< B2
	G88D	20 56 57.8	48 17 04	< 20	< 30	2'x1'	8.3	11.8	—	< $3x10^3$	< B2
G89.9+1.3	G89A	20 59 54.6	48 43 13	95±10	118±4	~1'	9.3	12.6	56±3	$1.5x10^4$	B0.5
	G89B	21 00 53.1	48 48 21	< 20	< 30	~4'x4'	9.3	12.6	—	< $4x10^3$	< B2
G93.2+1.7	G93A	21 16 42.1	51 37 12	< 15	< 30	~3'x4'	8.8	12.6	—	< $3x10^3$	< B2

[a] Errors are statistical only; calibration uncertainty is ±30%; for G69C, the errors include estimates of uncertainties in integrating map.

[b] For upper limits, the size means the size of the region we searched. For detections, size means the extent of emission at ≥3σ.

[c] $R_\odot = 8.5$ kpc; $v_\odot = 220$ km s^{-1}.

[d] A λ^{-1} emissivity law was assumed.

[e] Includes only ~ 40-150 μm flux; for G65A and G84B, only ~ 70-150 μm flux.

[f] Uncertain to ~ 2 subclasses in B1-B5 range; upper limits imply "later than".

[g] Limits are high because of apparent confusing source in reference beam.

REFERENCES

Avedisova, V. S. 1979, *Sov. Astron.*, **23**, 5.

Blitz, L., Fich, M., Stark, A. A. 1982, *Ap. J.*, **49**, 1983.

Burton, W. B., and Gordon, M. A. 1978, *Astr. and Ap.*, **63**, 7.

Cohen, R. S., and Thaddeus, P. 1977, *Ap. J. (Letters)*, **217**, L155.

Dame, T. M. 1983, Ph.D. Thesis, Columbia University.

Evans, N. J., II, *Interstellar Molecules* (Dordrecht: Reidel), p. 1.

Harvey, P. M., Wilking, B. A., and Joy, M. 1984, *Nature*, **307**, 441.

Henderson, A. P., Jackson, P. D., and Kerr, F. D. 1982, *Ap. J.*, **263**, 116.

Kutner, M. L. 1983, in *Surveys of the Southern Galaxy*, ed. W. B. Burton and R. P. Israel (Dordrecht: Reidel), p. 143.

_____. 1986, in *IAU Symposium No. 115, Star Forming Regions*, ed. M. Peimbert, in press.

Kutner, M. L., and Mead, K. N. 1981, *Ap. J. (Letters)*, **249**, L15.

_____. 1985, in *IAU Symposium No. 106, The Milky Way Galaxy*, ed. H. van Woerden, W. B. Burton, and K. J. Allen (Dordrecht: Reidel), p. 209.

Lester, D. F., Dinerstein, H. L., Werner, M. W., Harvey, P. M., Evans, N. J. II, and Brown, R. L. 1985, *Ap. J.*, **296**, 565.

Mead, K. N. 1986, *B.A.A.S.*, **17**, 870.

Mead, K. N., and Kutner, M. L. 1986, in preparation.

Mead, K. N., Kutner, M. L.,and Evans, N. J. 1986, in preparation.

Panagia, N. 1973, *Astr. Ap.*, **78**, 929.

Soloman, P. M., Sanders, D., Scoville, N. Z. 1977, *B.A.A.S.*, **9**, 554.

Spitzer, L. 1978, *Physical Processes in the Interstellar Medium* (New York: Wiley), p. 150.

Weaver, H., and Williams, D. R. W. 1973, *Astr. Ap. Suppl.*, **17**, 1.

Wilking, B. A., Harvey, P. M., Lada, C. J., Joy, M., and Doering, C. R. 1984, *Ap. J.*, **279**, 291.

FIGURE CAPTIONS

FIGURE 1. CO(J=1-0) contours of G65.5+1.3 start at 1K and increase in 1K increments. Contour levels of 6cm emission are 0.4 and 0.8 mJy/beam. The area searched with the KAO is indicated with a dotted outline. Squares indicate the two positions detected at 100μm; the strongest is indicated by a plus. The beam sizes for each type of observation are shown. A length scale of 10 pc, at the derived kinematic distance, is also indicated. Offsets are relative to ($19^h\ 49^m\ 17.^s2$, +29° 09' 57").

FIGURE 2. CO contours of G69.7+1.5 are in 1K increments starting at 1K. 6cm contour levels are 0.01, 0.04, 0.08, 0.12, and 0.16 Jy/beam. The areas searched with the KAO are indicated by a dotted outline. Far infrared contour levels are 25, 50, 100, 200, 300, and 400 Jy/beam. Beam sizes and a length scale are shown as in Figure 1. Offsets are relative to ($19^h\ 58^m\ 44^s$, +32° 51' 01".).

FIGURE 3. CO contours of G84.7+1.5, search areas and length scale are as in Figure 1. 6cm contour levels are 1.0, 5.0, and 10.0 Jy/beam. The two detected positions are indicated by squares; the + indicates the strongest position at 100μm. Offsets are relative to ($20^h\ 42^m\ 30.^s6$, +45° 14' 29").

FIGURE 4. In this figure, G89.9+1.3, both 6 and 20cm radio continuum contours are shown. 6cm levels are 0.4 and 3.0 mJy/beam. 20cm levels are 2.5, 5.0, 7.5, 10.0, and 12.5 mJy/beam. CO contours, search areas and length scale are all indicated as in the other figures. The heavy solid contour represents 50 Jy/beam of 100μm emission. Offsets are relative to ($20^h\ 59^m\ 30^s$, +48° 40' 00").

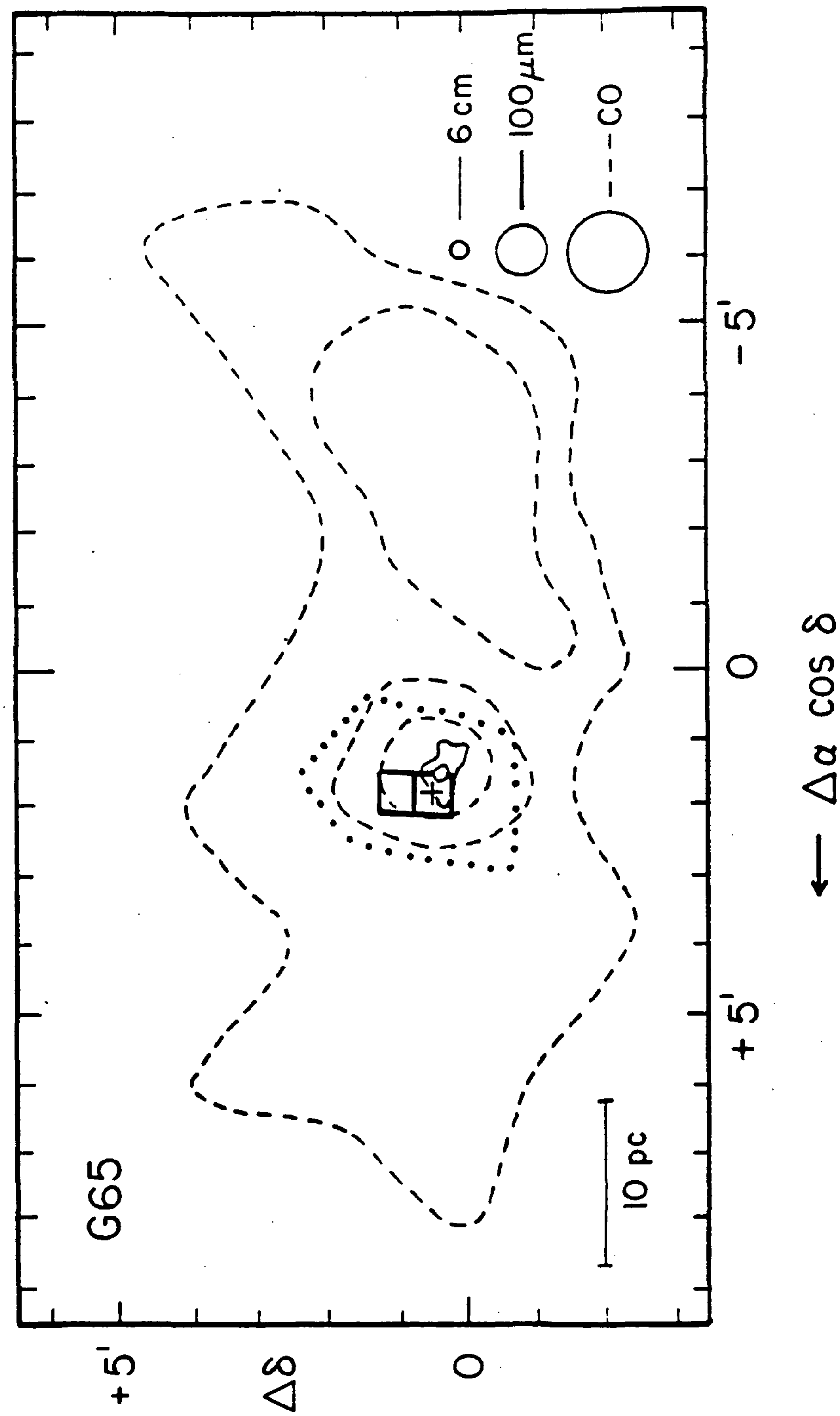


Figure 1

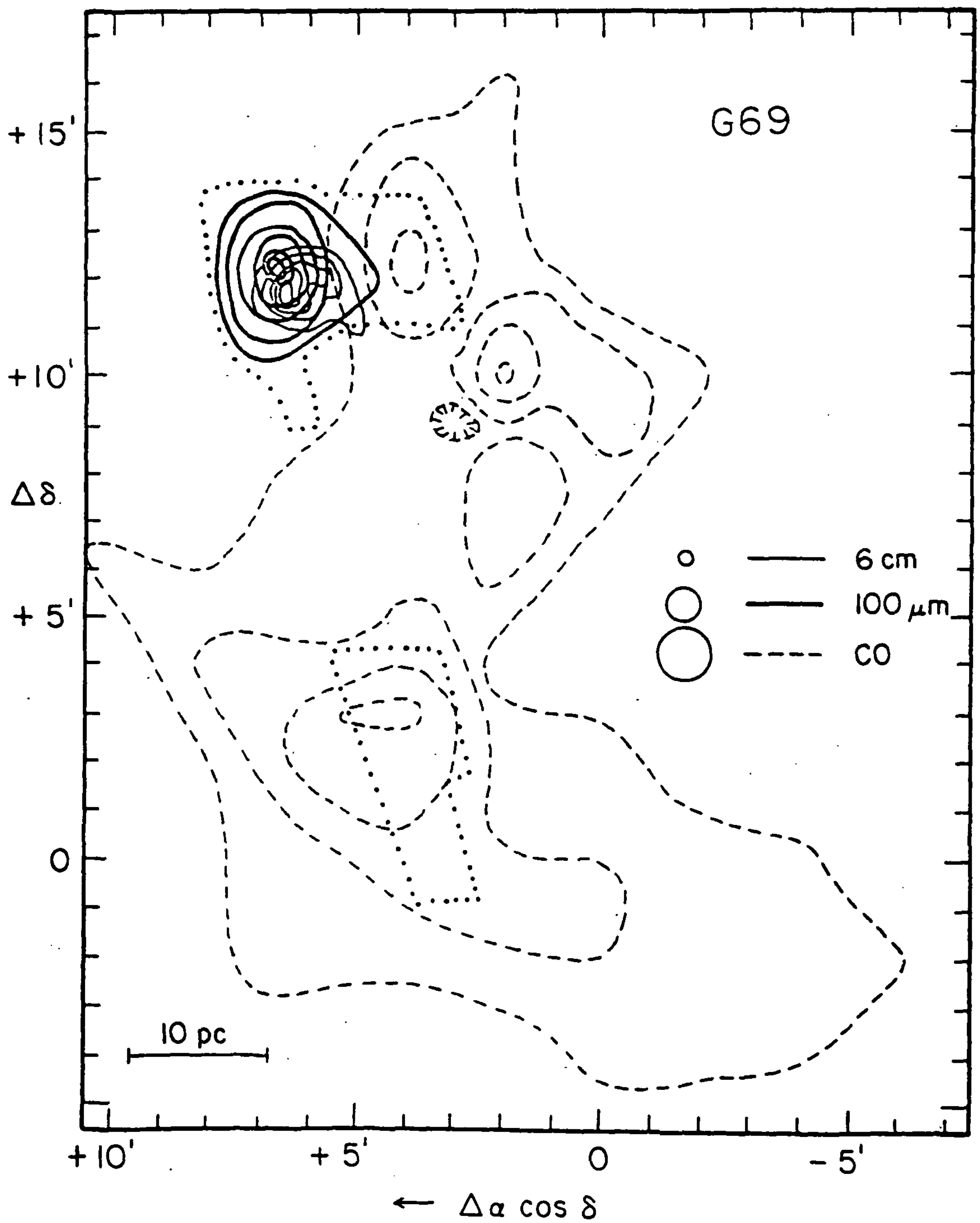
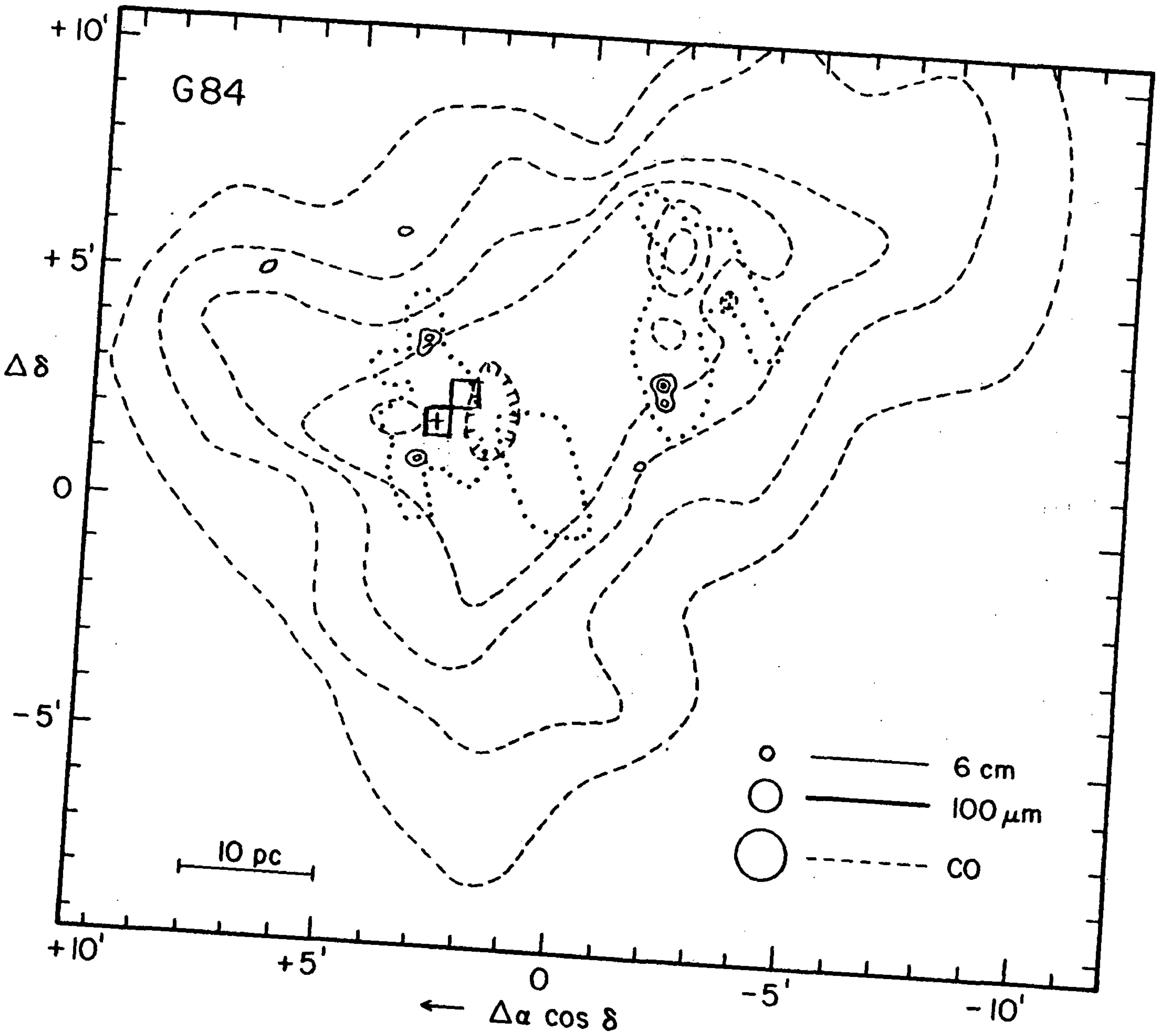


Figure 2


G84
+10'
+5'
0
-5'
Δδ
+10'
+5'
0
-5'
-10'
← Δα cos δ
10 pc
6 cm
100 μm
CO

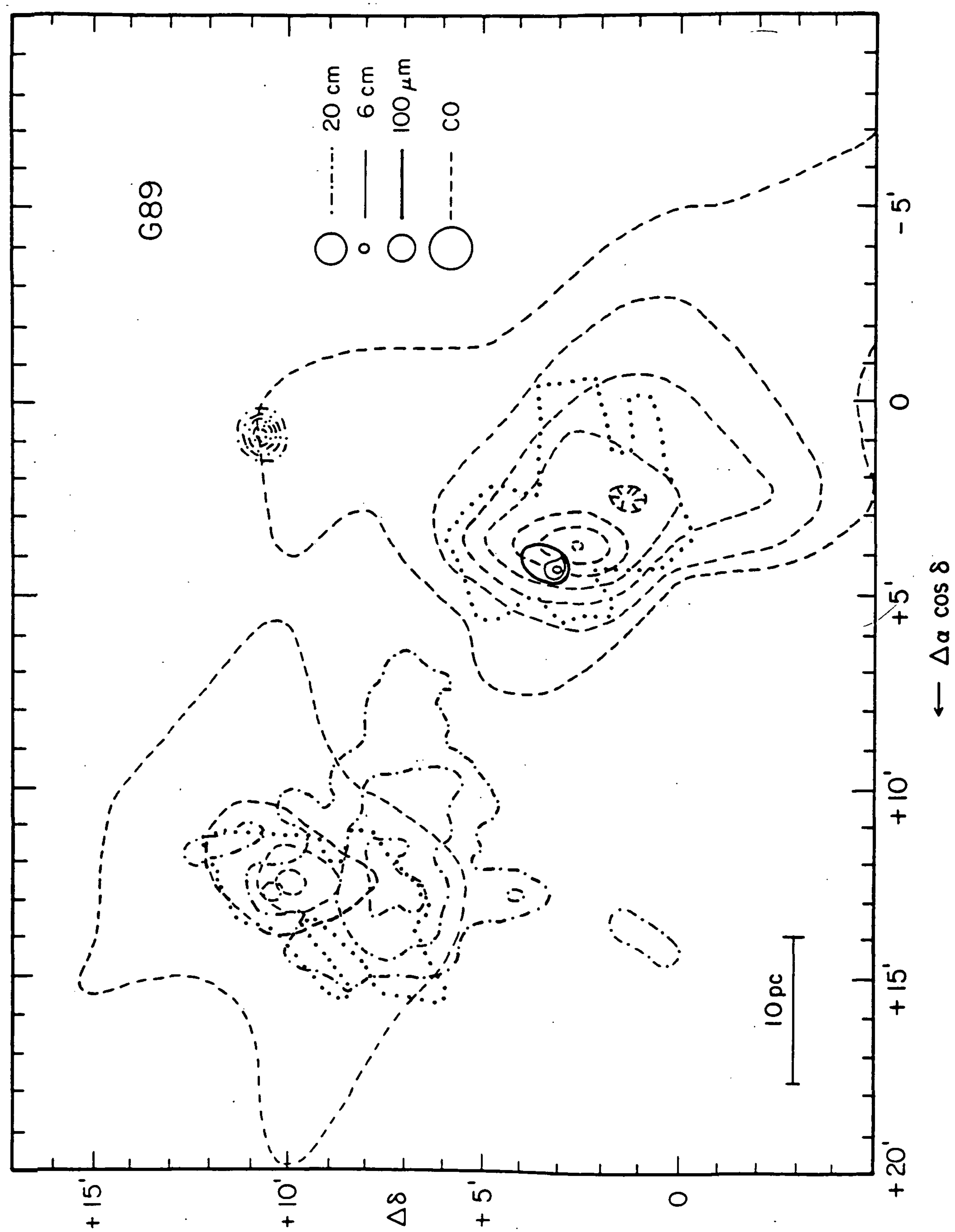


Figure 4

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