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# SURVEY OF MOLECULAR LINES NEAR THE GALACTIC CENTER. I. 6-CENTIMETER FORMALDEHYDE ABSORPTION IN SAGITTARIUS A, SAGITTARIUS B2, AND THE GALACTIC PLANE FROM $l^{\mathrm{II}} = 359^\circ.4$ TO $l^{\mathrm{II}} = 2^\circ.2$

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## ABSTRACT

The $1_{11} \rightarrow 1_{10}$, 4830-MHz transition of formaldehyde has been mapped in Sgr A, Sgr B2, and along the galactic equator from $l^{\mathrm{II}} = 359^\circ.4$ to $l^{\mathrm{II}} = 2^\circ.2$ with a 6′ beam and velocity resolution of 1 km s$^{-1}$. That this line is observed in absorption in all locations indicates a low 6-cm excitation temperature for all molecular clouds. Comparison with 21-cm data indicates that the $H_2CO$ is concentrated in distinct clouds to a much greater extent than atomic hydrogen, with many strong $H_2CO$ features occurring at velocities with weak or missing hydrogen lines. This suggests that most of the mass in these clouds is in the form of molecular hydrogen. There are four dominant clouds occurring at $l^{\mathrm{II}} = 0^\circ.0$, $0^\circ.7$, $0^\circ.9$, and $1^\circ.7$. In contrast with atomic hydrogen, the strongest formaldehyde features occur at $|V_{\mathrm{LSR}}| > 40$ km s$^{-1}$ and are apparently associated with the galactic nucleus. Estimates of the hydrogen density in these clouds, based on the assumption of stability and also on a comparison with local dark clouds, indicate a number density in the range of $10^3$–$10^4$ cm$^{-3}$, and a mass of approximately $5 \times 10^6\ M_\odot$.

## I. INTRODUCTION

It is clear from initial surveys of galactic continuum sources that the 6-cm line of formaldehyde ($H_2CO$) is a potentially valuable tool for detecting and studying dense interstellar dust clouds. Zuckerman *et al.* (1970) and Whiteoak and Gardner (1970) have found 6-cm absorption in the majority of H II regions searched, while Palmer *et al.* (1969) have discovered that in many diffuse dust clouds the line can be seen in so-called anomalous absorption of the microwave background radiation. In the vicinity of the galactic center Gardner and Whiteoak (1970) have observed intense formaldehyde absorption at several locations.

The purpose of this paper is to give the results of a 6-cm $H_2CO$ survey of the galactic plane between $l^{\mathrm{II}} = 359^\circ.4$ and $l^{\mathrm{II}} = 2^\circ.2$, and the mapping of Sgr A and B2 at an angular resolution of about 6′. This is significantly higher resolution than that hitherto attained in the OH and H I surveys of this region.

## II. EQUIPMENT, OBSERVATIONAL TECHNIQUE, AND DATA REDUCTION

Observations were made in May 1970 with the 140-foot antenna and a cooled 6-cm parametric amplifier of the National Radio Astronomy Observatory (NRAO)[1] in Green Bank, West Virginia. The system-noise temperature was only about 100° K. Multichannel spectral coverage was obtained with the NRAO 384-channel digital autocorrelation receiver. Data was taken in the "total power mode," a method suitable for receivers whose baselines are stable for long periods of time. For such receivers, rapid

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[1] Operated by Associated Universities, Inc., under contract with the National Science Foundation.

frequency switching becomes unnecessary and a simple calibration scan (OFF) may be used to subtract the baseline irregularities from many observation scans (ON). This technique results in a more efficient use of observing time and is of particular value for work on the galactic center, which can be observed for only about 4 hours each day with the 140-foot telescope. Typically an OFF, taken $45^m$ west of the galactic plane and lasting 30 minutes, was used in the reduction of about six subsequent ONs of 10 minutes each.

For most of these observations we employed a total receiver bandwidth of 5 MHz corresponding to a velocity range of 310 km $s^{-1}$ at 6 cm; the frequency resolution of the unfiltered data was 15.8 kHz or 0.98 km $s^{-1}$. With the $\sim 100^\circ$ K system-noise temperature this yielded a measured rms noise fluctuation of $0.07^\circ$ K for a typical 10-minute observation. All observations were made with the feed-horn $E$-plane oriented north-south; the measured half-power beamwidth (HPBW) of the antenna was 6′.6 with the linear feed.

All spectra have been cosine filtered to a velocity resolution of 1.63 km $s^{-1}$. Radial velocities have been calculated by using 4829.65961 MHz as the rest frequency, $\nu_{12}$, of the main component of the $H_2CO$ $1_{11}$–$1_{10}$ rotational transition (Tucker, Tomasevich, and Thaddeus 1970), and conversion of radial velocities to the local standard of rest (LSR) has been accomplished by using the standard components for solar motion given by Allen (1963).

The common practice of presenting absorption-line measurements in terms of antenna temperature is particularly misleading in regions such as the galactic center where the continuum structure is complex (see Fig. 1*a*). In order to reveal more clearly the distribution of the molecules themselves we have therefore reduced the line observations to apparent optical depth $\tau$ as obtained from the radiative-transfer relation

$$T'_L = (T'_C + T_B)(1 - e^{-\tau}) - T_{12}(1 - e^{-\tau}) , \tag{1}$$

where $T'_L$, $T'_C$, and $T_B$ are the brightness temperatures of the line, the discrete-source continuum, and the isotropic background, respectively. The calculation of the optical depth by means of equation (1) assumes that the cloud uniformly covers that portion of the continuum source contained in the antenna beam. Thus all estimates of the column densities given in this paper are minimum values since the true optical depth will exceed the apparent value if any continuum radiation originates in front of the cloud or if the cloud has substantial structure on a scale less than the beam size. (Evidence which will be presented in Papers II (Scoville *et al.* 1972) and III (Scoville and Solomon 1972) based on $^{12}CO$, $^{13}CO$, and additional formaldehyde observations indicates that the use of eq. [1] may lead to underestimates of the column density $N_1$ by a factor which may be as large as 10.)

To evaluate $\tau$ it is necessary to make some assumption concerning the excitation temperature $T_{12}$ of the $1_{11}$–$1_{10}$ levels producing the 6-cm transition. The usual method of determining molecular excitation temperatures requires the detection of an emission line, but the 6-cm formaldehyde line has been seen only in absorption, even in the direction of the "dark" clouds (Palmer *et al.* 1969). The lack of any continuum source behind these dark clouds implies that the molecules are absorbing the $2.7^\circ$ K isotropic background radiation, and Palmer *et al.* estimate that $T_{12} < 1.8^\circ$ K in these nebulae. The universality of the anomalous absorption is by no means definite, since we have found no examples where the measured 6-cm line temperature is greater than the measured continuum-source temperature, except in the dark nebulae. However, the fact that no 6-cm emission has been seen in this survey suggests rather strongly that the pumping mechanism producing anomalous absorption in the dark nebulae is also operative in the clouds seen in the direction of continuum sources; we have therefore adopted $T_{12} = 1.75^\circ$ K for all calculations presented in this paper. Calculations done with $T_{12}$ in the range $1^\circ$–$4^\circ$ K show that our results, as might be expected, are insensitive to this

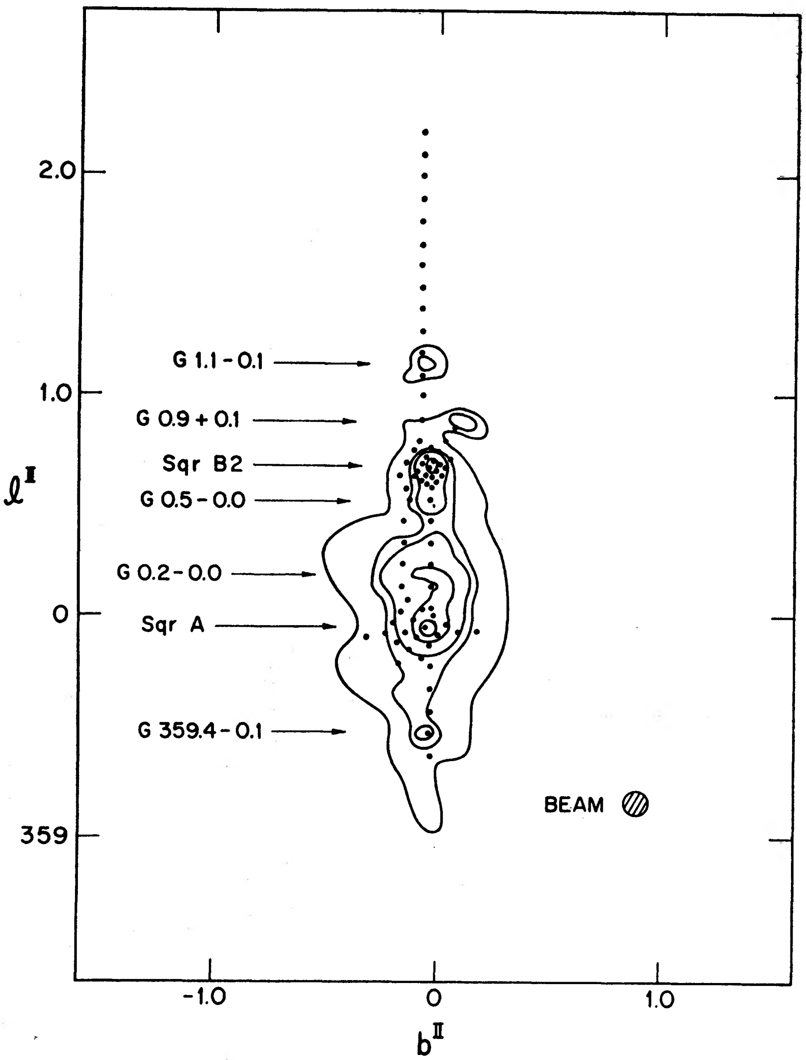



FIG. 1*a*.—Dots indicate locations at which 6-cm formaldehyde observations were made, shown against 6-cm continuum isophotes (HPBW = 4′.1) taken from the work of Broten *et al.* (1965). The contour levels are 1.2°, 2.3°, 3.5°, 9.2°, and 23° K $T_A$. The galactic-center continuum peaks are denoted by their most common names, and the relative size of the 6′.6 $H_2CO$ beam is also shown.

assumption except in the region $l^{\mathrm{II}} = 1^\circ.5$ to $l^{\mathrm{II}} = 2^\circ.2$ where the continuum temperatures are low ($\sim 1^\circ$ K).

Most of the 6-cm lines detected in this survey have low *apparent* optical depth (the maximum *apparent* $\tau$ is $\sim 1$, and most lines have $\tau \lesssim 0.3$), and we have accordingly calculated column number densities on the assumption that all lines lie on the linear part of the curve of growth. If the equivalent width is defined to be

$$W = \int_{\mathrm{line}} [1 - e^{-\tau(v)}] dv \,, \tag{2}$$

then the relation between equivalent width and the column number density $N_1$ of $H_2CO$ molecules in the lower level of the 6-cm transition, valid when $\tau(v) \ll 1$, is

$$W = \frac{8\pi^3 \nu_{12} \mu^2 N_1}{3hc} \frac{1}{2} [1 - \exp(-h\nu_{12}/kT_{12})] \,. \tag{3}$$

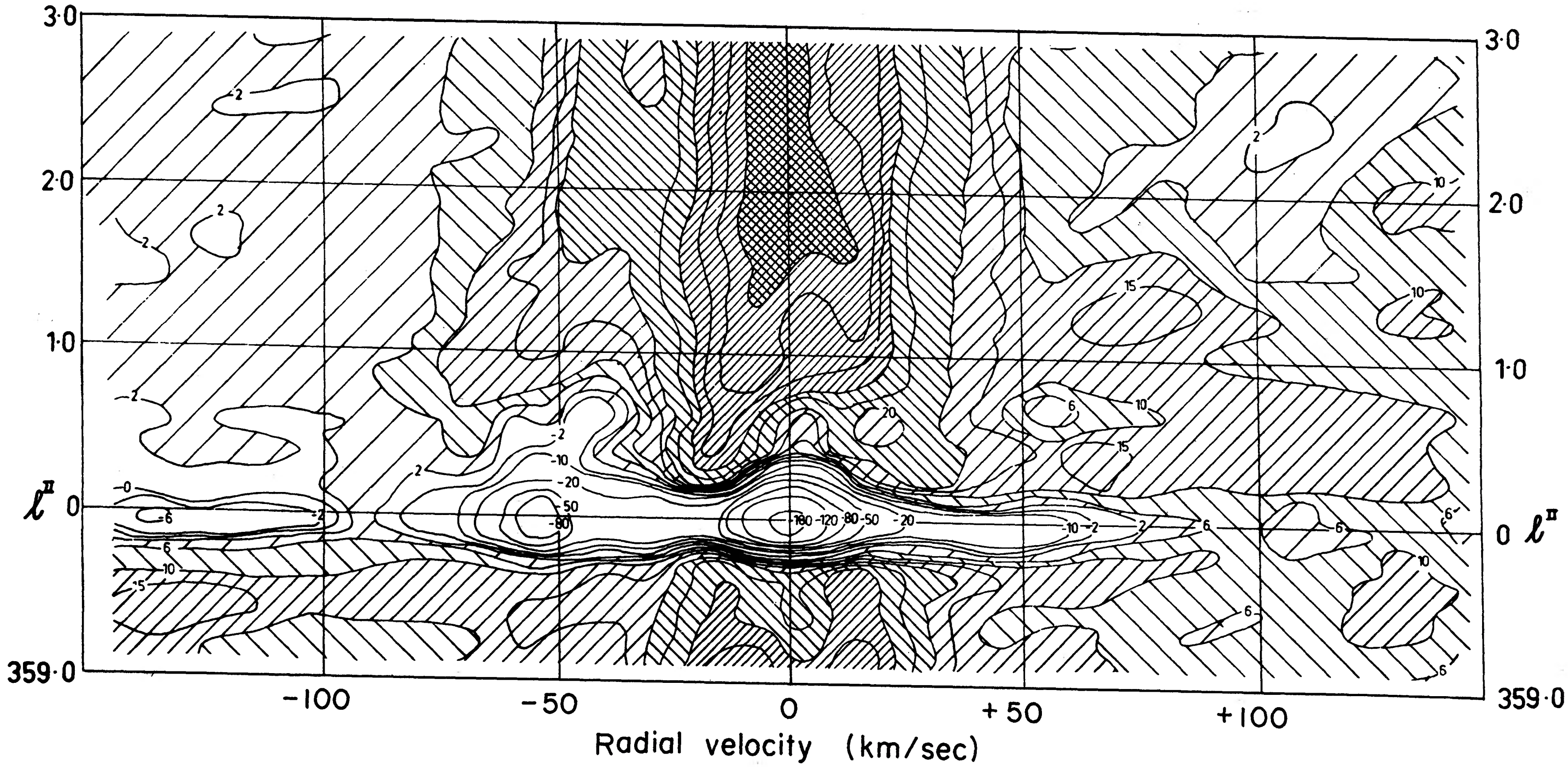



FIG. 1*b*.—Contour diagram of 21-cm line intensity in (longitude, velocity)-plane for the galactic equator from $l^{II} = 359°.0$ to $l^{II} = 3°.0$ (adapted from Kerr and Vallak 1967). Contour unit = 1.4° K $T_A$.

The use of equation (3) when $\tau \gtrsim 1$ underestimates the column density $N_1$ by a factor of $(1 - e^{-\tau})/\tau = 0.6$ for $\tau = 1$. In equation (3), $\mu = 2.34 \times 10^{-18}$ esu (cf. Townes and Schawlow 1955) is the $H_2CO$ electric-dipole moment, and the factor $\frac{1}{2}$ results from evaluation of the matrix element for the 6-cm transition. The column density in the lower level of the 6-cm doublet, $N_1$, can be related to the total $H_2CO$ column density $N_{H_2CO}$ under the following assumptions: (1) The excitation temperatures describing the populations for the levels of the ortho species of $H_2CO$ are in equilibrium with the background radiation at 2.7° K, which gives 2.3 $N_1$ for the total number of ortho molecules. (2) The ortho and para species are formed at rates in proportion to their statistical weights, with one-third as many para as ortho molecules.

Under the above conditions, $N_{H_2CO} = 3.1\ N_1$. This is a minimum, and any additional excitation to higher levels will increase the total column density. For example, with collisional excitation of the $J = 2$ levels at a kinetic temperature $>20°$ K, and a collision rate of greater than $10^{-5}$, the $J = 2$ levels would be thermalized and $N_{H_2CO} \gtrsim 7N_1$. This rate probably exists in the center of some of the observed clouds such as Cloud 10 (Sgr B2) where high excitation of methyl cyanide has been observed (Solomon *et al.* 1971). Nevertheless, the error in the factor of 3.1 is likely to be less than that involved in the use of equation (1).

## III. RESULTS

The observational results are presented in three different types of diagrams: line profiles, velocity-spatial, and two-dimensional spatial diagrams. Figures 2*a* and 2*b* display sample 6-cm absorption profiles taken from the series of observations parallel to the galactic equator. Figure 2*c* shows sample profiles from a sequence perpendicular to the galactic plane at $l^{II} = 0°.0$. The continuum temperatures $T_c$ listed in Figure 2 were measured with the 140-foot telescope immediately before each formaldehyde observation. Figures 3*a* and 3*b* present contours of 6-cm optical depth in the (radial velocity, angular coordinate)-plane. In Figure 3*a*, $b^{II} = -0°.03$, and the angular coordinate is $l^{II}$. In Figure 3*b* $l^{II} = 0°.0$ and $b^{II}$ is the angular variable. In Figures 4*a* and 4*b* contours of equivalent width and centroid radial velocity are given in the (right ascension, declination)-plane for the 40 km s$^{-1}$ Sgr A and the 60 km s$^{-1}$ Sgr B2 lines, respectively.

Besides the data presented in the figures, we have chosen to present in Table 1 summary information for fifteen of the most prominent formaldehyde absorption features, which we shall refer to by the number given in Table 1. Figure 5, which shows the location of the dominant clouds, serves as a useful link between Table 1 and the observed contours given in Figure 3*a*. The contents of the columns in Table 1 are as follows: column (1), cloud number; columns (2)–(5), galactic and equatorial coordinates at which the maximum optical depth was observed; column (6), radial velocity at maximum optical depth; column (7), full linewidth at half intensity; column (8), velocity of the 1667-MHz OH line (Robinson and McGee 1970; McGee 1970); column (9), velocity of the 21-cm H I line closest to the observed $H_2CO$ line (Kerr and Vallak 1967); column (10), measured antenna temperature of the $H_2CO$ line *at the position of maximum optical depth* (this is not necessarily the maximum observed line temperature).

Calculated quantities for the fifteen $H_2CO$ clouds are contained in Table 2, and the contents of the columns are as follows: column (1), cloud number; column (2), peak optical depth calculated from equation (1) with the data in Table 1 and the measured continuum temperature of Figure 2; column (3), optical depth ratio of $H_2CO$ to OH (McGee 1970); column (4), equivalent width from equation (2); column (5), column density of formaldehyde molecules in the $1_{11}$ rotational level $N_1$ as calculated from equation (3); column (6), estimated mean angular extent of the cloud; column (7), physical diameter calculated on the assumption that the cloud is located near the galactic center, 10 kpc from the Sun.

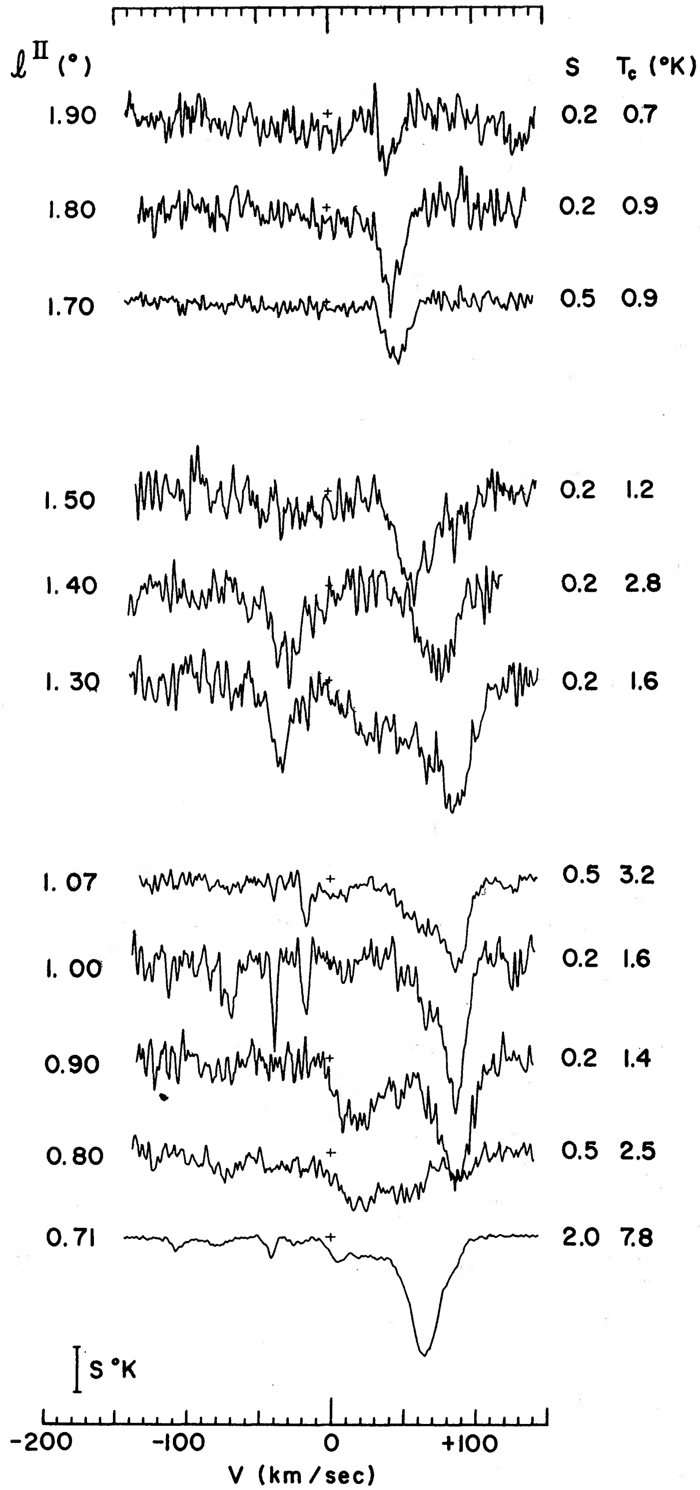
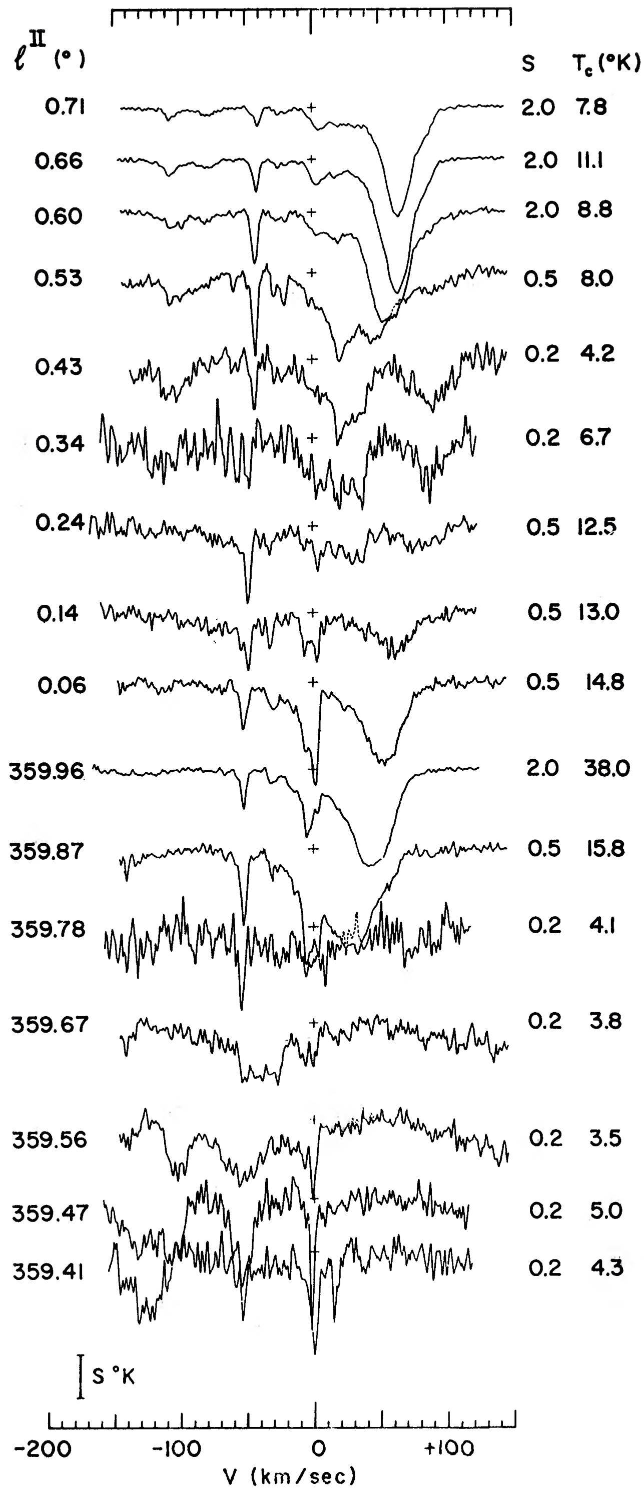



FIG. 2*a*

FIGS. 2*a* AND 2*b*.—Sample $H_2CO$ 6-cm spectra from the series of observations taken in a strip parallel to the galactic plane ($b^{II} = -0.^{\circ}03$) from $l^{II} = 359.^{\circ}41$ to $l^{II} = 1.^{\circ}9$. The vertical scale, antenna temperature $T_A$, varies from observation to observation; the quantity $S$, listed to the right of each profile, determines the antenna temperature that is equivalent to the vertical bar in the lower left. The measured continuum antenna temperature $T_C$ is listed on the far right. (The noise levels in all the profiles are approximately the same, the apparent difference being caused by the different plotting scales.)



$\ell^{II}$ (°)
S
$T_c$ (°K)
0.71
0.66
0.60
0.53
0.43
0.34
0.24
0.14
0.06
359.96
359.87
359.78
359.67
359.56
359.47
359.41
2.0 7.8
2.0 11.1
2.0 8.8
0.5 8.0
0.2 4.2
0.2 6.7
0.5 12.5
0.5 13.0
0.5 14.8
2.0 38.0
0.5 15.8
0.2 4.1
0.2 3.8
0.2 3.5
0.2 5.0
0.2 4.3
S °K
-200
-100
0
+100
V (km/sec)


FIG. 2b

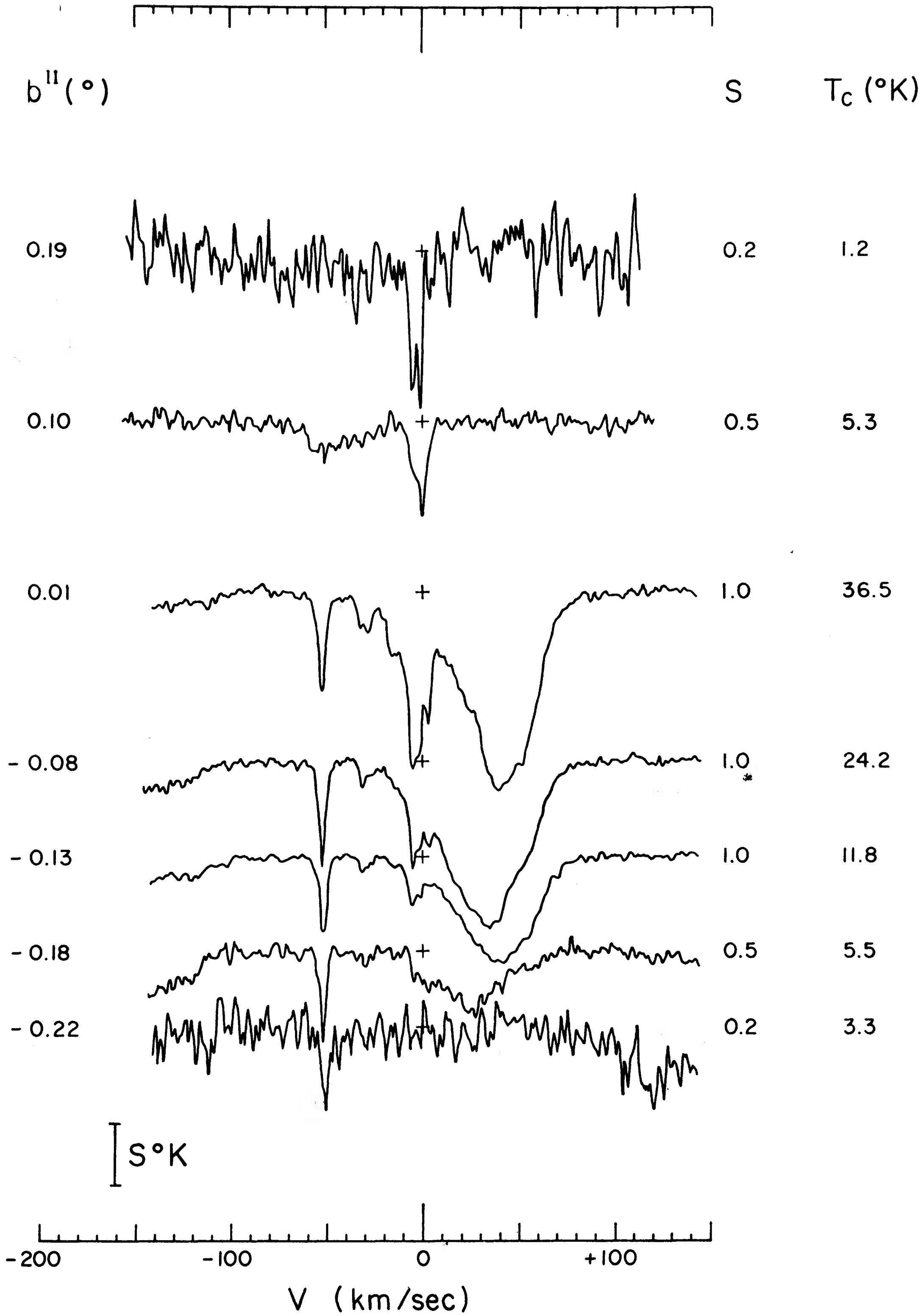



FIG. 2c.—Spectra taken in a strip perpendicular to the galactic plane ($l^{II} = 0°.0$) from $b^{II} = -0°.22$ to $b^{II} = 0°.19$ are plotted in the same manner as Figures 2a and 2b.

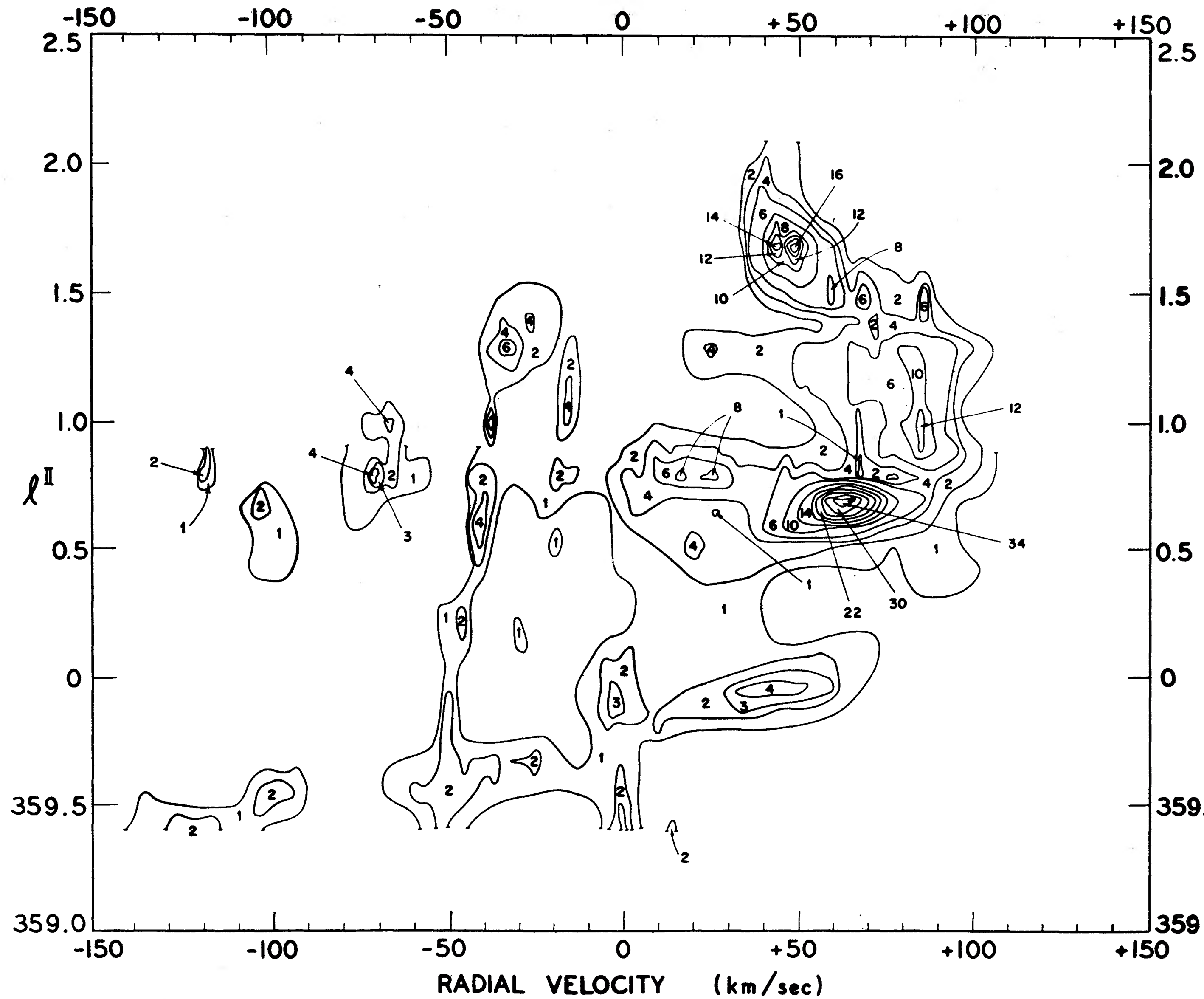



FIG. 3*a*.—Contour diagram of $\tau(v)$ for 6-cm $H_2CO$ in the (galactic longitude, velocity)-plane at $b^{II} = -0\overset{\circ}{.}03$. Optical-depth contour unit is 0.025.

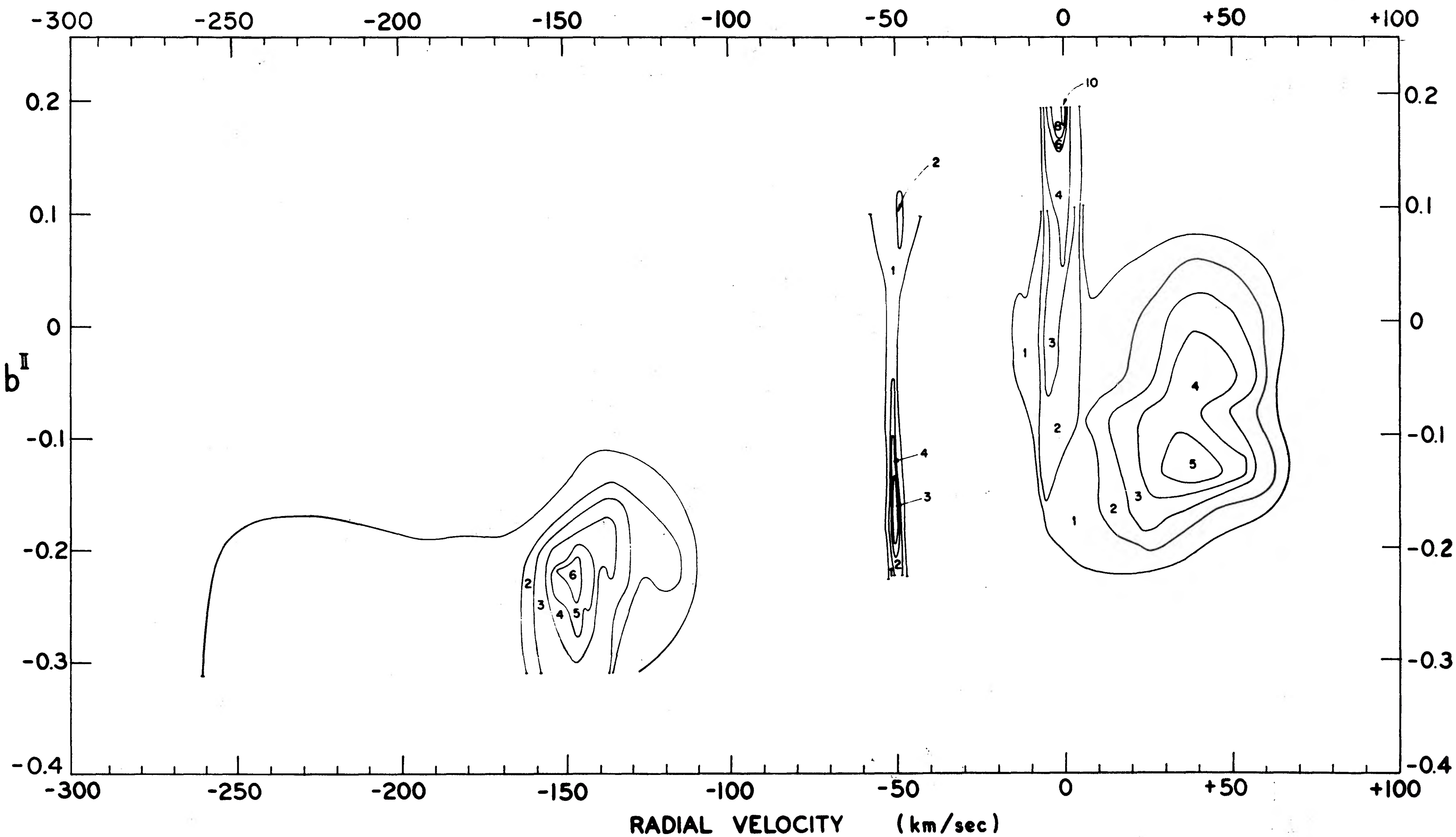



FIG. 3b.—Contour diagram of $\tau(v)$ in the (galactic latitude, velocity)-plane at $l^{II} = 0\overset{\circ}{.}00$. Optical-depth contour unit is 0.025.

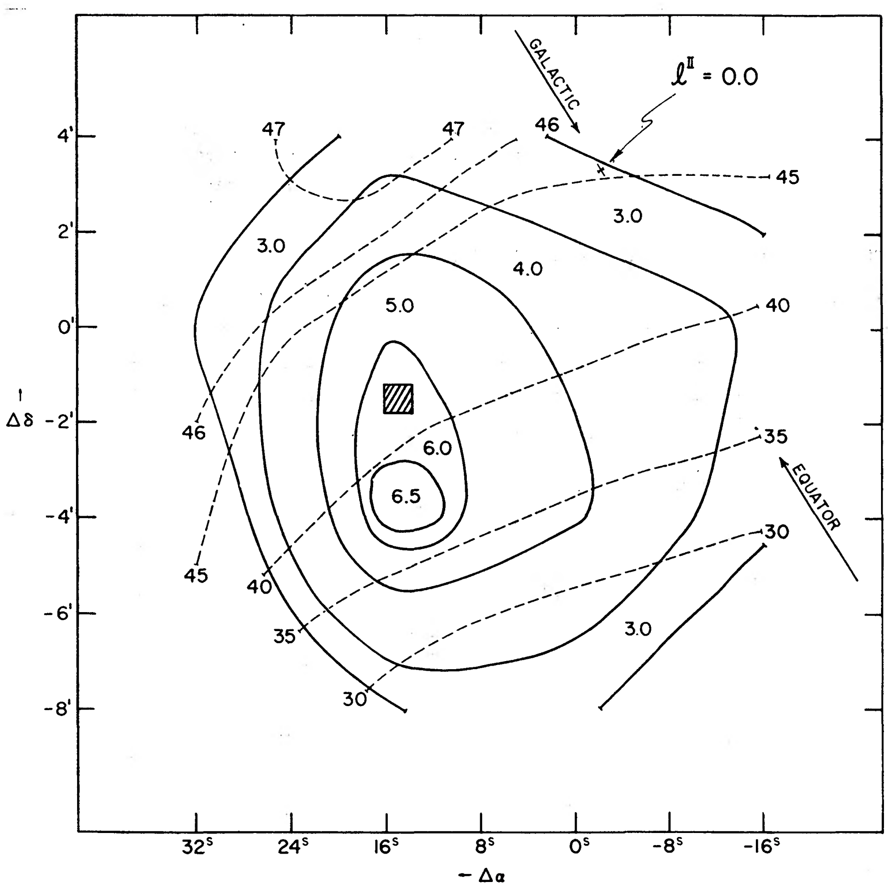



FIG. 4a

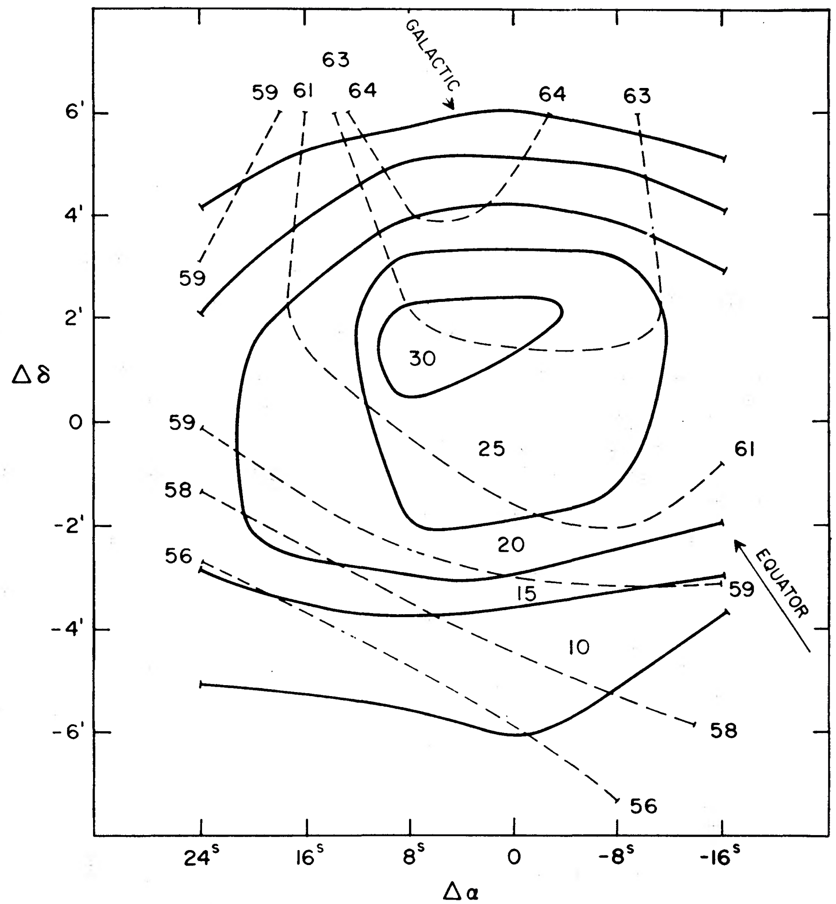



FIG. 4b

FIG. 4a.—Contour diagram of $W$ (equivalent width) (*solid contours*) and $V_c$ (velocity centroid of the line) (*dashed contours*) in the $\Delta\alpha$ and $\Delta\delta$ plane for Cloud 5. $\Delta\alpha$ and $\Delta\delta$ are the right-ascension and declination displacements from the Sgr A continuum peak at 6 cm ($\alpha_{1950} = 17^h42^m28^s$, $\delta_{1950} = -28°58'30''$). The units of $W$ are km s$^{-1}$. ▨, position of the infrared emission source D (Becklin and Neugebauer 1968).

FIG. 4b.—Contour diagram of $W$ (equivalent width) (*solid contours*) and $V_c$ (velocity centroid of the line) (*dashed contours*) in the $\Delta\alpha$ and $\Delta\delta$ plane for Cloud 10. $\Delta\alpha$ and $\Delta\delta$ are the right-ascension and declination displacements from the Sgr B2 continuum peak at 6 cm ($\alpha_{1950} = 17^h44^m07^s$, $\delta_{1950} = -28°21'36''$). The units of $W$ are km s$^{-1}$.

## TABLE 1

SUMMARY OF OBSERVED QUANTITIES FOR FIFTEEN CLOUDS

| Cloud (1) | $l^{II}$ (2) | $b^{II}$ (3) | $\alpha_{1950}$ (4) | $\delta_{1950}$ (5) | $V_{H_2CO}$ [km s$^{-1}$] (6) | $\Delta V_{H_2CO}$ [km s$^{-1}$] (7) | $V_{OH}$* [km s$^{-1}$] (8) | $V_{H\,I}$† [km s$^{-1}$] (9) | $T_L$ [° K] (10) | Remarks (11) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1...... | 359°5 | 0°0 | $17^h41^m14^s$ | −29° 20′ 31″ | − 1.4 | 3.0 | ... | 5 | 0.62 | |
| 2...... | 359.6 | 0.0 | 17 41 29 | −29 15 25 | − 55.2 | 32.0 | ? | − 50 | 0.32 | |
| 3...... | 359.9 | −0.2 | 17 42 59 | −29 06 26 | −148.6 | 28.0 | −136 | −135 | 0.60 | OH Cloud 6‡ |
| 4...... | 359.9 | 0.2 | 17 41 25 | −28 53 50 | − 0.2 | 6.5 | − 3 | ? | 0.52 | OH Cloud 25‡ |
| 5...... | 0.0 | −0.1 | 17 42 40 | −29 02 00 | 45.8 | 31.0 | 36.6§ | 38<br>45 | 3.88 | OH Cloud 40‡ |
| 6...... | 0.1 | −0.1 | 17 43 04 | −28 53 03 | − 30.9 | 4.5 | ... | − 33 | 0.43 | |
| 7...... | 0.2 | 0.0 | 17 42 55 | −28 44 48 | − 47.8 | 4.5 | − 55‖ | ... | 0.89 | |
| 8...... | 0.5 | −0.1 | 17 44 02 | −28 32 36 | 20.1 | 28.0 | 26 | 20 | 1.06 | OH Cloud 41‡ |
| 9...... | 0.6 | −0.1 | 17 44 16 | −28 27 30 | − 42.1 | 5.0 | ... | − 43 | 1.23 | |
| 10...... | 0.7 | 0.0 | 17 44 13 | −28 23 06 | 61.6 | 24.0 | 60§ | 57 | 5.9 | OH Cloud 42‡ |
| 11...... | 0.7 | −0.1 | 17 44 30 | −28 22 23 | −104.8 | 9.0 | − 95# | [−110] | 0.749 | OH Cloud 10‡ |
| 12...... | 0.8 | 0.0 | 17 44 21 | −28 14 08 | 24.1 | 28.0 | 26 | ... | 0.65 | OH Cloud 43‡ |
| 13...... | 0.9 | −0.1 | 17 44 59 | −28 12 08 | 84.6 | 16.0 | 78# | 75 | 0.70 | OH Cloud 59‡ |
| 14...... | 1.3 | 0.0 | 17 45 32 | −27 48 31 | − 32.4 | 12.5 | − 25 | ... | 0.41 | OH Cloud 28‡ |
| 15...... | 1.7 | 0.0 | 17 46 28 | −27 28 01 | 48.5 | 14.5 | 44 | ... | 0.69 | OH Cloud 50‡ |

NOTE.—$H_2CO$ measurements pertain to the position of observed maximum optical depth. Velocities are with respect to local standard of rest. A "?" indicates the existence of a possible feature in OH or H I.

* OH velocities are taken from Robinson and McGee (1970) and McGee (1970) unless otherwise noted.

† Kerr and Vallak (1967).

‡ McGee (1970).

§ Palmer and Zuckerman (1967).

‖ Estimated from Fig. 1*f* in McGee (1970).

\# Estimated from Fig. 1*e* in McGee (1970).

TABLE 2

DERIVED QUANTITIES FOR $H_2CO$ CLOUDS

| Cloud (1) | $\tau_{max}$* (2) | $\tau_{max}/\tau_{OH}$† (3) | $W$ [km s$^{-1}$] (4) | $N_1$ [$10^{14}$ cm$^{-2}$] (5) | $\Delta\theta$ [′] (6) | $D$‡ [pc] (7) |
|---|---|---|---|---|---|---|
| 1.... | 0.11 | ... | 0.49 | 0.12 | 11 | $\ll$32§ |
| 2.... | 0.076 | ... | 2.27 | 0.52 | 21 | 61 |
| 3.... | 0.17 | 0.75 | 5.26 | 1.23 | $\gtrsim$ 9 | $\gtrsim$26 |
| 4.... | 0.31 | 1.0 | 2.52 | 0.58 | >16 | §‖ |
| 5.... | 0.155 | 0.60 | 6.55 | 1.36 | 9 | 26 |
| 6.... | 0.032 | ... | 0.22 | 0.05 | 11 | 32 |
| 7.... | 0.069 | 0.69 | 0.37 | 0.09 | > 8 | >23 |
| 8.... | 0.13 | 0.39 | 3.17 | 0.74 | $\lesssim$ 5 | $\lesssim$14 |
| 9.... | 0.14 | ... | 0.81 | 0.19 | 12 | 35 |
| 10.... | 0.924 | 2.2 | 31.02 | 7.23 | 8 | 23 |
| 11.... | 0.078 | 0.21 | 1.03 | 0.24 | 12 | 35 |
| 12.... | 0.22 | 0.70 | 7.44 | 1.73 | 7 | 20 |
| 13.... | 0.35 | 1.1 | 6.29 | 1.47 | 30 | 87 |
| 14.... | 0.19 | 0.31 | 3.72 | 0.87 | >20 | >57 |
| 15.... | 0.52 | 1.1 | 9.96 | 2.32 | 25 | 72 |

* For the reasons given in § II, the true value of $\tau$ is probably much larger than $\tau_{max}$.
† $\tau_{OH}$ McGee (1970).
‡ Calculated under the assumption that the cloud is at a distance of 10 kpc.
§ These clouds are probably much closer than 10 kpc.
‖ Full extent of this feature not mapped.

The assumption that the clouds are at a distance of 10 kpc is certainly questionable for the lines which have nearly zero radial velocity; Clouds 1 and 4, following the 21-cm analysis, probably originate in the intermediate spiral arms. Clouds 1, 3, and 4 are all apparently centered outside the latitude of the survey (see Fig. 3*b*) and probably have greater peak optical depth and angular extent than is listed in Table 2.

## IV. DISCUSSION

### *a) Comparison of* $H_2CO$, OH, *and* H *Lines*

The $H_2CO$ absorption lines in the direction of the galactic center show a general resemblance to those of OH, but differ markedly from the 21-cm lines, especially at low velocities.

Kerr and Vallak (1967) have noted that the major 21-cm feature is the near-zero velocity ridge produced by hydrogen in the Local, the Sagittarius, and the Norma-Scutum arms (see Fig. 1*b*). This broad and pervasive feature obscures H I clouds of small angular extent located at low positive and negative velocities. In formaldehyde at low velocities (Figs. 3*a* and 3*b*) there are only a few narrow features and no evidence for a broad ridge as in 21-cm emission. Even at high velocities ($|V| > 30$ km s$^{-1}$), where there is no masking by a strong and broad H I ridge, there are only ***weak*** 21-cm counterparts to the intense $H_2CO$ absorption features (see Figs. 1*b* and 3*a*). Although the broad H I absorption is difficult to delineate within the H I emission background, the depth of this absorption is undoubtedly small.

The large discrepancy between the H I and $H_2CO$ observations may be due either to instrumental smoothing caused by the poorer spatial resolution of the 21-cm observations, or to a formaldehyde distribution which is much clumpier than the H I. Of these alternatives, it appears that the second is the most important effect in the light of the OH observations, which have nearly the same resolution as the H I, but which show almost the same concentration as the higher-resolution $H_2CO$. Thus the relative smoothness of the observed H I does not seem to be the result of poor 21-cm angular resolution, but is indicative of real variations in the $H_2CO$/H I relative abundance. Arguments presented in the next section show that the regions producing strong formaldehyde absorption have extremely high hydrogen column densities—an indication that the missing hydrogen is mostly molecular. While it is possible that a fortuitous combination of spin temperature and continuum temperature could make large column densities of atomic hydrogen invisible, we regard this as extremely unlikely.

### b) *Formaldehyde Absorption Features*

From the standpoint of both angular and velocity resolution the observations presented here generally represent an improvement over previous surveys of the galactic-center gas. The clear separation of features 5, 10, and 13 into discrete clouds is readily apparent in Figure 3*a*. The last two of these features are probably part of the "rotating nuclear disk" in Rougoor's (1964) interpretation of the 21-cm observations.

Cloud 10 is apparently associated with the H II region Sgr B2: it is nearly centered on the continuum peak, its size is only slightly larger than the continuum source, and its velocity agrees well with the 61.6 km $s^{-1}$ H109$\alpha$ recombination line (Reifenstein *et al.* 1970).

The velocities of Clouds, 2, 7, and 9 are about that of the 4-kpc expanding arm seen at 21 cm (Rougoor and Oort 1960; Rougoor 1964). For this reason, and because the weak bridges that link Cloud 2 to Cloud 7 and Cloud 7 to Cloud 9 are probably real, we identify these clouds with this arm; Cloud 14 should probably be included as well. Cloud 9 is at the same longitude as the continuum source Sgr B2, and its 6-cm optical depth implies that the Sgr B2 continuum source is behind the 4-kpc arm. Surprisingly, however, there is no observed OH absorption at the position and velocity of Cloud 9 (Robinson and McGee 1970), and thus the possibility that Sgr B2 is in front of the 4-kpc arm cannot be entirely ruled out, since the $-42$ km $s^{-1}$ line (Cloud 9) could arise from absorption of the diffuse galactic continuum and the microwave background. We do not favor this

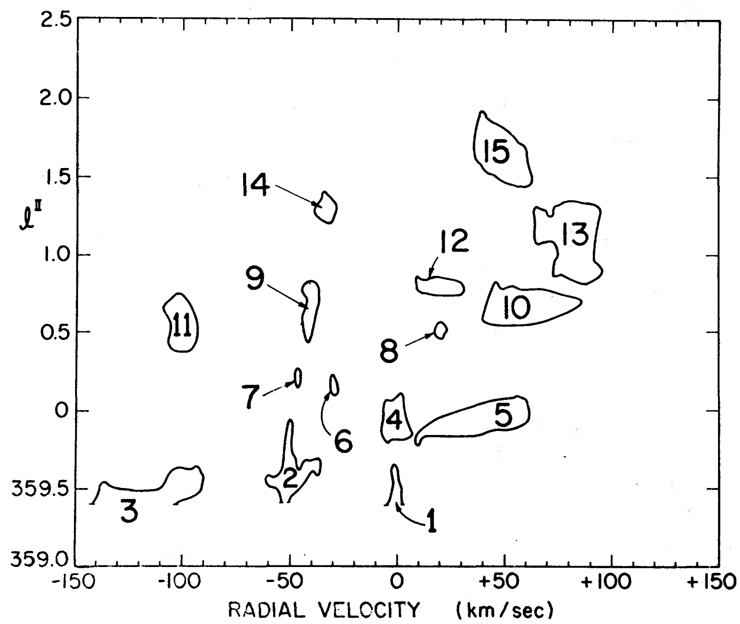



FIG. 5.—Drawing of the outside contours for clouds plotted in Fig. 3*a*, listed in Table 1, and discussed in the text.

interpretation because the optical depth required to explain the observed line strength would be very large, far larger in fact than for any other feature observed. We find the most reasonable explanation for the absence of an OH feature corresponding to Cloud 9 to be an anomalously low OH abundance in that cloud.

Cloud 3 offers still another interesting discrepancy between the formaldehyde and OH observations. The OH line in Sgr A at $-135$ km s$^{-1}$ has half the intensity of the line at $+46$ km s$^{-1}$. On the other hand, there is no $-135$ km s$^{-1}$ $H_2CO$ line in the direction of Sgr A, it only becoming clearly visible 10′ to the southeast (cf. Figs. 2*c* and 3*b*). The most obvious explanation is that the $H_2CO$ is confined to a smaller region in this cloud than the OH.

Clouds 11 and 3 are two $H_2CO$ features that may be associated with an "expanding or contracting arm" observed in H I and OH. The continuity of this arm is absent from the $H_2CO$ observations, but the optical depth is so low in the two observed features that we would not expect to be able to see a bridge between them. It is of some interest that while the OH/H I optical-depth ratio is unusually high in the features that make up this arm, the $H_2CO$/OH optical-depth ratio is very low for the same features.

Determination of the actual distance of gas seen in the direction of the galactic center has always been a major problem in studying the central region of the Galaxy. Rotational velocities are perpendicular to the line of sight, and large noncircular motions make conventional arguments based on galactic-rotation models unreliable. Distances to the molecular clouds, however, can be inferred from their angular distribution with respect to the galactic center, or by establishing a connection between $H_2CO$ lines and H I features or radio sources with known distances.

The observations presented in this paper are too limited in their angular coverage to draw conclusions about the distribution of the $H_2CO$ clouds relative to the galactic center. In Paper III of this series where $H_2CO$ observations out to $l^{II} = 4\overset{\circ}{.}7$ are described, only two additional clouds are found—both at $l^{II} < 3\overset{\circ}{.}2$. This cutoff in the number of $H_2CO$ clouds at high longitudes strongly suggests that the wide-line, high-velocity molecular clouds are located near the center of the Galaxy. The latitude distribution of these clouds cannot be determined from our $H_2CO$ observations, but it is noteworthy that the OH clouds are tightly packed in latitude near the galactic plane (Robinson and McGee 1970; McGee 1970).

Clouds 3, 5, 10, and 13 have, as already noted above, apparent H I counterparts, and these are thought to originate in galactic-center arms and the nuclear disk (Rougoor and Oort 1960), suggesting that the corresponding molecular clouds are also in the central part of the Galaxy.

The best evidence of large distances for the wide-line molecular clouds is provided by Cloud 10, which appears to be associated with the H II region Sgr B2, as noted in the beginning of this subsection. The strong absorption of continuum radiation from Sgr B2 by the 4-kpc arm (Cloud 9) implies that Sgr B2, and consequently Cloud 10, are behind the 4-kpc arm.

None of the above arguments is foolproof, but taken as a whole they strongly suggest distances comparable to that of the galactic center for many of the broad-line, high-velocity $H_2CO$ clouds considered in this paper. The distances of the narrow-line, low-velocity clouds are another matter; they will be discussed later in this section.

### i) *Cloud 5*

Cloud 5, the intense line seen in the direction of Sgr A, warrants considerable discussion (Figs. 2*b*, 2*c*, 3*a*, 3*b*, and 4*a*). Kerr and Sandquist (1968), in a series of lunar-occultation measurements, studied the OH counterpart of this $H_2CO$ cloud. They found the OH cloud to be symmetrically placed about Sgr A with a diameter of $3' \times 5'$, and interpret an observed velocity gradient in the cloud as rotation. From Figure 4*a* we see that the location of maximum 6-cm equivalent width is 6′ from the Sgr A continuum peak (Fig. 1*a*). This, together with the fact that the angular diameters of the cloud and the continuum source (Reifenstein *et al.* 1970) are less than 9′ and 7′, respectively, makes it unlikely that the cloud and the nonthermal component of Sgr A are physically associated. However, it is noteworthy that a 2.2-$\mu$ infrared source (Becklin and Neugebauer 1968) is centered on the $H_2CO$ cloud, has about the same angular diameter $\sim$6′, and may therefore be physically associated with Cloud 5.

The plot in Figure 4*a* of equivalent-width and velocity-centroid contours for Cloud 5 is helpful in estimating the physical and dynamical structure of the cloud. An incomplete map of this region which has the same appearance as ours has been obtained by Zuckerman *et al.* (1970) (but note that they plot the optical depth and velocity measured at the line peak instead of equivalent width and velocity centroid). As can be seen from Figure 4*a*, the equivalent-width contours are smooth (probably a consequence of the relatively large telescope beam), but become closely spaced at the edge of the cloud. Thus the cloud appears to be nearly spherical, with rather sharp boundaries. The behavior of the velocity-centroid contours is interesting, since they are almost perpendicular to the galactic equator and are essentially straight lines across the face of the cloud. The observed velocity gradient is roughly constant, and is

$$\frac{dV_c}{dl^{\mathrm{II}}} \sim 2 \text{ km s}^{-1} \text{ per minute of arc} .$$

The true velocity gradient may be larger than this since our 6.′6 beam is comparable in size to the region over which the gradient exists. This gradient is compatible with either rotation about an axis which is perpendicular to the galactic plane (cf. Kerr and Sandquist 1968), or contraction or expansion of the cloud parallel to the galactic plane. *A priori* we can see little reason for an expansion or contraction in a single direction which would have a nearly constant velocity gradient. Expansion or contraction velocities of 10 km s$^{-1}$ would transform the cloud into an extreme prolate or oblate configuration in a time $\tau_{\mathrm{ex}}$ of less than $10^6$ years, assuming the distance of the cloud is 10 kpc. If instead we interpret the observed velocity gradient as solid-body rotation of this cloud, then the rotational period is simply $2\pi\tau_{\mathrm{ex}}$, or $6 \times 10^6$ years.

Another time scale of importance for the dynamics of gas near the galactic center is the rotation period of the nuclear disk. From the 21-cm observations (Rougoor 1964) we may estimate, by interpolation from the outer parts of the disk, that the central region has a rotation period of $\sim 10^7$ years. Although the near coincidence of the rotation period of the disk and the possible rotation period of Cloud 5 may merely be fortuitous, the possibility of synchronous rotation for this cloud, if it is part of the nuclear disk, is one possible explanation for the similarity of the two rotation periods. Both the magnitude and the sense of the observed rotation correspond to synchronous motion. On the other hand, it is possible to imagine that Cloud 5 is not part of the nuclear disk, but has been ejected from the galactic center at an angle $\theta$ with respect to the galactic-center direction. Although it seems unlikely that we should observe it during its relatively short lifetime $\tau = (4.5 \times 10^5) \cot(\theta)$ years, which is less than the cloud-rotation time scale unless $\theta < 5°$, we cannot at present rule out this explanation since the age of the cloud could be as small as $10^6$ years.

We may use the virial theorem to estimate the mass needed by Cloud 5 if it is to be gravitationally bound. In applying the virial theorem we can neglect the thermal energy of the gas and consider the total kinetic energy to be the sum of the "rotational" energy and the turbulent energy as estimated from the measured velocity width given in Table 1. Assuming the cloud is spherically symmetric and of uniform density, we find that

$$M/M_{\odot} \simeq 6.5 \times 10^4 d , \tag{4}$$

where $d$ is the distance of the cloud in kiloparsecs. Thus if the cloud is located near the galactic center, the required binding mass is $6.5 \times 10^5 M_{\odot}$. For a uniform cloud, the average density required by the virial theorem, $\rho_v$, is given by

$$\rho_v \simeq \frac{3 \times 10^5}{d^2} m_{\mathrm{H}} \mathrm{cm}^{-3} . \tag{5}$$

At the distance of the galactic center, the implied particle density would be greater than $3 \times 10^3$ cm$^{-3}$ for atomic hydrogen and $1.5 \times 10^3$ for molecular hydrogen. In this calculation, the turbulent kinetic energy is greater than the "rotational" energy by only a factor of $\sim$4; thus the derived density required for binding is only weakly dependent on the particular model employed.[2]

The most important objection to the use of the virial theorem is that the cloud may not be gravitationally bound. In order to see whether the density required by the virial theorem is consistent with what is expected on other grounds, we can estimate the density in Cloud 5 from the measured *equivalent* width of the formaldehyde line which is given in Table 2. This calculation requires an assumption about the ratio of the $H_2CO$ density to the total gas density in the cloud.

It has been suggested from analysis of 21-cm observations by Heiles (1969) and Mészáros (1968) that dense clouds are composed primarily of molecular hydrogen. Solomon and Wickramasinghe (1969) have shown that the rate of $H_2$ formation on dust grains in clouds with gas densities greater than 100 cm$^{-3}$ is sufficient to produce a layer of $H_2$ in the outer part of the cloud which will be self-shielding against photodissociation. The interior of the clouds will then be almost completely molecular hydrogen. Measurements of the ratio of the hydrogen column density to the visual extinction indicate a value of $2 \times 10^{21}$ for the dust-to-gas ratio in atomic-hydrogen clouds (Lilley 1955; Lambrecht and Schmidt 1957; Heiles 1967). As a working hypothesis we assume that the formaldehyde-to-dust ratio is the same in all dense clouds, and that a constant mass ratio of hydrogen to dust applies for all interstellar clouds, whether atomic or molecular.

Formaldehyde observations of dark clouds (Palmer *et al.* 1969; Kutner *et al.* 1972) indicate that a cloud with about 5 mag of extinction will have a 6-cm line with an equivalent width of $\sim$1 km s$^{-1}$. Therefore, if the observed lines are optically thin and the relative $H_2CO$ abundance is the same in Cloud 5 as in the dark clouds, there will be a hydrogen column density of $\sim 6.55 \times 10^{22}$ in Cloud 5 where the formaldehyde equivalent width is 6.55 km s$^{-1}$. The cloud density obtained with the $H_2CO$ equivalent width, $\rho'$, is then given by

$$\rho' = 8.4 \times 10^3/d \; m_{\mathrm{H}} \mathrm{cm}^{-3} . \tag{6}$$

Equation (6), which uses the equivalent width based on apparent optical depth (eq. [1]) must be considered a minimum if the assumption of constant $H_2CO/H_2$ is correct. The discrepancy between the densities given in equations (5) and (6) is less than a factor of 4 ($\rho'/\rho_v = 0.3$), if this cloud is located near the galactic center ($d \sim 10$ kpc). The uncertainties in the physical model implicit in the use of the virial theorem and in the use of equation (1) are much greater than this agreement would indicate, but the equivalence of the dynamical density (5) and the equivalent-width density (6) is suggestive. In Paper II (Scoville *et al.* 1971) we present evidence based on CO observations consistent with these values.

ii) *Cloud 10* (*Sgr B2*)

The analysis employed above for Cloud 5 may also be applied to Cloud 10 (Sgr B2), which has several remarkable similarities to Cloud 5. The Cloud 10 line is both broad and optically thick; and the line has an angular extent comparable with Cloud 5. Cloud

[2] It is also interesting to note that if Cloud 5 is located only 20 pc from the galactic center (its apparent distance), then its own self-gravitation would probably be small compared to the external forces acting on it and a much larger mass would be required for stability. This is a good indication that Cloud 5 is much farther from the galactic center than its apparent distance. (We thank J. Oort for pointing this out to us.)

10, Figure 4*b*, has no obvious rotation, and if it is located in the nuclear disk, it is not rotating synchronously. For Cloud 10, equations (4), (5) and (6) give

$$M/M_\odot \simeq 2.7 \times 10^4\, d\,, \tag{7}$$

$$\rho_v \simeq \frac{1.8 \times 10^5}{d^2}\, m_{\rm H}\ {\rm cm}^{-3}\,, \tag{8}$$

and

$$\rho' = 4.5 \times 10^4/d\ m_{\rm H}\ {\rm cm}^{-3}\,. \tag{9}$$

The two independent estimates of density (virial theorem and equivalent width) are in good agreement for each cloud. Although the close agreement is partly fortuitous, this suggests that the $H_2CO/H_2$ relative abundance $\sim 10^{-8}$ is similar in nearby dark clouds and in the galactic-center clouds. It is interesting to note that the mass estimate for these regions based on an optically thin interpretation of 21-cm results gives only $10^{-3}$ of the mass calculated from the formaldehyde observations.

#### iii) *"Local" Clouds*

Galactic-center lines which are actually formed near the Sun are likely to be at near-zero velocity, narrow, and of large angular extent, possibly with their maximum depth above or below the galactic plane. On the basis of these criteria, it is likely that Clouds 1 and 4 are comparatively local. Figure 3*b* clearly shows both that the Cloud 4 line is narrow and that it reaches its highest level 0°2 above the galactic plane. It is reasonable to assume that we have not located the true maximum for this line, which may be at still higher latitude. The true location of Cloud 1 is more uncertain, but the narrowness of the line and its low velocity strongly imply that it is not at the galactic center.

### *c) Observations with High Velocity Resolution*

Some of the line profiles observed at a resolution of 1.63 km $s^{-1}$ showed evidence of fine velocity structure. Several examples may be seen in Figure 2*b*. We therefore studied a few selected positions with a resolution of 0.41 km $s^{-1}$, covering the velocity range $-60$ to 20 km $s^{-1}$. It is unlikely that additional cloud structure would be brought out at still higher resolution because of the 6-cm hyperfine structure.

We have found little evidence for fine velocity structure except in the case of the "local origin" lines, e.g., Cloud 4. This line definitely has three and in some directions four distinct components. One of these components, at $+4.0$ km $s^{-1}$, appears in the directions of both Sgr A and Sgr B2, but we do not know whether this component can be continuously traced between these positions which are separated by more than 0°7 of longitude.

The lines originating in the 4-kpc arm also show some velocity structure, although not to the extent that the "local" features do. More importantly, the measured peak temperatures for the features of the 4-kpc arm can be significantly underestimated when low velocity resolution is used. In some cases the maximum depth is increased by approximately a third with higher resolution.

## V. CONCLUSIONS

The most important results of this galactic center formaldehyde survey are:

1. The $H_2CO$ distribution in the galactic-center direction shows a greater similarity to the OH than to the H I distribution; in particular, the low-velocity ridge—which shows up strongly at 21 cm—is very nearly absent from the $H_2CO$ observations, and several of the strongest $H_2CO$ lines have no 21-cm counterparts. This might mean that the 21-cm spin temperature is very low in most clouds containing $H_2CO$, but, since neither 21-cm emission or absorption is pronounced, the most reasonable explanation is that a large fraction of the hydrogen is in the form of $H_2$.

2. The $H_2CO$ appears to lie in rather discrete, generally unconnected clouds, indicating that the molecular regions are extreme condensations within the smoother density distributions of the H I arms and nuclear disk. Out of fifteen observed clouds only the Sgr B2 line (Cloud 10) is known to be associated with an H II region.

3. The estimated masses of two of the galactic-center molecular clouds (Sgr A and B2) are in the range $10^5$–$10^6$ $M_{\odot}$ which corresponds to average densities of the order $10^3$–$10^4$ H atoms per $cm^3$. Other clouds observed in the vicinity (Clouds 12, 13, and 15) may be similarly massive and dense.

4. The excitation temperature of the $H_2CO$ 6-cm transition is definitely less than 4° K in many of the clouds near the center, but no case of anomalous absorption ($T_{12} <$ 2.7° K) has been conclusively demonstrated in these regions.

5. The most interesting result of this work is the strong evidence that very dense and massive gas and dust clouds exist in the central region of the Galaxy. These dense clouds are in no way apparent from 21-cm surveys and it is evident that observations of formaldehyde absorption provide a powerful tool for analyzing the distribution of dense interstellar gas. The question of the relation of these dense clouds to the interstellar medium as a whole has not been raised in this article, but their contribution to the total mass of the interstellar matter, particularly near the center of the Galaxy, may be substantial.

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