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SURVEY OF MOLECULAR LINES NEAR THE GALACTIC CENTER. III. 6-CENTIMETER FORMALDEHYDE ABSORPTION AT $b = -2'$ FROM $l = 2°0$ TO $l = 4°5$ AND AT $b = -12'$ FROM $l = 358°5$ TO $l = 2°0$

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ABSTRACT

Our initial survey in the 6-cm transition of formaldehyde near the galactic plane ($b = -2'$) has been extended out to $l = 4°5$, and a parallel strip at $b = -12'$ has been mapped between $l = 358°5$ and 2°0. These new observations suggest that the group of dense, low-positive-velocity clouds does not continue beyond $l = 2°$ and that the negative-velocity clouds are part of an arm structure within 300 pc of the galactic center and having a total mass of $\sim 10^6\ M_\odot$. We also note the existence of molecular gas at $l = 2°3$ with a velocity of 240 km s^{-1} (similar to that of H I in the rotating nuclear disk).

Subject headings: molecules — galactic structure — galactic nuclei

I. INTRODUCTION

Comparative surveys of 6-cm formaldehyde (H_2CO) absorption and 2.6-mm carbon monoxide (CO) emission in the galactic center have been reported by Scoville, Solomon, and Thaddeus (1972, hereinafter Paper I) and Solomon *et al.* (1972, hereinafter Paper II). Both lines were observed in Sgr A, Sgr B2, and along a strip parallel to the galactic plane ($b = -2'$) from $l \approx 359°5$ to $l \approx 2°2$. A good correspondence is generally found between these H_2CO and CO results and the earlier observations of 18-cm OH absorption (McGee 1970), although the relative optical depths in the three lines vary somewhat from feature to feature. All three molecules appear to be concentrated in clouds to a much greater extent than H I. Indeed, several of the strongest H_2CO and CO features show only weak (or missing) 21-cm counterparts, suggesting that most of the mass in these clouds is molecular hydrogen. The H_2CO lines from two clouds (5 and 10, Paper I) seen in the directions of Sgr A and B2 indicate masses of $\sim 5 \times 10^5\ M_\odot$ and densities of 10^3–10^4 cm^{-3}; the CO, ^{13}CO, and $C^{18}O$ observations in one of these clouds yield lower limits which are similar to these values.

The 6-cm observations that we present here more than double the angular coverage of those in Paper I and represent a preliminary investigation into the longitude and latitude distributions of the H_2CO absorption near the galactic center. We have extended the observations at $b = -2'$ out to $l = 4°5$, and have also obtained a 6-cm map at $b = -12'$ from $l = 358°5$ to $l = 2°0$.

II. OBSERVATIONAL TECHNIQUE AND DATA REDUCTION

The observations were carried out in 1971 April using the 140-foot (43-m) antenna, a cooled 6-cm parametric amplifier, and the 384-channel digital autocorrelation

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receiver of National Radio Astronomy Observatory (NRAO)[1] in Green Bank, West Virginia. The final velocity resolution after cosine filtering is 1.63 km s^{-1} while the half-power beamwidth (HPBW) of the telescope at 6 cm is 6′.6.

Data were taken in the "total power mode" and have been reduced as previously described in Paper I. In order to neutralize the effect of continuum intensity variations, all observed line temperatures were converted to apparent optical depth τ, as defined by equation (1) of Paper I. We must, however, caution that this procedure gives a good representation of variations in gas column density only if the molecules are in front of the sources of continuum radiation; the present survey includes areas where much of the continuum radiation is diffuse galactic emission some of which presumably arises in front of molecular clouds in the galactic center. The calculated optical depth also depends critically on the adopted excitation temperature ($= 1.75°$ K) of the 6-cm levels if the continuum intensity is low, as is the case at $l > 2°$.

III. DISCUSSION

The results are presented in two longitude-velocity contour diagrams. The first shows the 6-cm optical depth along a strip parallel to the galactic equator at $b = -12'$ from $l = 358°.5$ to $l = 2°.0$. The observations were separated by 6′ in longitude, so that figure 1 is analogous to figure 3*a* of Paper I except that it is 10′ lower in latitude.

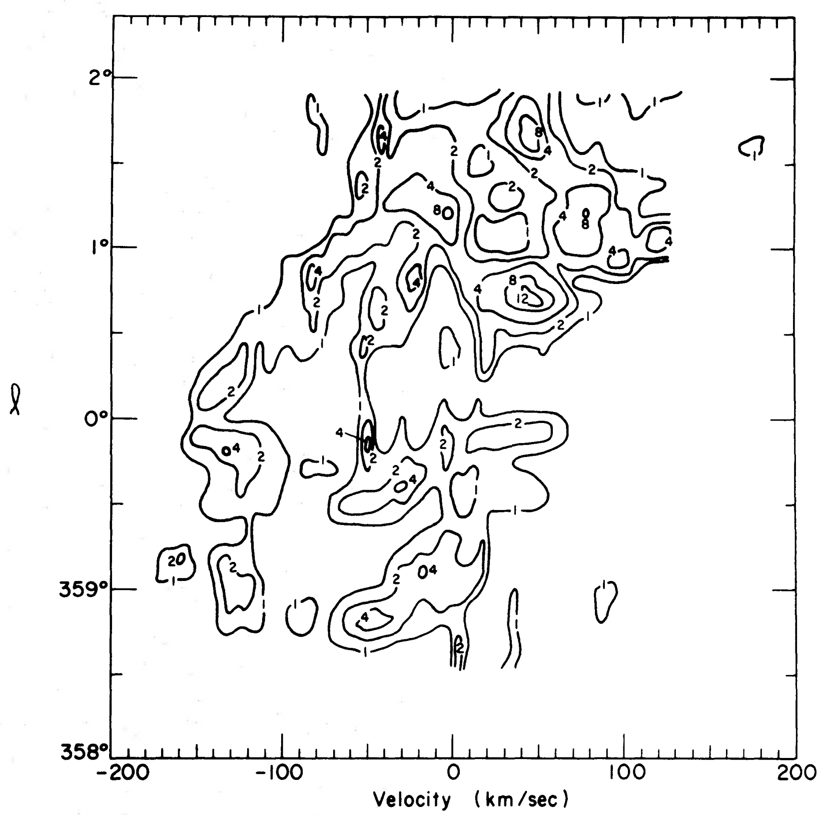

FIG. 1.—Contour diagram of $\tau(v)$ for 6-cm H_2CO in the galactic longitude-velocity plane at $b = -12'$. Optical-depth contour unit is 0.025.

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

Figure 2 is a similar contour diagram for observations at $b = -2'$ from $l = 2^\circ\!.0$ to $l = 4^\circ\!.5$; this serves as an extension to higher longitudes of figure 3*a* in Paper I. The longitude spacing of these observations was 6′ between $l = 2^\circ\!.0$ and $l = 3^\circ\!.0$ and 12′ for $l > 3^\circ\!.0$. The noise level of the optical depth in the second figure is about twice that in the first because of the lower continuum intensities at $l > 2^\circ$.

a) *$l = 358^\circ\!.5$ to $2^\circ\!.0$, $b = -12'$*

The greatest differences between these observations (at $b = -12'$) and those at $b = -2'$ occur in the clouds producing broad absorption lines (compare fig. 1 with fig. 3*a* of Paper I). Four of the clouds with velocities between +40 and +90 km s^{-1} have optical depths which are lower by a factor of 2 at $b = -12'$ than those at $b = -2'$. These positive-velocity features were discussed in detail in Paper I, and the above optical-depth decreases are consistent with the small angular sizes previously estimated.

A more novel result of the lower-latitude observations is the fairly continuous sequence of broad-line clouds at large *negative* velocities seen over almost the entire longitude interval. Several of these clouds are observed at $b = -2'$, but there is little evidence of continuity between them. In general this gas has lower peak optical depths than the positive-velocity clouds, and appears to be less condensed into discrete clouds since relatively strong bridges exist between the local maxima in the negative-velocity absorption. This group of negative-velocity "clouds" is also seen in the 18-cm OH line (McGee 1970) with even greater continuity between clouds. Moreover, there is an H I feature (feature V [Van der Kruit 1970]) with about the same longitude-velocity dependence as this negative-velocity molecular gas.

In OH, H I, and apparently H_2CO this feature can be traced to low velocities at about $l = 1^\circ\!.5$ on one end and at $l = -1^\circ\!.25$ on the other. The apparent lack of its

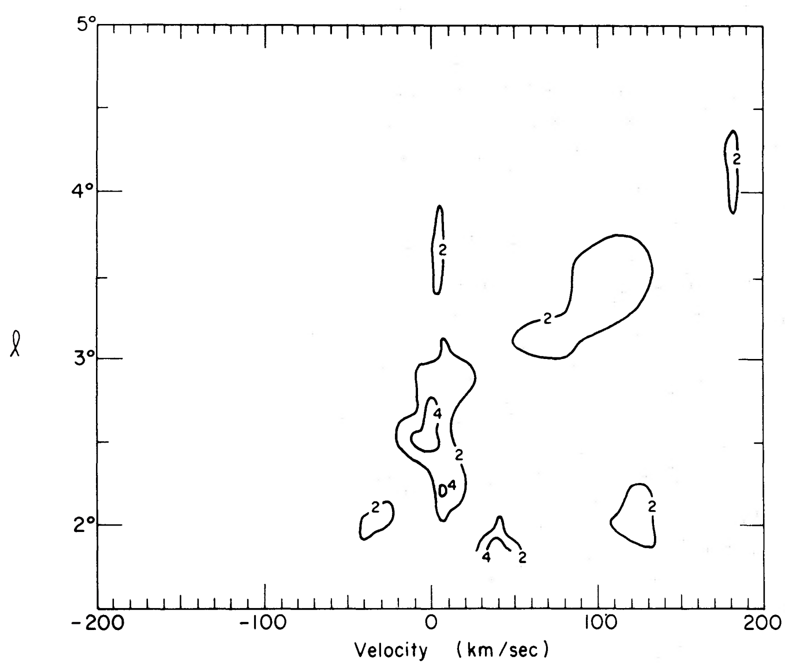

FIG. 2.—Contour diagram of $\tau(v)$ for 6-cm H_2CO in the galactic longitude-velocity plane at $b = -2'$. Optical-depth contour unit is 0.025. This diagram is a continuation to higher longitudes of fig. 3*a* in Paper I.

continuation to higher or lower longitudes suggests that the gas is situated within several hundred parsecs of the galactic center. However, the 6-cm absorption at negative velocities and positive longitudes indicates that these clouds have a large component of motion directed toward or away from the galactic center and are not simply rotating with the H I nuclear disk.

The total mass of this feature can be estimated from the equivalent width of its formaldehyde line. The average equivalent width of 1 km s^{-1} suggests a hydrogen (atomic and molecular) column density of $\sim 10^{22}$ cm^{-2} (see Paper I). Upon integrating this average column density over the angular extent of the negative-velocity gas ($\Delta b \sim 20'$; $\Delta l \approx 2\overset{\circ}{.}8$), we find a total mass of $\sim 10^6$ $M_\odot$. In contrast, a rough estimate of the H I mass in the possible 21-cm counterpart gives only 10^3–10^4 $M_\odot$ (Van der Kruit 1970). Part of the discrepancy in these two mass estimates might arise from masking of this 21-cm feature by other H I features which are closer to the Sun. However, a more reasonable explanation is that most of the hydrogen in this feature is molecular hydrogen, as is almost surely the case in the positive-velocity clouds (Paper I).

The mass estimated above is in fact comparable to that ($\sim 2 \times 10^6$ $M_\odot$; Paper I) of the denser but less continuous positive-velocity clouds. Neither the positive- nor the negative-velocity clouds appear to extend beyond $l = 2°$ (see below), and it is likely that all this gas may be contained in a single ring-shaped structure (see Scoville 1972).

b) $l = 2°$ *to* $4\overset{\circ}{.}5$, $b = -2'$

As can be seen from figure 1 (and fig. 3*a* in Paper I), there are at least 12 distinct molecular clouds with 6-cm optical depths greater than 0.1, all less than 2° of longitude from the galactic center. In order to determine if this group of molecular clouds continues out to higher longitudes, we have made the observations shown in figure 2. Although it was noted in § II that the apparent optical depths may be unreliable if the continuum intensity is low, it is probably significant that only one cloud is detected at these higher longitudes with an optical depth greater than 0.1. This suggests either that most of the galactic-center molecular clouds are limited to 2° of longitude (corresponding to 300 pc) from the galactic center, or that those at $l > 2°$ have radial velocities outside the observed range ($|V| \lesssim 150$ km s^{-1}).

McGee *et al.* (1970) have mapped the 18-cm OH absorption in five clouds between $l = 2°$ and $l = 4°$, four of which correspond to the H_2CO lines seen in figure 2 with large widths. The optical depths in these four clouds are several times higher in OH than in H_2CO. The two narrow H_2CO lines near the top of figure 2 were not seen in OH, and their reality is questionable, especially as one of them occurs near the edge of our receiver band.

c) *Gas at High Radial Velocities* (*Cloud 16*)

Conventional models for the H I nuclear disk indicate that there should be gas with radial velocities up to at least 200 km s^{-1} inside of $l = 1°$ (Rougoor and Oort 1960; Oort 1971; Sanders and Lowinger 1972), but to date the extreme velocities have not been observed for molecules there. If these indirectly derived rotation curves are correct, a lack of high-velocity molecules at low longitudes implies either that there are no molecules in the inner region of the disk or that they are not in pure rotation about the galactic center.

It is noteworthy, though, that high-velocity molecular lines can be seen a little farther out from the disk center. In an attempt to verify a high-velocity CO line we searched for 6-cm absorption in about five positions near $l \approx 2°$ at $150 < V < 450$ km s^{-1}. We detected a feature at $l = 2\overset{\circ}{.}30$ and $b = -6'$ (designated Cloud 16;

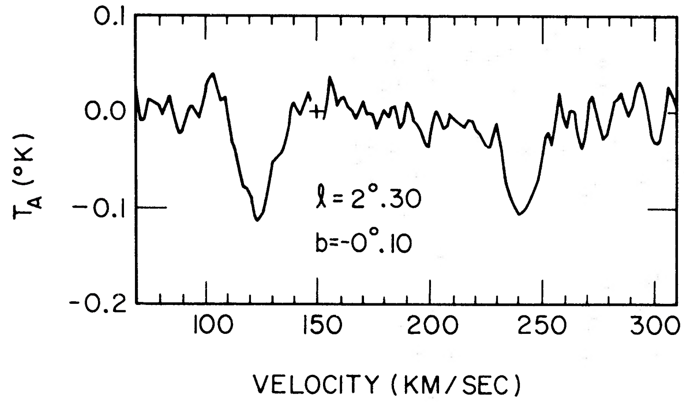

FIG. 3.—High-velocity absorption line at $l = 2\overset{\circ}{.}30$ and $b = -6'$

$\tau = 0.06$; $\alpha_{1950} = 17^h48^m13^s$, $\delta_{1950} = -27°00'03''$; $\Delta\theta \approx 10'$) with a velocity of 240 km s^{-1} (see fig. 3), nearly twice that of any previously reported H_2CO feature. OH absorption is also seen with similar negative velocities at $l < -1°$ (McGee 1970). These two very limited observations suggest that although there is an absence of the expected high-velocity molecules in the center region ($-1° \leq l \leq 1°$), there may be molecular gas in the outer portions of the disk with kinematics quite similar to the H I there.

IV. CONCLUSIONS

1. A fairly continuous sequence of negative-velocity clouds showing broad 6-cm lines extends from $l = -1\overset{\circ}{.}25$ to $l = +1\overset{\circ}{.}5$ with maximum optical depths at $b = -12'$. The total mass of these clouds ($\sim 10^6\ M_\odot$) is much larger than is indicated from 21-cm observations.

2. There are only a few H_2CO clouds at longitudes between 2° and $4\overset{\circ}{.}5$ near the galactic plane with $|V| < 150$ km s^{-1}. This suggests that the group of dense H_2CO clouds with $V < 100$ km s^{-1} reported in Paper I does not extend beyond $l = 2°$.

3. One molecular cloud (Cloud 16) was observed at a velocity of 240 km s^{-1} ($l = 2\overset{\circ}{.}3$), indicating that some of the molecular gas in the galactic center is clearly partaking in the same motion as the H I nuclear disk.

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