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KINEMATICS OF MOLECULAR CLOUDS NEAR THE GALACTIC CENTER

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ABSTRACT

A model is proposed in which most of the molecular clouds near the galactic center are situated in a radially moving ring of radius 250 pc.

I. INTRODUCTION

Surveys of molecular lines in the direction of the galactic center have shown a preponderance of broad lines ($\Delta V \gtrsim 20$ km s^{-1}) at high radial velocities ($V \gtrsim 40$ km s^{-1}). Most of the molecules producing these lines appear to be in discrete clouds having large diameters (∼30 pc, McGee 1970) and masses (10^4–10^6 $M_\odot$, Scoville, Solomon, and Thaddeus 1972). In this *Letter* we show that these clouds may delineate a single, large-scale structure within 300 pc of the galactic center. The kinematics of the structure resemble those of a rotating, expanding ring concentric with the galactic center and lying in the galactic plane.

II. H_2CO AND CO OBSERVATIONS

The most complete surveys of molecules near the galactic center have been made in 18-cm OH absorption (Robinson and McGee 1970; McGee *et al.* 1970), 6-cm H_2CO absorption (Scoville *et al.* 1972; Scoville and Solomon 1972), and 2.6-mm CO emission (Solomon *et al.* 1972). Our discussion is based primarily on observations of the last two lines because of their higher angular resolution (6′ and 1′, respectively); the OH observations are, however, most extensive in angular coverage.

The longitudes and velocities of clouds producing strong molecular absorption lines in the direction of the galactic center are shown in figure 1. Here we have plotted the average 6-cm H_2CO optical depth at latitudes of $-2'$ and $-12'$; *the distribution of OH clouds is very similar to that shown in figure 1*, although a large range in relative opacity of the two lines is apparent (cf. fig. 1*d* of McGee 1970).

At present CO emission has been surveyed only at positive velocities near the strongest sources of centimeter-wavelength continuum radiation in the galactic center (corresponding to the right-hand side of fig. 1). It is in the direction of these sources that we might expect the greatest misrepresentation from absorption lines, which are biased toward gas lying in front of the sources. Thus it is noteworthy that in addition to CO emission from virtually all the positive velocity H_2CO clouds in figure 1, Solomon *et al.* (1972) also detect a CO feature at ∼90 km s^{-1} between the two molecular clouds at $l = 0^\circ.0$ and $l = 0^\circ.7$. This "emission bridge," which has only a very weak counterpart in H_2CO (not apparent in fig. 1; but see fig. 2*b* of Scoville *et al.* 1972), provides the first evidence of a physical link between the well-studied molecular clouds in the directions of Sgr A and Sgr B2. The emission can in fact be continuously graced out to $l = 1^\circ.7$, where it either shifts out of the observed CO velocity range at $+25$ km s^{-1} or fades out entirely.

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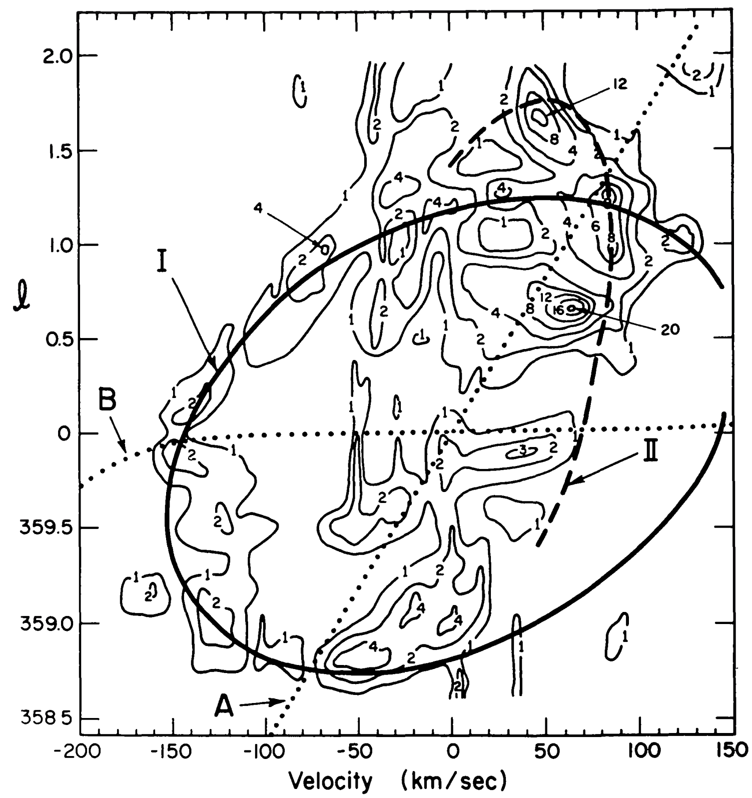

FIG. 1.—Contour diagram in the longitude-velocity plane of the average 6-cm H_2CO optical depth measured at $b = -2'$ (Scoville *et al.* 1972) and at $b = -12'$ (Scoville and Solomon 1972). Optical-depth contour unit is 0.025. As discussed in text, the OH and CO distributions are similar to that of H_2CO. The dotted curves (A and B) show the minimum and maximum radial velocities expected from gas in the disk obeying the rotation law of Sanders and Lowinger (1972). The solid (I) and dashed (II) curves show the longitude-velocity shape of two ring models in table 1.

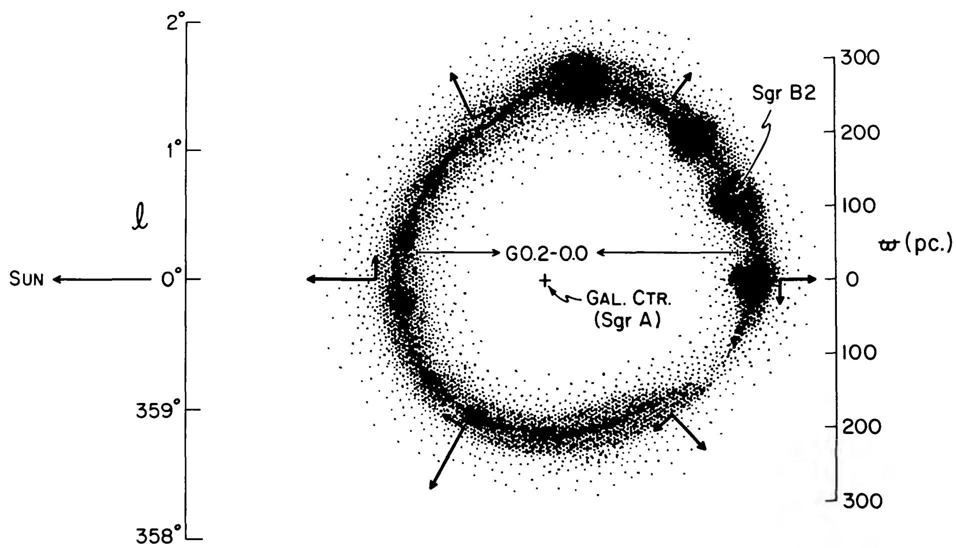

FIG. 2.—Sketch of rotating molecular ring near the galactic center as seen from above the galactic plane. Here the ring is taken to be expanding, although as discussed in the text, contraction cannot be ruled out. The suggested locations of continuum sources relative to ring are included; the label Sgr A refers only to the nonthermal component at $l = 0\overset{\circ}{.}0$, $b = -0\overset{\circ}{.}0$.

III. DISCUSSION

The molecular clouds of figure 1 may be separated into three distinct groups: "local" clouds, 3-kpc arm clouds, and galactic-center clouds. The local and 3-kpc arm clouds have characteristic velocities of 0 and -50 km s^{-1} and show very narrow lines ($\sim$2 km s^{-1}).

The broad lines and high velocities of most other clouds in figure 1 indicate that they are very different from the 3-kpc arm and local clouds. We shall limit our discussion to these clouds, first introducing evidence that they are in the nuclear disk, then showing that they may be joined into one continuous feature, and finally presenting a kinematical model for this feature.

a) *Distance*

That the broad-line clouds are in the galactic nucleus is most clearly manifest by their high velocities; over half of them are observed at velocities greater than 40 km s^{-1}. If they were between 3 and 10 kpc from the galactic center, their kinematics would probably be similar to those of hydrogen gas in the same region, that is, $|V| < 40$ km s^{-1} for this range of longitudes (Kerr and Vallak 1967; Mezger *et al.* 1970). The general velocity gradient of the clouds (negative velocities at negative longitudes and positive velocities at positive longitudes) is also much steeper than that of gas between the 3-kpc arm and the Sun, although the sense of the gradient is the same.

Both the latitude and longitude distributions of the broad-line clouds are suggestive of their location in the nuclear disk. The OH observations cover the greatest latitude range and clearly show most of these clouds in a thin layer ($\Delta b \approx 20'$) aligned with the galactic plane and centered at $b \approx -10'$. From the lack of dense H_2CO clouds at longitudes between 2° and 4°.5 (at $b = -2'$) and the small number of OH clouds between $l = 2°$ and $l = 4°.25$ we infer that the molecular clouds are concentrated about $l = 0°$ with only a few beyond $l = 2°$. At present there are no systematic molecular observations for $l < -2°$ (mainly because of the lack of dense clouds between $l = -1°.5$ and $l = -2°$). Finally, we make use of the physical association between the cloud appearing in figure 1 at $l = 0°.7$ with $V = 62$ km s^{-1} and the H II region Sgr B2. The radiation from this H II region is also absorbed by H_2CO in the 3-kpc arm, and thus both the cloud and H II region must lie behind the 3-kpc arm.

Although direct evidence for one cloud and the longitude, latitude, and velocity distributions of these clouds, taken as a group, suggest that they are probably at distances of several hundred parsecs from the galactic center, their velocities show little correspondence to pure rotation in the H I nuclear disk. Because H I lines near the center of the disk are severely blended with low-velocity galactic background emission, the rotation curve there is probably best determined indirectly from the gravitational potential of stars in this region. Becklin and Neugebauer (1968) have estimated the stellar density in the galactic nucleus from 2.2-μ observations, and Sanders and Lowinger (1972) have used these data to derive circular velocities (θ_c) in the disk given by

$$\theta_c = \sqrt{(7 \times 10^4 \varpi^{0.2} + 10^4 \varpi - 41 \varpi^3)} \text{ km s}^{-1} , \qquad (1)$$

where ϖ is the distance in kiloparsecs from the center of the Galaxy.

A majority of the clouds in figure 1 have velocities not "permitted" by this rotation law (allowed motion corresponds to the region between curves A and B in fig. 1); indeed, much gas is seen at positive longitudes with negative velocities and must therefore have large radial motions either toward or away from the galactic center.

b) *A Ring with Circular and Radial Motions*

Inasmuch as the kinematical behavior of the clouds does not correspond to either spiral-arm or nuclear-disk circular motion, we consider the two alternatives of the clouds being in unrelated elliptical orbits or in a single coherent structure possessing both circular and radial motions. The first alternative is not easily ruled out on the basis of the observed velocities but does appear unsatisfactory in light of the obvious links between many of the clouds.

The continuity of the negative-velocity gas producing broad absorption lines is evident in both 6-cm H_2CO and 18-cm OH (see fig. 1*d* in McGee 1970). The absorption appears much less continuous between the more centrally condensed positive-velocity clouds; indeed, no absorption is apparent in figure 1 between those clouds at $l = 0\overset{\circ}{.}0$ and $l = 0\overset{\circ}{.}7$. However, very definite CO emission does bridge this gap at 90 km s^{-1} (§ II), and the low, nearly constant intensity of the corresponding H_2CO absorption could be understood if G0.2−0.0, the dominant continuum source in this region, were in front of the 90 km s^{-1} gas.

We therefore suggest that most of the galactic-center molecular clouds at both positive and negative velocities are situated in a single structure. There is great nonuniformity in this structure, especially at positive velocities, and a real gap may exist at slightly negative longitudes and low positive velocities. Moreover, at $l = 1\overset{\circ}{.}5$ the situation becomes confused, there being two possible connections between the negative- and positive-velocity clouds. Such confusion could, however, result from "local" and 3-kpc arm absorption lines.

The elliptical shape of this sequence of clouds in the longitude-velocity diagram might be described kinematically as a ring that is rotating and either expanding or contracting. The ring would have its center at $l = 0\overset{\circ}{.}0$ and lie in the galactic plane. Rotational motion could account for the displacement of the ends of the sequence from zero velocity while the expansion or contraction would cause the velocity separation of the two sides. Table 1 lists parameters obtained by fitting model rings separately to the negative- and positive-velocity H_2CO and CO clouds (curves I and II of fig. 1). Most of the broad H_2CO lines near the top and bottom of figure 1, not described by either model I or model II, can be encompassed by a series of models which continuously change parameters from I to II in going from negative to positive velocities. Since a single model clearly does not fit all clouds, the real structural form is probably not a ring at all but more like one or two tightly wound arms, but the ring description has the obvious advantages of simplicity and definiteness.

Whether the ring is expanding or contracting is a difficult question whose answer will require higher-resolution absorption measurements. Analysis of variations in the 6-cm absorption intensity near the sources G0.2−0.0 and Sgr B2 indicates that the ring is expanding (Scoville 1971), and a suggested picture including the possible locations of continuum sources is shown in figure 2. However, if the ring is expanding, it is difficult to understand the high intensity of the OH and H_2CO absorption at +40 km s^{-1} in the direction of Sgr A since that gas should lie behind the galactic center (Kerr and Sand-

TABLE 1

MODEL RINGS OF FIGURE 1

Parameter	Model I*	Model II†
Radius‡ (pc)	218	305
Rotational velocity (km s^{-1})	50	50
Expansion or contraction velocity (km s^{-1})	145	70

* Fit to negative velocity clouds in figure 1.

† Fit to positive velocity clouds in figure 1 and figure 1 of Solomon *et al.* 1972.

‡ The assumed ring center is the galactic center ($l = 0\overset{\circ}{.}0$ at 10 kpc).

quist 1968; Fomalont and Weliachew 1971). If one makes the usual assumption that the nonthermal component in Sgr A is at the galactic center, then in order to form this absorption line, most of the other components in Sgr A must be beyond the galactic center and unrelated to the nonthermal component. The direction of the ring's radial motion is therefore uncertain, and we must await better knowledge of the structure in both the molecular clouds at +40 and -140 km s^{-1} and the Sgr A sources. Eventually, the apparent inconsistencies in the position of the 40 km s^{-1} cloud may force a revision of the model proposed here—for example, possibly there are two separate arms (negative- and positive-velocity gas), both of which are in front of the galactic center, or possibly the 40 km s^{-1} cloud is not part of the ring at all—however, we do not feel that such complexities are warranted on the basis of the present observations.

The existence of large expansion motions in the gas near the center of our Galaxy has long been known from 21-cm observations. Rougoor and Oort (1960) and Rougoor (1964) made detailed studies of the 3-kpc and the +135 km s^{-1} expanding arms, and more recent observations have revealed additional features above and below the galactic plane which are presumably also moving outward from the galactic center. (Shane 1971; van der Kruit 1970; Simonson and Sancisi 1972; Sanders and Wrixon 1972). Including the molecular ring discussed here, there would appear to be evidence for at least three distinct, radially moving gas structures near the galactic center, and it becomes increasingly difficult to understand their formation from resonances in the galactic gravitational potential (Lin and Shu 1971) or from a continual gentle outflow (Moore and Spiegel 1968). If instead, these radial motions are the result of explosive events in the galactic nucleus, such events must have occurred often in the recent past of our galaxy (see Sanders, Scoville, and Spiegel 1972 and references cited there).

The total mass of the molecular ring, estimated from H_2CO observations (Scoville and Solomon 1972), is $3 \times 10^6 M_\odot$, and the kinetic energy of its radial motion is 6×10^{53} ergs. [These estimates are probably only lower limits since they are based solely on molecular observations close to the galactic plane. Van der Kruit (1970) notes an H I feature (V in his notation) at $b = -1°$ with longitude-velocity dependence similar to the negative velocity side of the ring. Also, the existence of CO emission at 2.6 mm requires a minimum density of hydrogen molecules $N_{H_2} \gtrsim 10^3$ cm^{-3}, to excite the rotational transition above the background. This emission is observed over $\Delta b > 20'$ and at all longitudes in the ring where observations have been made, which gives a total mass $\sim 10^8 M_\odot$ and a total radial kinetic energy of 2×10^{55} ergs.] The low angular momentum of the ring, corresponding to circular motion at $\varpi = 50$ pc, suggests that much of this gas may have come from close to the center of the nuclear disk. An energy in excess of 4×10^{54} ergs would be required to move $3 \times 10^6 M_\odot$ from 50 pc out to 250 pc from the galactic center; and if this was supplied by a *spherically symmetric* explosion about 10^6 years ago, the total energy would be several times the above number.

Our conclusions follow.

1. Most of the molecular clouds producing broad lines in the direction of the galactic center are probably within 300 pc of the galactic center.

2. The observed velocities of these clouds show little correspondence to pure rotation in the nuclear disk, and many clouds clearly have large radial motions either toward or away from the galactic center.

3. The apparent physical links between clouds suggest that they are contained in a coherent structure resembling a ring, probably expanding outward at $\sim$100 km s^{-1}.

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