KINEMATICS OF MOLECULES AT THE GALACTIC CENTRE

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Abstract. Dense gas clouds containing OH, CO, NH_3 and H_2CO are found in the inner part of the H I nuclear disk. The molecular spectral lines allow direct observations of the kinematics of the gas near the galactic centre. Strong absorption of the thermal continuum sources by OH and H_2CO shows that much of the gas on the near side of the centre can be located in a massive 'ring' expanding at 130 km s^{-1}, which may have originated close to the nucleus about 10^6 yr ago. Observations of CO emission from beyond the centre show that the far side of the 'ring' is expanding at a lower velocity, less than 90 km s^{-1}. Observations of CO and NH_3 emission with positive velocities for $l < 360°$ are needed to establish whether the 'ring' is a continuous structure.

OH and H_2CO are also observed to be falling towards the centre. There is no agreement as to the location of this infalling matter.

The nuclear regions of the Galaxy are compared with those of NGC 253, particularly in regard to expansional velocities, IR and radio emission, and OH absorption.

I. Introduction

The most direct observations of the galactic centre can be made in the infrared, in the radio continuum and recombination line emission, and by means of molecular spectral lines. At visual wavelengths our view is obscured by 27 mag of absorption in the dust found near the centre and in the intervening spiral arms. High-velocity hydrogen near the centre can be observed at 21 cm wavelength, but for H I with radial velocities between ± 50 km s^{-1} the central regions are blanketed by the wings of the 21-cm emission from the spiral arms in front of and behind the centre.

The molecular spectral lines provide a particularly powerful probe of the central regions. The density of molecules there is several orders of magnitude greater than in the spiral arms, so that there is negligible confusion from gas in the intervening (or distant) arms. The high molecular densities are found in the inner parts of the 'nuclear disk' inferred from 21 cm observations. The kinematics of the region are defined by the radial velocities of the four molecules which are widely distributed: hydroxyl, formaldehyde, carbon monoxide and ammonia. Many exotic molecules have been observed in the dense clouds near Sgr B2 (G0.7 – 0.0) and Sgr A (G0.0 – 0.0), but they have not been seen at other longitudes and so provide little kinematic information. Hydroxyl and formaldehyde are seen in absorption against the continuum sources near the centre, while carbon monoxide and ammonia appear in emission and so can be detected on the far side of the continuum sources.

II. The Nuclear Disk

High-velocity 21 cm emission is seen between longitudes $356° < l < 0°$ with radial velocity $-250 < V < -70$ km s^{-1}. This gas has been associated with a rapidly rotating

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nuclear disk extending to a radius R of about 800 pc from the galactic centre (Rougoor, 1964). For $l > 0°$ the distribution of the high-velocity H I is confused by emission from H I beyond the centre, and the structure of the disk has been inferred from models. The basic parameters of the disk derived by Oort (1971) and by Sanders and Wrixon (1973) are shown in Table I.

TABLE I

Parameters of the H I nuclear disk

Parameter	Oort (1971)	Sanders and Wrixon (1973)
Radius (pc)	750	750
Thickness (pc)	100 for $R < 300$ pc 250 for $R > 300$ pc	100 for $300 < R < 500$ pc 120 on average
Maximum rotational velocity (km s^{-1})	230	230
Velocity dispersion (km s^{-1})	–	13
H I density (atoms cm^{-3})	3 for $R < 100$ pc 0.3 on average	5 for $R < 110$ pc 1.5 on average
Total H I mass ($M_\odot$)	4×10^6	2×10^6 for $R < 500$ pc
Dust mass ($M_\odot$)	10^5	–
Mass of H_2 ($M_\odot$)	10^7	–

Oort's (1971) model is symmetric about the centre, with the gas increasing in density smoothly towards the centre and rotating in circular orbits. The model of Sanders and Wrixon (1973) is based on higher-resolution observations and has *no* neutral hydrogen in the inner 300 pc on the positive longitude side of the disk; at negative longitudes the H I density increases smoothly to within 100 pc of the centre.

We should bear in mind that the techniques which best probe the galactic centre *all* show a marked asymmetry about $l = 0°$. The 100 μm IR observations (Hoffman *et al.*, 1971) and the radio continuum observations (reviewed by Gordon in this volume) show a much greater extent (and strength) of the emission at positive longitudes than at negative longitudes. The molecules show an even more pronounced asymmetry.

III. Distribution and Motions of OH Molecules

The most complete survey of the distribution of a molecular species near the galactic centre has been made for OH in absorption at 18 cm wavelength (Robinson and McGee 1970; McGee *et al.*, 1970). As shown in Figure 1, absorption extends in longitude from $359° < l < 2°$ for $-180 < V < +90$ km s^{-1}. Weaker absorption can be traced up to $l \approx 4°$ at $b = 0°$, but considerable searching has failed to reveal OH absorption in the range $357° < l < 358°30'$. At a distance of 10 kpc, $l = 2°$ corresponds to a radial distance of 350 pc from the centre.

We see that the OH is concentrated in the inner part of the H I nuclear disk on the positive longitude side. The OH can be traced nearly to the edge of the disk, to $R = 700$ pc (corresponding to $l = 4°$). Much of the OH has large radial motions towards

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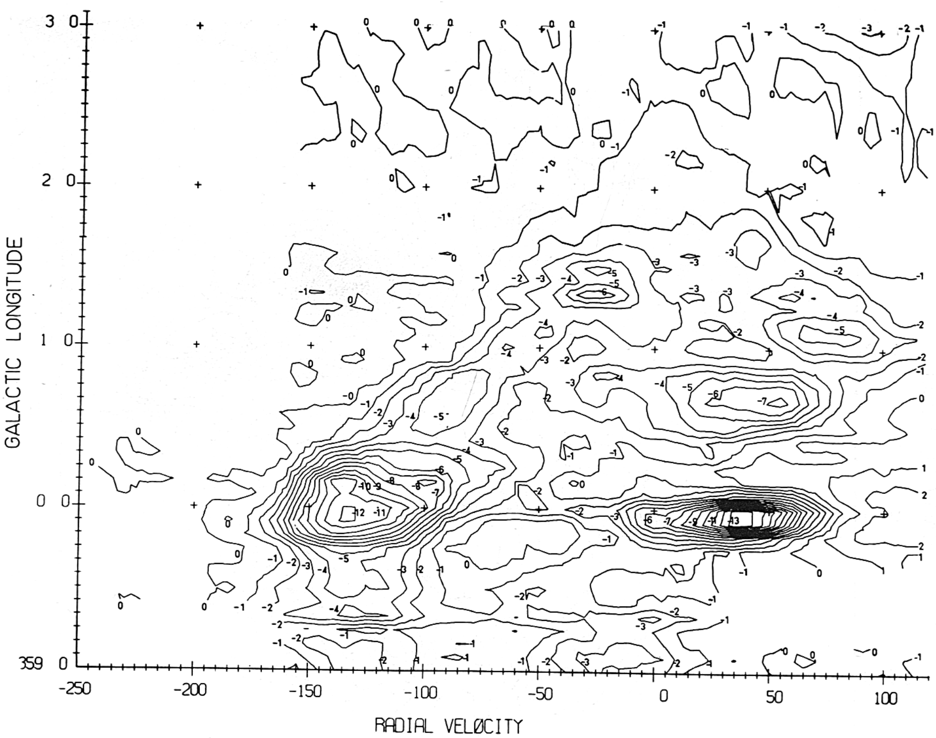

Fig. 1. Galactic longitude – radial velocity ($l-V$) plot of 1667 MHz OH absorption for $b=-0°10'$. Beamwidth is 12.2′, velocity resolution is 6.6 km s^{-1}. Observations were made every 5′ in longitude. Contour unit is 1.7 K in antenna temperature. (From Robinson and McGee, 1970).

and away from the centre, unlike the circular motions adopted in the H I nuclear disk model.

The thickness of the hydroxyl layer for $R \leqslant 350$ pc is about 50 to 70 pc (see McGee, 1970), compared to 100 pc for the H I disk. For $R > 400$ pc the hydroxyl layer becomes somewhat thinner while the H I layer expands.

For $R \leqslant 350$ pc the hydroxyl absorption reaches a maximum about 10′ south of the galactic plane, corresponding to $z = -30$ pc. No similar displacement is seen in the radio continuum or 100 μm IR emission.

It might be argued that the asymmetry in longitude of the OH absorption simply reflects the asymmetry in distribution of the radio continuum. But McGee (1970) has shown that the asymmetry is even more marked in the distribution of apparent OH opacity. If we compare the apparent opacity in Figure 2 with the directly observed absorption in Figure 1, we see that the influence of strong continuum sources like Sgr A, Sgr B2 (G0.7 – 0.0) and G1.1 – 0.1 has been almost eliminated, and the highest opacity is found near $l = 1°30'$ and $l = 3°$.

Kaifu *et al.* (1972) drew attention to the continuity of the OH absorption in the $l-V$ plane shown by Figure 2, and suggested that the locus of the absorption was an ellipse as shown in Figure 3. Such a locus could be produced by a ring of OH with

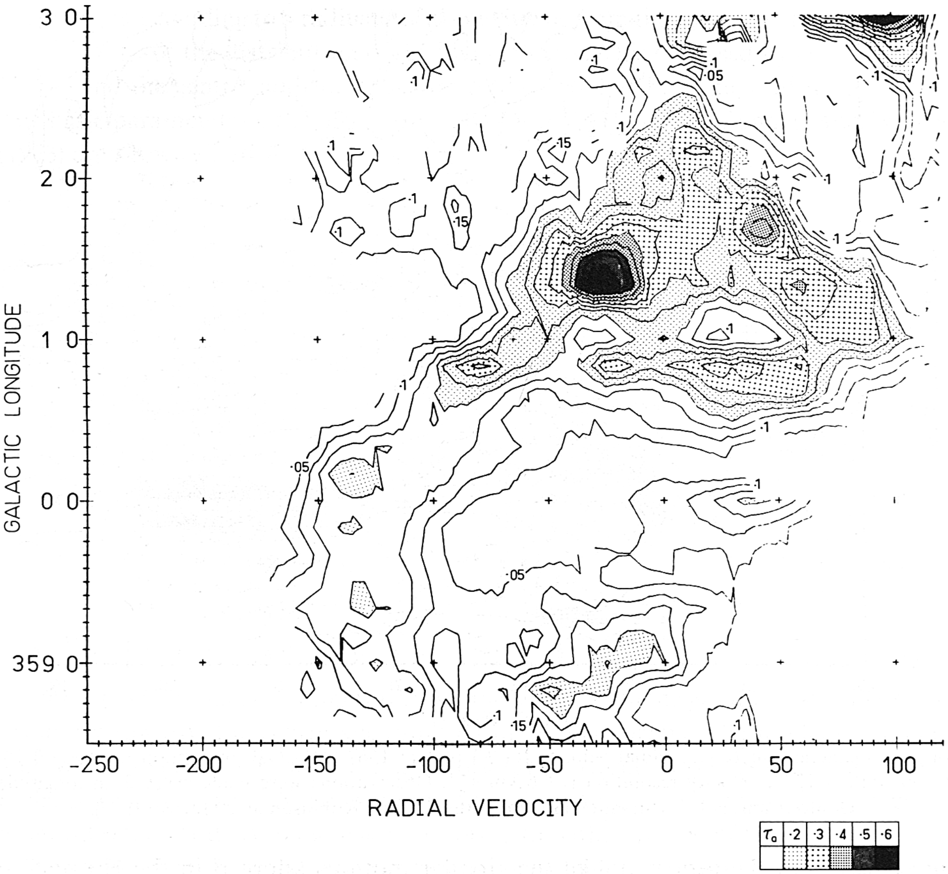

Fig. 2. Contours of apparent OH opacity at 1667 MHz for $b = -0°10'$, derived from Figure 1. (From McGee, 1970).

$R = 270$ pc, rotating at 50 km s^{-1} and expanding at 130 km s^{-1}. The positive velocity side of the ring is not observed, since the OH would be behind the continuum sources. However, Kaifu *et al.* showed that the velocities of some NH_3 emission lines observed by Knowles and Cheung (1971) at $l = 359°35'$ and $l = 1°12'$ (marked by squares in Figure 3) fell on the locus "…thus confirming the existence of the expanding ring…". Models for this 'ring' will be discussed in a later section.

IV. Distribution and Motions of H_2CO Molecules

Absorption by the $1_{10} \leftarrow 1_{11}$ transition of formaldehyde at 6 cm has been surveyed by Gardner and Whiteoak (1970), Scoville *et al.* (1972) and Scoville and Solomon (1973). Figure 4 shows an $l - V$ contour diagram of the apparent opacity at $b = -0°12'$. In general outline it shows marked similarities to the OH opacity in Figure 2, but more detail is apparent because of the four times higher resolution in velocity; the

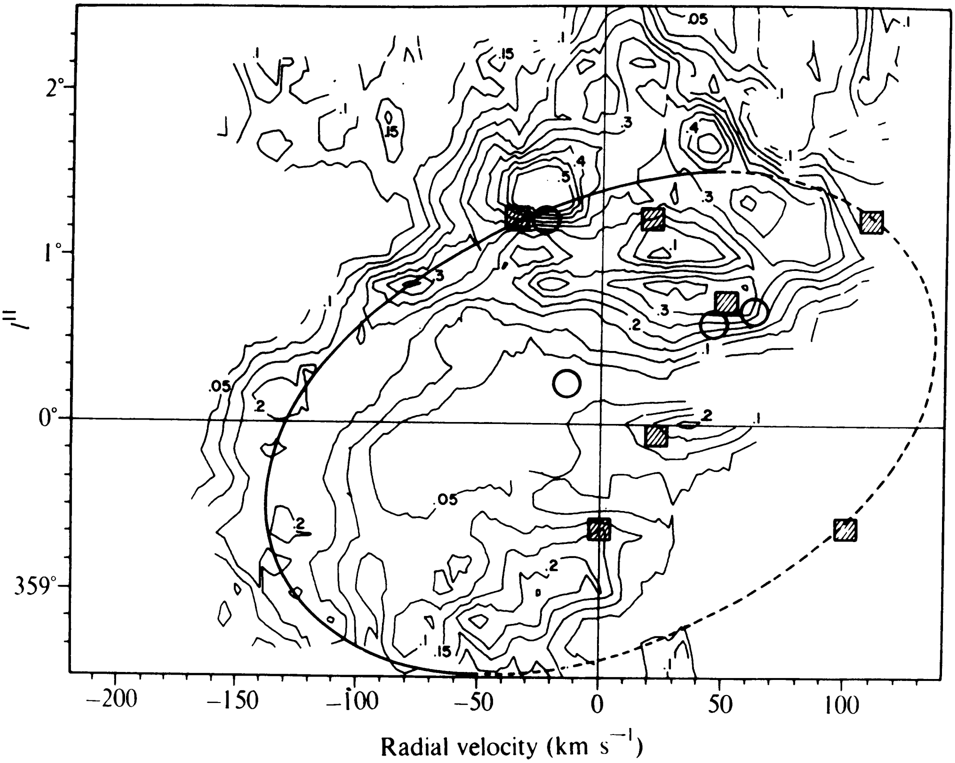

Fig. 3. Locus of 270 pc expanding molecular ring suggested by Kaifu *et al.* (1972) from OH absorption (Figure 2) and NH_3 emission velocities (shown by hatched rectangles). The circles indicate the hydrogen recombination line velocities of the H II regions near the galactic centre.

observations were undersampled in longitude. Narrow-band absorption by the 3 kpc expanding arm (near $V = -50$ km s^{-1}) and in the nearby spiral arms (near $V = 0$ km s^{-1}) is much more marked in the H_2CO observations than for OH. As was the case for OH, the H_2CO opacities are higher below the plane ($b = -0°12'$) than close to the plane ($b = -0°02'$); this is most marked for the negative velocity gas. H_2CO observations at other latitudes have not been published.

Scoville (1972) showed that the maximum H_2CO opacity also lies on part of an elliptical locus in the $l - V$ plane. This locus is shown by the continuous line in Figure 5, superimposed on contours of the average H_2CO opacity at $b = -0°02'$ and $b = -0°12'$ The elliptical locus would correspond to a ring of gas of radius about 220 pc rotating at 50 km s^{-1} and expanding at 145 km s^{-1}; the ring extends further at positive longitudes ($R = 305$ pc) than at negative longitudes ($R = 218$ pc). As with the OH observations in Figure 3, data on the H_2CO distribution at positive velocities are incomplete, presumably because the H_2CO then lies beyond the continuum sources near the centre.

V. Distribution and Motions of CO Molecules

A preliminary CO emission line survey at $\lambda = 2.6$ mm covering a strip at $b = -0°02'$

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from $l = 359°.7$ to $l = 2°.8$ has been published by Solomon *et al.* (1972). As well as being restricted to positive longitudes the survey is also restricted to positive velocities ($+28 < V < +130$ km s^{-1}). The survey is also heavily undersampled in longitude, observations with a 1 arcmin beam being separated by 6′ (identical with the spacing used for OH and H_2CO).

The $l-V$ contour map for CO at $b = -0°02'$ is shown in Figure 6. Between the centre and $l = 1°.8$, CO emission is observed over almost the complete velocity range of the measurements. The high-velocity CO features near $l = 0°$ ($60 < V < 95$ km s^{-1}), $l = 0°.7$ ($80 < V < 105$ km s^{-1}) and between these longitudes ($60 < V < 90$ km s^{-1}) are extremely weak or missing from the OH and H_2CO maps. The CO at these velocities is presumably beyond the centimetric continuum sources which are absorbed by OH and H_2CO.

At $l = 1°.4$ scans perpendicular to the plane showed that the CO emission extended beyond $b = +14'$ and $b = -6'$.

The CO observations indicate high densities and low temperatures in the molecular

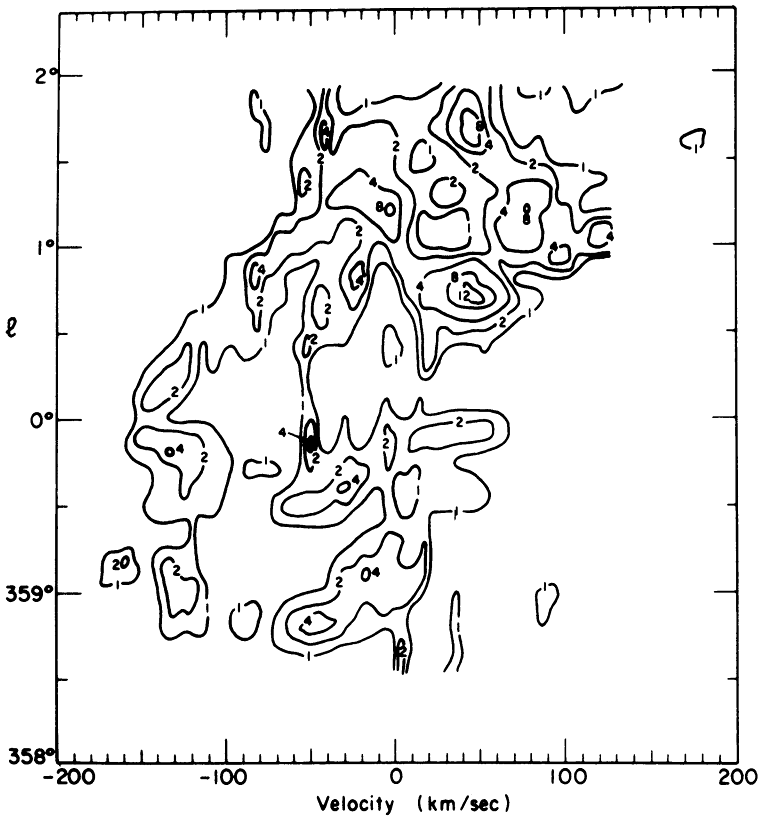

Fig. 4. Contours of apparent H_2CO opacity at 4830 MHz for $b = -0°12'$. Beamwidth is 6.6′, velocity resolution is 1.63 km s^{-1}. Observations were made every 6′ in longitude. (From Scoville and Solomon, 1973).

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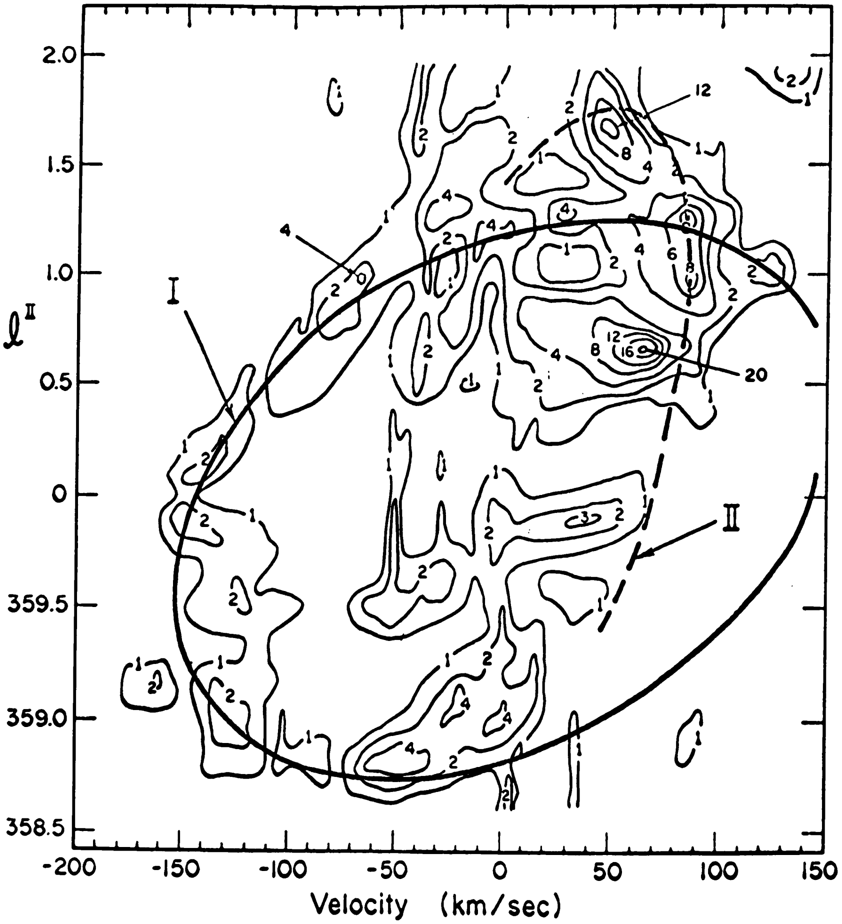

Fig. 5. Locus of expanding molecular ring suggested by Scoville (1972) from H_2CO absorption. The H_2CO opacity contours are the average of those at $b = -0°02'$ and $b = -0°12'$.

clouds. The upper state ($J = 1$) of the 2.6 mm CO transition has a lifetime of 1.6×10^7 s and will be appreciably populated by collisions when the hydrogen density exceeds 10^3 atoms and/or molecules per cubic centimetre. The observation of CO emission against the isotropic background radiation implies that the molecular clouds near the centre have hydrogen densities $\geqslant 10^3$ cm^{-3}. A density exceeding 10^3 cm^{-3} is also required to excite the 1.3 cm ammonia emission lines. The 21 cm model for the nuclear disk has $0.3 < n_H < 5$ cm^{-3}, so the hydrogen in the clouds must be mainly in the molecular form.

Comparison of $^{12}C^{16}O$ and $^{13}C^{16}O$ lines shows that the ^{12}CO line is optically thick. Thus the observed brightness temperatures of 13 to 17 K are a measure of the kinetic temperature in the molecular clouds. Solomon *et al.* (1972) have pointed out that this temperature is close to the IR brightness temperature at 100 μm, suggesting

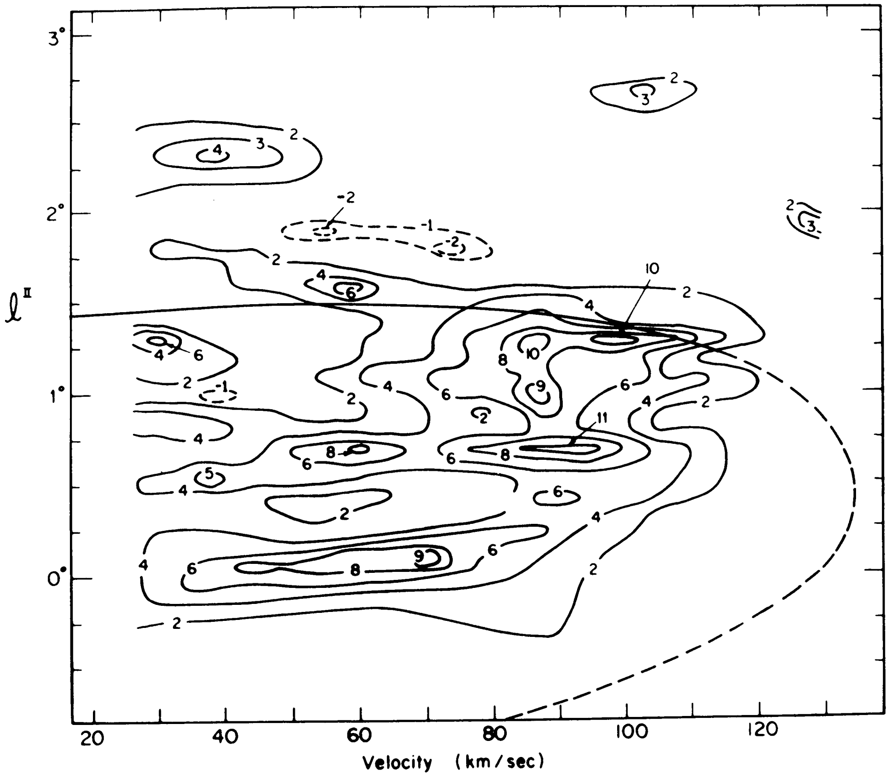

Fig. 6. Contours of 115 GHz CO emission for $b = -0°02'$. Beamwidth is 1′, velocity resolution 5 km s^{-1}. Observations were made every 6′ for $359.°7 < l < 2°$, every 12′ for $l > 2°$. The observations were restricted to $+28 < V < +130$ km s^{-1}. (From Solomon *et al.*, 1972). Part of the elliptical locus from Figure 3 is superimposed on the contours.

that the grains and gas are in thermal equilibrium and that the clouds are optically thick at 100 μm. This would imply 200 mag of extinction at optical wavelengths.

VI. Models for the Molecular Ring

The model for the expanding and rotating molecular ring derived by Kaifu *et al.* (1972) from OH absorption and NH_3 emission is shown in Figure 7, and the parameters describing it are listed in Table II. The model proposed by Scoville (1972) from the H_2CO absorption is shown in Figure 8, with the parameters also in Table II.

Kaifu *et al.* (1972) have noted that *positive* velocity OH and H_2CO absorption is seen against Sgr A, Sgr B2 and other continuum sources near the center, and have put the infalling material in a smaller rotating and *contracting* ring with radius 140 pc. The recombination line velocities of the H II regions enable them to be located on this contracting ring (except for G1.1 − 0.1, which is located on the expanding ring). Scoville's (1972) model accounts for the positive velocity molecular absorption by

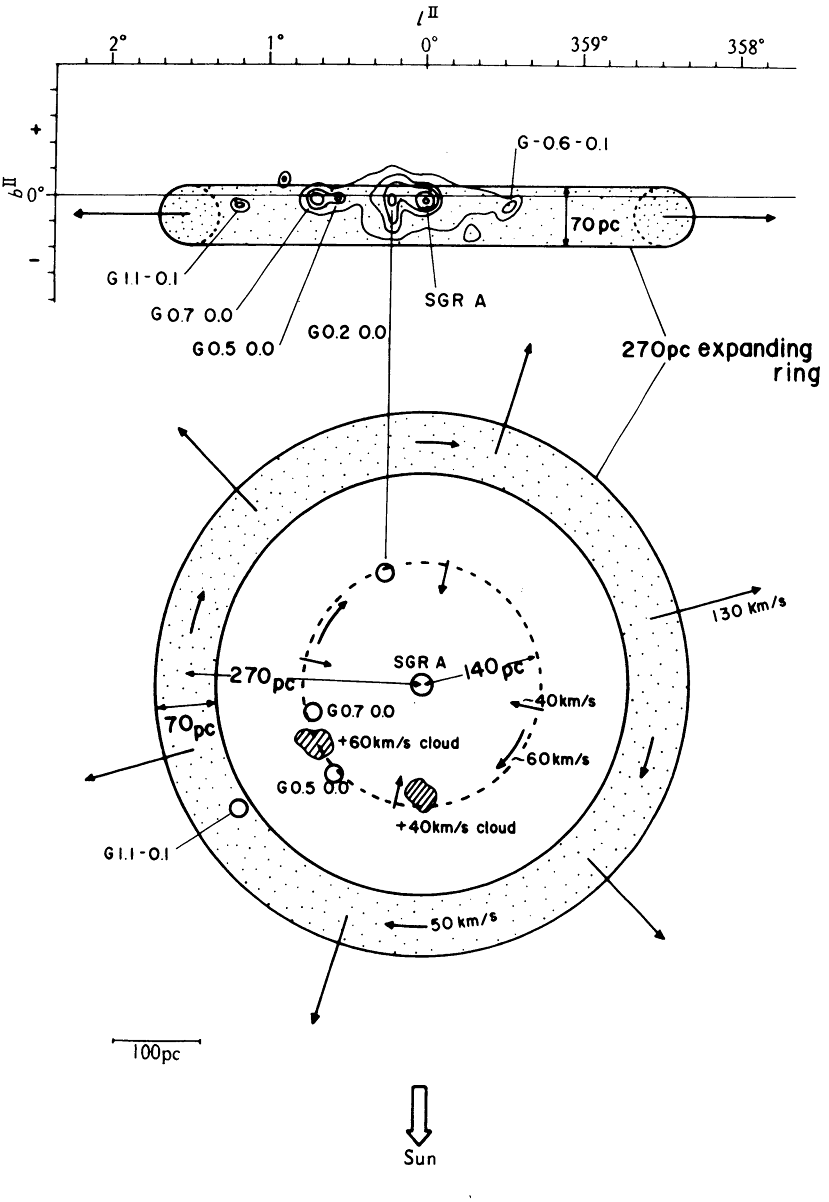

Fig. 7. Model for the 270 pc expanding molecular ring proposed by Kaifu *et al.* (1972) from OH absorption and NH_3 emission velocities. The broken circle shows the inner contracting ring, containing OH clouds (shaded patches) and H II regions (circles). The contours in the upper picture are 8 GHz continuum contours.

TABLE II

Parameters for the expanding molecular ring

Parameter	Kaifu *et al.* (1972)	Scoville (1972)
Radius (pc)	270	218
Thickness Δz (pc)	70	–
Tilt to galactic plane	6°	3°
Rotational velocity (km s^{-1})	50	50
Expansion velocity (km s^{-1})	130	145
OH column density (cm^{-2})	10^{16}	–
H_2CO column density (cm^{-2})	2×10^{13}	–
H_2 density n_{H_2} (cm^{-3})	$\approx10^3$	$\leqslant10^3$
H density n_H (cm^{-3})	2	–
n_H/n_{H_2}	$\approx10^{-3}$	–
Total mass of ring ($M_\odot$)	$\approx10^8$	$\geqslant10^8$
Expansion time (years)	2×10^6	$\approx10^6$
Kinetic energy of expansion (erg)	$\approx10^{55}$	2×10^{55}

putting all the H II regions and all but the nonthermal core of Sgr A on the far side of the expanding ring. However, this disposition of the thermal sources is quite inconsistent with their recombination line velocities (see the points marked with circles on Figure 3).

To excite CO and NH_3 emission the H_2 density must exceed 10^3 cm^{-3}, and this makes the total mass of the expanding ring as high as 10^8 $M_\odot$. The kinetic energy of the expansion may exceed 10^{55} erg.

The angular velocity of the ring corresponds to that at a radius of about 50 pc from the centre, so that the gas has probably expanded out from near the centre. At a constant speed of 135 km s^{-1} the expansion would have taken 2×10^6 yr. We do not

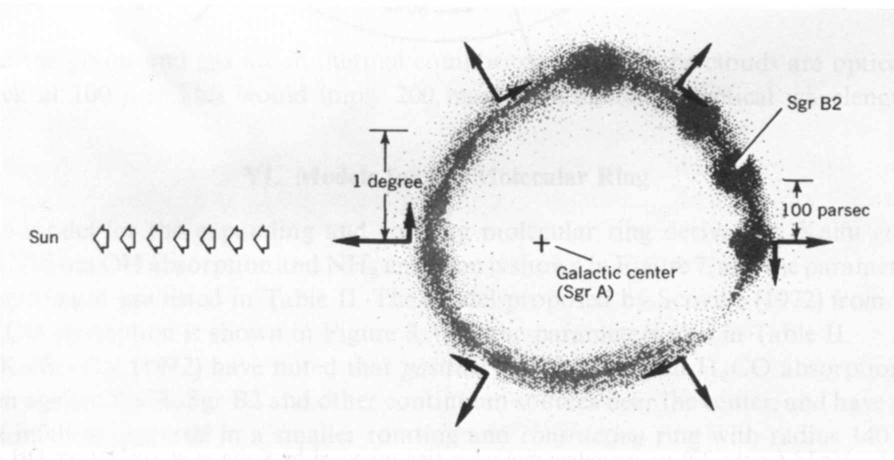

Fig. 8. Model for the expanding molecular ring proposed by Scoville (1972) from H_2CO absorption velocities. The label Sgr A refers only to the nonthermal continuum component. The thermal continuum sources are located on the far side of the ring.

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understand what force could drive such an expansion and resort to an explanation in terms of 'an explosive event' in the nulceus about 10^6 yr ago. Sanders and Lowinger (1972) have computed circular velocities V_c in the nuclear disk; at $R = 270$ pc. V_c is about 230 km s^{-1} and so the escape velocity is about 330 km s^{-1}. We see that the velocity of the expanding ring is far below the escape velocity. Thus unless there is some force to accelerate the ring the material will ultimately spiral back towards the nucleus.

Kaifu *et al.* (1972) note that the expansion velocity of 130 km s^{-1} far exceeds the sound velocity in the region (1 to 10 km s^{-1}), and regard the expanding ring as a shock front. Strong compression by the shock leads to the formation of the observed molecular clouds and of stars and H II regions. Their contracting ring with $R = 140$ pc may be a shock wave propagating towards the centre as the counter motion of gas after being swept by the outgoing shock wave (Kaifu *et al.*, 1973).

We should take a critical look at the experimental data on which these models are based. Is the 'expanding ring' a continuous structure? Can we discriminate between a ring and an expanding spiral arm (or arms)? It is obvious from Figures 3, 5 and 6 that there is a serious lack of positive velocity data for OH, H_2CO and CO for $l < 360°$. Only one point appears in this quadrant, the NH_3 velocity of +100 km s^{-1} at $l = 359.°35$, $b = -0.°15$ (Figure 3). There is an urgent need for a survey of CO emission in this quadrant.

For $l > 0°$, the CO emission in Figure 6 for $80 < V < 120$ km s^{-1} should arise beyond the centre, as little absorption at these velocities is seen for OH and H_2CO. However, when we draw the locus of the expanding ring (from Figure 3) on the CO contours in Figure 6, we see that the CO data give no support for the symmetric ring models in the part of the locus shown by the dashed line. The expansion velocity of the far side of the ring cannot be more than 90 or 100 km s^{-1}.

VII. Similarity of the Nuclear Regions of the Galaxy and NGC 253

Because high obscuration prevents any visual observations of the galactic centre it is fruitful to draw analogies with optical data on external galaxies. The popular model has been the nucleus of M31 (see Oort, 1971).

In M31 Rubin and Ford (1970) have found a striking asymmetry of the radial velocities near the nucleus; on the NE side the gas out to $R = 800$ pc rotates at about the same velocity as the nuclear disk in the Galaxy; on the other side the motions are quite irregular. In the nucleus of M31 Sandage *et al.* (1969) found that the distribution of the 2.2 μm IR radiation is identical with that at optical wavelengths; the 2.2 μm distribution within $R = 50$ pc is also identical with that in the Galaxy (Becklin and Neugebauer, 1968). This suggests that the 2.2 μm distribution in the nucleus of the Galaxy can be used as a measure for the density distribution of the stars; within $R = 20$ pc the stellar mass must be about 2×10^8 $M_\odot$. Circular velocities computed for this stellar distribution are similar to those required for the H I nuclear disk.

An even better model for the nucleus of the Galaxy is provided by the nucleus of

NGC 253. It is strikingly similar to the nucleus of the Galaxy in the IR, contains a nonthermal radio source similar to Sgr A, and contains a high density of OH molecules. Optical and OH observations reveal expansion from the nucleus.

A full comparison of the nuclei of the Galaxy and of NGC 253 is made in Table III. Expansion at a velocity of 120 km s^{-1} has been measured optically by Demoulin and Burbidge (1970) within $R=750$ pc of the nucleus of NGC 253. In addition, the first spiral arm at $R=3.5$ kpc is expanding at $V=40$ km s^{-1}, figures which are strikingly similar to those for our '3 kpc expanding arm'.

TABLE III

Comparison of the nuclei of the Galaxy and NGC 253

Property	Galactic centre	NGC 253
Expansion:		
At $R<750$ pc	$V_E=130$ km s^{-1}	$V_E=120$ km s^{-1}
Of first spiral arm	$V_E=53$ km s^{-1}	$V_E=40$ km s^{-1}
(radius)	($R=4$ kpc)	($R=3.5$ kpc)
IR source:		
Size	300 pc × 600 pc	150 pc × 150 pc
Luminosity	3.4×10^8 $L_\odot$	3×10^9 $L_\odot$
Radio source:		
Nonthermal radio energy	3×10^{50} erg	2×10^{53} erg
Molecules:		
OH absorption – $V_{expansion}$	– 130 km s^{-1}	– 50 km s^{-1} [a]
OH masers (number)	1	2

[a] Extends to – 150 km s^{-1}.

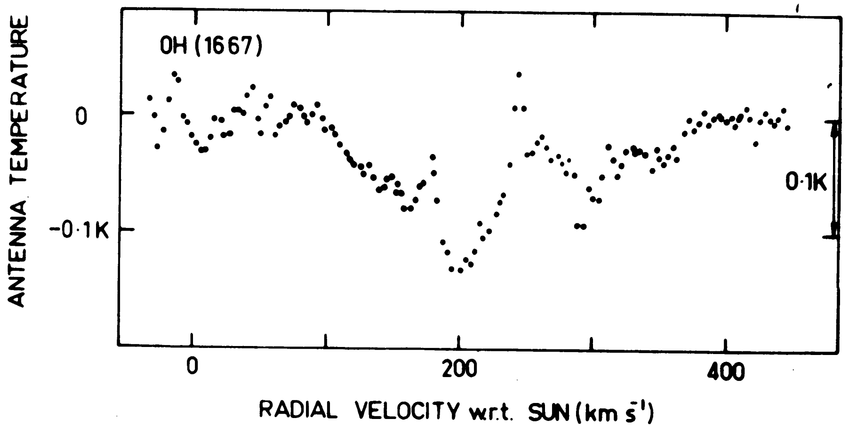

Fig. 9. OH absorption at 1667 MHz of the nuclear radio source in NGC 253 (Whiteoak and Gardner, 1974).

The far IR source in NGC 253 (Becklin *et al.*, 1973) is somewhat smaller than the one at the centre of the Galaxy, but about ten times as luminous. The IR observations show that both nuclei have Seyfert characteristics. The nonthermal radio source in NGC 253 is nearly three orders of magnitude more energetic than Sgr A is at the present epoch.

Wideband OH absorption of the nonthermal radio source in NGC 253 is shown in Figure 9 (Whiteoak and Gardner, 1974). The systemic velocity is 250 km s^{-1}, so that the strongest OH absorption corresponds to expansion at a velocity of 50 km s^{-1} there is less dense OH expanding at velocities up to 150 km s^{-1}. Weaker OH absorption at velocities higher than the systemic velocity shows that there must also be infalling OH with $V \approx 50$ km s^{-1}. Two narrow spikes on the profile may be OH maser sources. In all, the OH profile in Figure 9 is strikingly similar to the OH profile of Sgr B2 (see Robinson *et al.*, 1970, Figure 7).

VIII. Conclusions

Observations of hydroxyl, formaldehyde, carbon monoxide and ammonia lines near the galactic centre provide evidence for a section of a dense ring of matter about 270 pc in radius, expanding at about 130 km s^{-1} (see Table II). The ring must have a mass of about 10^8 $M_{\odot}$. It lies well within the rapidly rotating H I nuclear disk (see Table I); few molecules are seen in the outer parts of the nuclear disk, or inside the radius of the molecular ring.

The molecular ring has a rotational velocity of 50 km s^{-1} and so does not share the rotation of the H I nuclear disk – which would be about 230 km s^{-1} at $R = 270$ pc. The expansion velocity of the ring is well below the escape velocity at $R = 270$ pc, which would be about 340 km s^{-1}.

Kaifu *et al.* (1972) have suggested that the molecular ring has been produced by a shock wave travelling outwards from about 100 pc from the centre. The strong compression produced by the shock wave would lead to the formation of molecules and of young stars and H II regions. Since the expansion time of the ring would be about 2×10^6 yr, this model implies that the formation time for the molecules is about 10^5 to 10^6 yr. This requires high densities. High densities are also indicated by the excitation of CO and NH_3 to emit.

The observations of OH and H_2CO show that material is also falling in towards the galactic centre. Kaifu *et al.* (1972) locate these positive velocity molecular clouds on an inner ring of radius about 140 pc, contracting inwards at $V = 40$ km s^{-1} and rotating at 50 km s^{-1}. The recombination line velocities of many of the H II regions allow them to be located on this inner ring. The inner ring is perhaps a counter shock produced by particles spiralling back towards the nucleus under its gravitational attraction. Scoville (1972) places the positive velocity molecular clouds and the H II regions on the far side of the 270 pc expanding ring, but this location conflicts with the observed recombination line velocities.

Observational data about the far side of the 270 pc expanding ring are very limited.

The CO data for $l > 0°$ do not support the elegant symmetry of the ring proposed by Kaifu *et al.* (1972) and Scoville (1972). Observations of CO and NH_3 emission with positive velocities for $l < 360°$ are badly needed to define the structure of the ring, or to test whether it may be an expanding spiral arm (or arms).

Finally, attention is drawn to the strong similarities between the nuclei of the Galaxy and of NGC 253 in the infrared, radio continuum and OH absorption. Optical and OH velocities for NGC 253 show similar expanding and contracting motions to those found at the centre of the Galaxy.

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DISCUSSION

Morimoto: Shock wave calculations by Kaifu and others show that a secondary shock traveling outward with particles moving inward (thus appearing as a contracting ring) can develop as the particles behind the expanding ring fall back to the equilibrium position. This can explain the positive velocity features. The place where you left the symmetrical ellipse for an expanding ring in the l, v diagram is where confusion from the contracting ring is the heaviest.

Robinson: At the outer edges of the ring, the galactic rotation curve deduced from the infrared observations gives circular velocities between 200 and 250 km s^{-1}. The rotational velocity in the ring is on the

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order of 50 km s^{-1}. If it has been blown out from the center, it started much closer in and has angular momentum comparable with that distance much closer in. There is then a problem of how it is going to stay up there without spiraling back into the center.

Morimoto: Matter is just starting to go back in.

Caswell: If they are real, how strong are the maser emission sources in NGC 253 compared with the strongest ones in our own Galaxy?

Gardner: It is somewhat more than 10 times greater than W49.

Batchelor: To what extent is the southern velocity quadrant of the OH map influenced by the continuum background?

Robinson: We worked very hard to get absorption down there at 18 cm. The CO observations are not affected by the continuum, so you should see CO, but it certainly doesn't show up on the map.

Zuckerman: Those masers in NGC 253 must be really strong, since that was at 1667 MHz and the strongest galactic masers are at 1665 MHz.

Robinson: It is comparable with the 1667 MHz emission from G330.9 − 0.4.

Zuckerman: Those southern sources!

Robinson: You'll have to take our word for it that they exist.