Publl. Astron. Soc. Japan **42**, 827–836 (1990)

Radio Continuum and CO Line Emissions in the Galactic Center Region

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(Received 1990 May 25; accepted 1990 August 10)

Abstract

A comparison of radio continuum maps at 10 GHz and molecular-line emission data has been made for the central region of the Galaxy. Thermal continuum sources (H II regions) are generally associated with molecular clouds. However, the peak positions of the continuum and molecular features tend to spatially avoid each other. The young star-forming region Sgr B2 is associated with a dense compact molecular cloud. The neighbouring H II region Sgr B1 is enclosed by a molecular shell. This shell is in contact with the Sgr B2 molecular complex, suggesting that star formation in Sgr B2 has been triggered by an expanding shell driven by Sgr B1. The H II regions near G−0.27−0.03 are surrounded by molecular arcs, while no dense clouds are associated, suggesting that the star-forming activity has passed its peak in these regions.

Key words: Galactic center; H II regions; Molecular gas; Radio emission; Star formation.

1. Introduction

Radio continuum surveys in the microwave range of the galactic center have revealed a number of discrete sources (e.g., Reich et al. 1984; Handa et al. 1987). Most of the strongest sources are H II regions like Sgr B1, B2, or C, except for the central Sgr A and the radio Arc region. From the very high concentration of the sources in the central 1–2°, compared to the surrounding regions, the majority of sources are most probably galactic center objects (Sofue 1988). This fact indicates an intense star-forming activity in the central few hundred parsecs.

The galactic center region has also been observed intensively at various molecular lines (Brown and Liszt 1984; Bally et al. 1987, 1988; Güsten 1989). In particular, CO line observations have shown a global distribution of the molecular gas and have revealed a high concentration in the central few hundred parsecs. This fact clearly

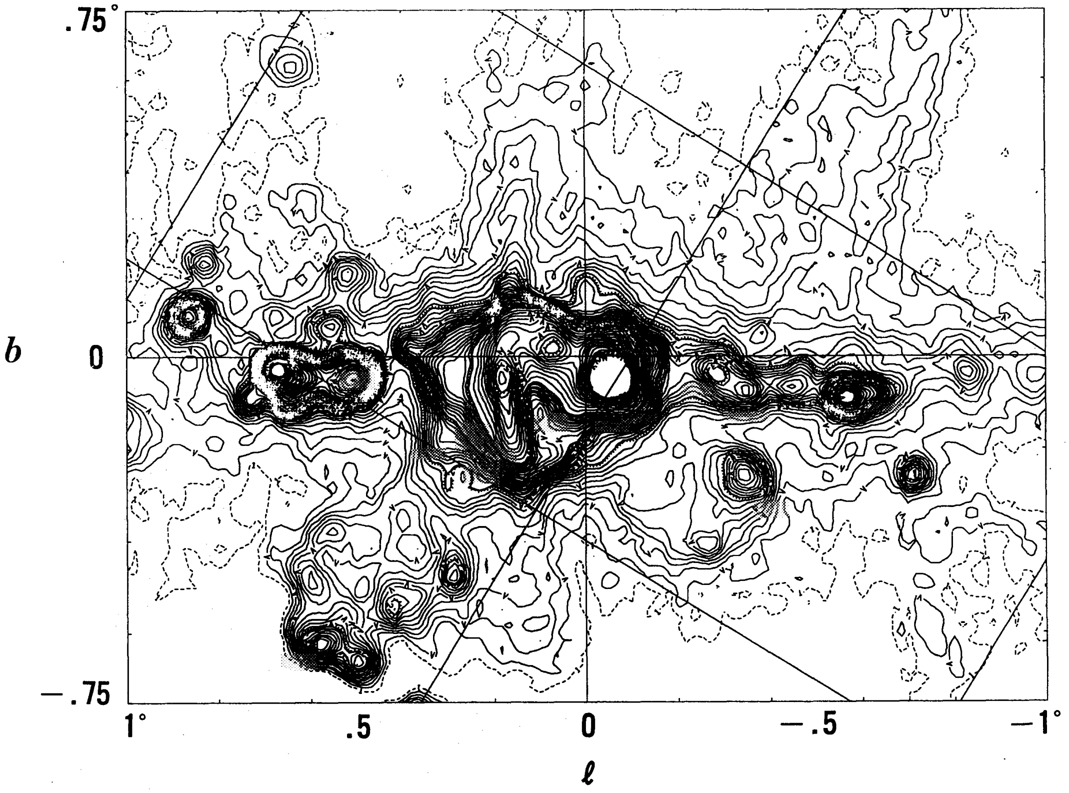

Fig. 1. A radio continuum map at 10 GHz showing discrete sources. Diffuse, extended components with scale sizes greater than 0°.4 have been subtracted from the original data by Handa et al. (1987). Hatched contours are at 1, 2, 4, 10, and 20 K T_B, intervals of which are divided equally by the thin contours.

indicates that intense star formation in the central region occurs deeply coupled with the wealth of molecular gas.

The survey data both in the radio continuum and molecular lines with comparable angular resolutions of a few arc minutes give an opportunity to study the detailed spatial relationship between the molecular gas and the star-formation sites in the galactic center region. In this paper we discuss H II regions near the galactic center, such as Sgr B and C, and their associated molecular features, but do not discuss Sgr A and its close vicinity, for which there have been many extensive studies related to nucleus activity [see, e.g., Güsten (1989) for a review].

2. Spatial and Velocity Correlation between Continuum and Molecular Sources

In figure 1 we present a 10-GHz continuum map for the central 2° × 1°.5 region as taken from Handa et al. (1987). In the figure we have subtracted diffuse emission components with scale sizes greater than 0°.4 by applying a background filtering method (Sofue and Reich 1979) in order to enhance discrete sources. Figure 2 shows

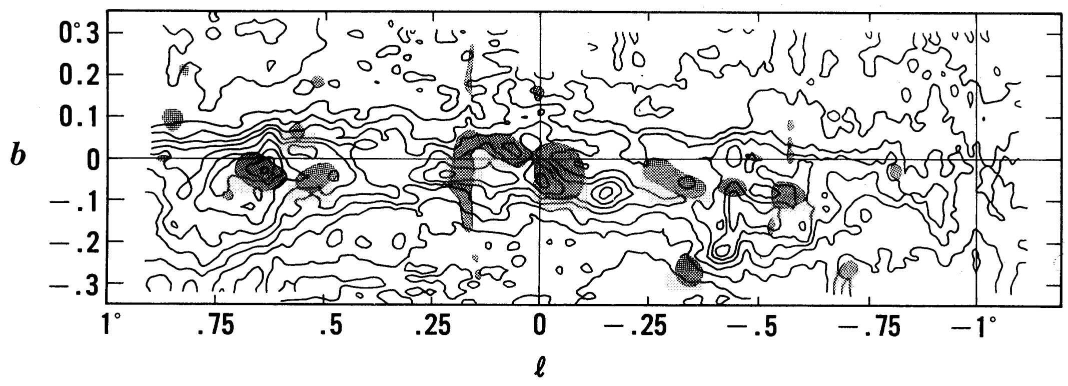

Fig. 2. Superposition of radio continuum sources on a ^{13}CO map (Stark et al. 1989). Contour intervals are 40 K km s^{-1}.

Table 1. Spatial and velocity relationship between H II regions and molecular complexes.

H II	Cont. G(l, b)(°)	$V^{(a)}_{\mathrm{LSR,H\,II}}$ (km s^{-1})	MC	p t p t	$V_{\mathrm{LSR,CO}}$ (km s^{-1})	V_{exp} (km s^{-1})	M_{MC} ($M_{\odot}$)	E_{kin} (erg)
Sgr B1	G+.52−.05	45	Shell	p t	30 − 40	25	2×10^{6}	1.3×10^{52}
Sgr B2	G+.66−.04	65	Complex	p t	60 − 70	···	1.5×10^{6}	···
G−0.27	G−.27−.03	−43	Arcs	p t		25	$\sim10^{5}$	$\sim6\times10^{50}$
	G−.34−.07		G−.3+.05	p t	−70			
	G−.45−.06		G−.3−.12	p t	−20			
		···	Barrel$^{(b)}$	p t	20	70	10^{5-6}	10^{52-53}
Sgr C	G−.56−.08	−60	Complex	p t	−60	···	···	···

(a) Downes et al. (1980); Pauls and Mezger (1975).
(b) Tsuboi et al. (1989).

positional relationship between the distributions of the ^{13}CO (Stark et al. 1989) and the continuum emission features. It is obvious that the intensity distributions both for the continuum and molecular line emissions are significantly asymmetric with respect to the galactic center (Sgr A). They are both stronger in the positive longitude side than in the negative longitude regions. For various thermal radio sources, velocity data from hydrogen recombination line observations are available (Downes et al. 1980), and are summarized in table 1 together with their galactic coordinates.

2.1. Sgr B2 and a Molecular Complex

The radio source Sgr B2 comprises of compact H II regions with strong thermal emission (e.g., Akabane et al. 1988) with recombination-line velocity of $V_{\mathrm{LSR}} = 65$ km s^{-1}. A dense molecular cloud with an angular size of about 0°.05 at $V_{\mathrm{LSR}} =$ 60–70 km s^{-1} (Bally et al. 1987) is associated not only regarding velocity, but also

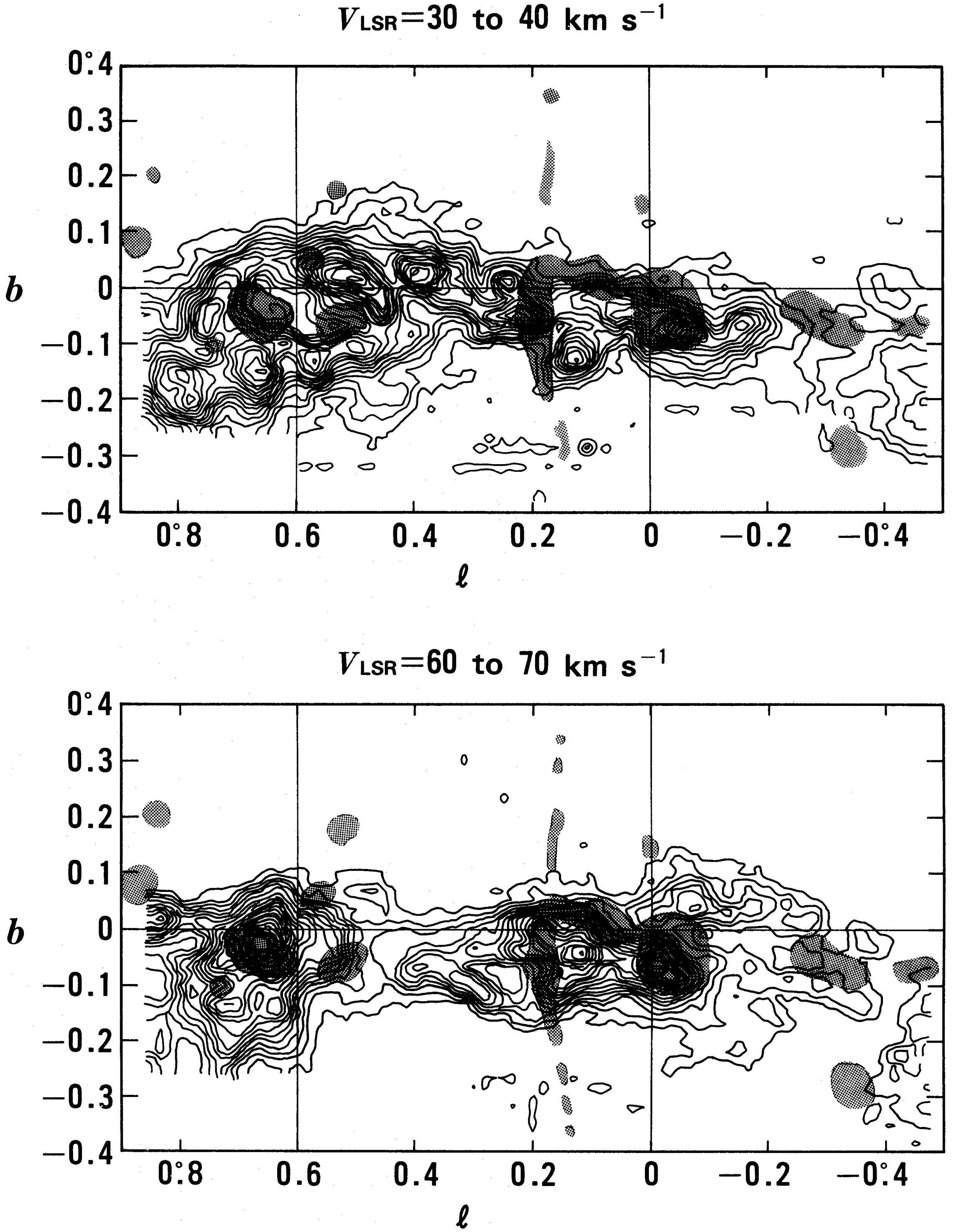

Fig. 3. ^{13}CO features (Bally et al. 1987) and radio continuum structures around Sgr B1 and B2. Contour intervals are 2.5 K km s^{-1}.

positionally coincides with Sgr B2 (figure 3, table 1). The continuum radio emission suffers from strong H_2CO molecular line absorption at $V_{\rm LSR} = 62.5$ km s^{-1} (Downes et al. 1980). This indicates that the molecular cloud lies in front of the continuum source, and that probably Sgr B2 (H II region) and the molecular cloud are in contact with each other along the line of sight. Namely, star formation in Sgr B2 may be taking place at the farther end of the molecular cloud along the line of sight.

The Sgr B2 molecular cloud is a part of even larger molecular complex: At a similar velocity, 60–70 km s^{-1}, the cloud is embedded in a wide outskirt with a diameter of approximately $0^\circ\!.25$. We call this complex the "Sgr B2 molecular complex." The total mass of this complex can be estimated using the integrated intensity and the extent as read from the ^{13}CO maps (Bally et al. 1987). We use the relation $\sigma = 32I$, with σ being the surface mass density of molecular gas in $M_\odot$ pc^{-2} and I being the ^{13}CO line intensity in K km s^{-1} (Solomon et al. 1979). The total mass of the Sgr B2 molecular complex, including its outskirt, is estimated to be $1.5 \times 10^6 M_\odot$.

2.2. *Sgr B1 and a Molecular Shell*

The thermal source Sgr B1 lies close to Sgr B2. At the same velocity as Sgr B1 (45 km s^{-1}) there exists a molecular complex which extends for an angular extent of $\Delta l \times \Delta b \simeq 0^\circ\!.4 \times 0^\circ\!.3$. It is remarkable that this molecular complex makes a large loop with its clearest appearance at $V_{\rm LSR} = 30$–40 km s^{-1} (Bally et al. 1987). Figure 3 shows this molecular loop as superposed on the 10 GHz continuum map. The radio continuum sources, Sgr B1 and B2, apparently lie in the cavity of this molecular loop feature.

This loop feature has a systemic velocity of about 40 km s^{-1} and can be recognized over a wide velocity range from $V_{\rm LSR} \simeq 70$ km s^{-1} to $V_{\rm LSR} \simeq 20$ km s^{-1}. We emphasize that the recombinatioin-line velocity ($V_{\rm LSR} = 45$ km s^{-1}) of Sgr B1 coincides with the velocity of this molecular loop, which indicates that the loop is physically related to Sgr B1, possibly driven by the activity of this H II region. From these facts we may interpret that the loop feature is a molecular shell surrounding Sgr B1; we call it the "Sgr B1 molecular shell." We mention that Bally et al. (1987) have interpreted the relation between the Sgr B1 loop and Sgr B2 complex as a "hole" which formed as the result of a local gravitational condensation of gas into the Sgr B2 cloud, while the present interpretation suggests an expanding motion in the loop feature.

The large velocity dispersion of the shell ($V_{\rm LSR} = 20$–70 km s^{-1}) suggests that it is expanding at a velocity of about 25 km s^{-1} referring to its center velocity. The size of this shell is about 40 pc × 30 pc for a distance of 8 kpc. If the expanding velocity is 25 km s^{-1}, the age of the shell would be of the order of 10^6 years. Hence, the expansion of the shell may have started about 10^6 years ago when Sgr B1 was still more active than today. The total mass of the shell is estimated to be $2 \times 10^6 M_\odot$. This leads to a kinetic energy of the expanding motion of about 1.3×10^{52} erg.

It is possible that the Sgr B1 molecular shell, after $\sim 10^6$ years since it began to expand, hit another nearby dense molecular cloud (Sgr B2 molecular complex), and triggered another star formation. This new star-forming site may be the young H II region, Sgr B2. Whiteoak et al. (1987) have suggested that an overall alignment of compact continuum sources within Sgr B2 may be accounted for if the star formation in Sgr B2 was triggered by a single large-scale event, such as an interaction between

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molecular clouds: we suggest that this event may possibly be shock due to an expanding shell from Sgr B1. After the passage of the shell front, star formation settles and winds from massive stars in Sgr B2 may have further pushed the shell toward the north-east, making it more compressed at $l = 0^\circ\!.72$. Table 1 summarizes the positional and velocity relationship between the molecular and H II features around Sgr B1 and B2.

2.3. Molecular Gas Avoidance near a Continuum Chain at Negative Longitude

Radio continuum sources at negative longitudes, G−0.27−0.03, G−0.34−0.07, and G−0.45−0.06, comprise a chain aligned near the galactic plane, which we call the "G−0.27 continuum chain."

An elongated molecular feature of ^{13}CO is found above these radio sources and is known as the "negative-velocity arc" (Bally et al. 1988). This feature is aligned parallel to the galactic plane at $b \simeq 0^\circ\!.02$ and the velocity varies continuously from $V_{\rm LSR} = -50$ km s^{-1} ($l \sim -0^\circ\!.2$) to -90 km s^{-1} ($\sim -0^\circ\!.5$). Another arc-shaped molecular feature is found at $b \sim -0^\circ\!.2$ and runs parallel to the negative-velocity arc but at lower latitude in the opposite side of the continuum chain. This lower arc has a continuously changing velocity from $V_{\rm LSR} = -20$ km s^{-1} ($l \sim -0^\circ\!.2$) to -40 km s^{-1} ($l \sim -0^\circ\!.5$). Figure 4 illustrates the positional relationship between the continuum sources and the molecular features. At $V_{\rm LSR} = -30$ to -50 km s^{-1} there are several small clouds which are more closely associated with the continuum chain, and the velocity coincides with that of G−0.27. The clouds seem to be related to the southern molecular arc at its larger velocity ends.

Note that the continuum chain lies near the center of the molecular arcs and positionally coincides with a region of empty molecular gas: The continuum and molecular features seem to avoid each other. We emphasize that these molecular arcs are concave with respect to each other, and that they appear to surround the continuum chain, comprising an elliptical ring with its center at G−0.27−0.03. This suggests that the two arcs comprise opposite parts of an expanding ring at a velocity of about 25 km s^{-1}. The ring radius, as estimated from its angular extents, will be about 30 pc, and it is tilted by about 20° from the galactic plane, so that its age of the order of 10^6 yr. The radial velocity of G−0.27 ($V_{\rm LSR} = -43$ km s^{-1}) is nearly equal to the mean velocity of the two molecular arcs. However, on the velocity-position diagrams it is not clear that these two arcs are connected to each other. The upper arc might be an isolated cloud (Stark et al. 1989).

The total mass of H$_2$ gas involved in the upper arc (the negative-velocity arc) can be estimated in the same manner as in section 2.2 by using a map presented by Stark et al. (1989), and is of the order of $3 \times 10^4 M_\odot$. The mass distribution in the lower half is rather complex, but is of the same order as the upper half. We then estimate that the total mass of the G−0.27 molecular arcs to be of the order of $10^5 M_\odot$. If the two arcs are parts of a ring expanding at 25 km s^{-1}, the kinetic energy of the ring is about $\sim 6 \times 10^{50}$ erg, which could be driven by a single supernova explosion.

2.4. "Barrel"

From their CS ($J = 1-0$) line observations, Tsuboi et al. (1989) have found a barrel-shaped shell of radius 20 pc at G−0.3−0.1. The "barrel" has a central LSR

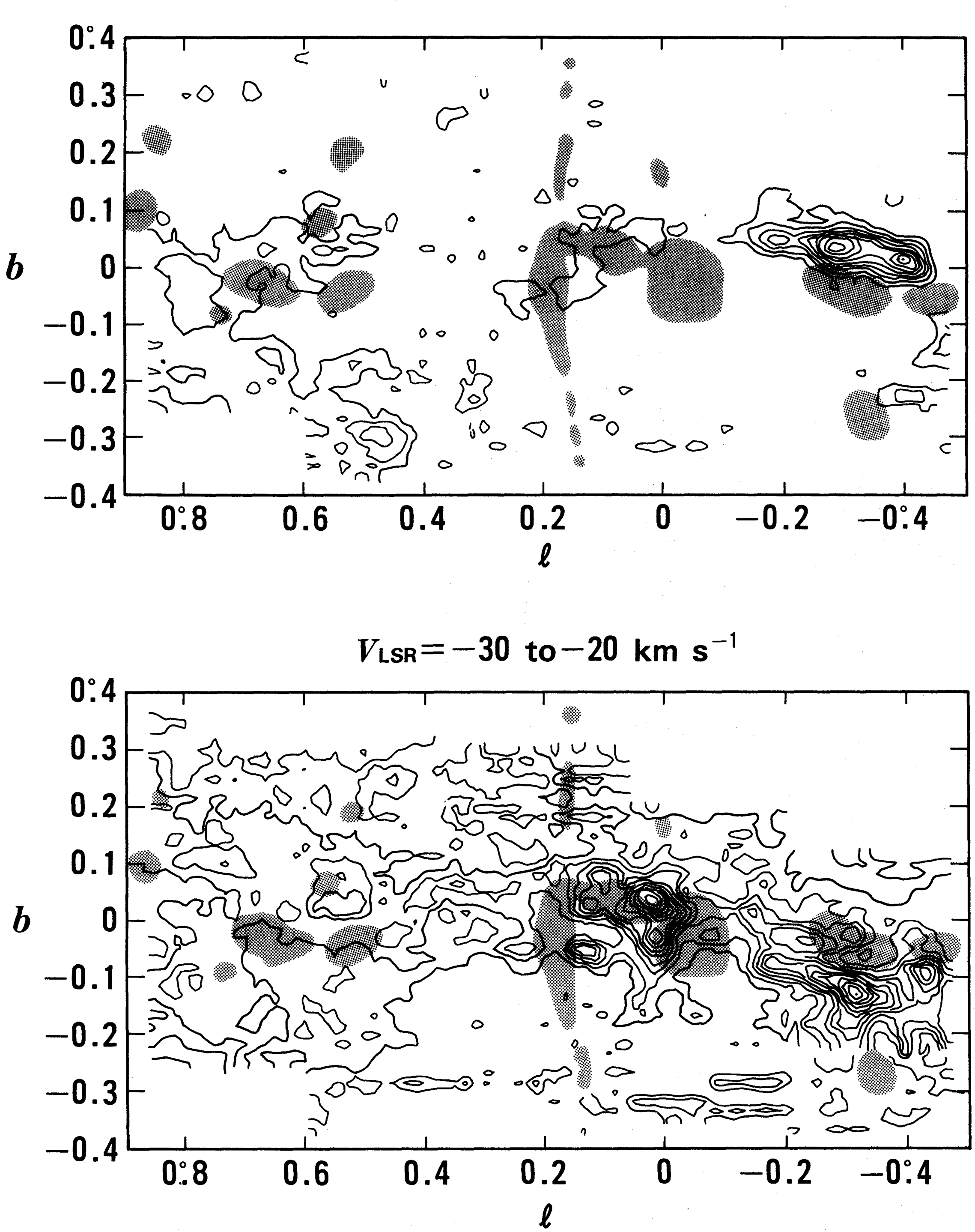

Fig. 4. ^{13}CO features and the radio continuum chain near G–0.27–0.03. Contour intervals are 2.5 K km s^{-1}.

velocity of $V_{\mathrm{LSR}} \sim +20$ km s^{-1}. On the l - V_{LSR} map it makes a ring-like feature fitted with an expanding loop at a velocity of 70 km s^{-1} and radius 20 pc. Tsuboi et al. (1989) attributed this ring to a shell expanding at a velocity of 70 km s^{-1}, which was caused by an explosion with an energy of 10^{52-53} erg.

The center position of this barrel apparently coincides with the continuum source G$-$0.27$-$0.03, which has $V_{\mathrm{LSR}} = -43$ km s^{-1}, and the negative velocity side of the ring on the l - V_{LSR} diagram at $V_{\mathrm{LSR}} = -40$ to -50 km s^{-1} is close to the recombination-line velocity of G$-$0.27$-$0.03. Tsuboi et al. (1989) suggest that the continuum source G$-$0.27$-$0.03 may be a shock-triggered star-forming site on the surface of this expanding barrel. From the ring radius, 20 pc, and the expansion velocity, 70 km s^{-1}, the barrel's age must be of the order of 3×10^5 years. This time scale might be too short for other star formation to be triggered. Hence, it is not clear if the barrel and the continuum source G$-$0.27 are related to each other. We also note that no continuum source, and therefore no recombination source, has been found near the center velocity of the barrel.

2.5. Sgr C and Molecular Complex

On the integrated ^{13}CO map (figure 1) the continuum source Sgr C lies near a position where the molecular emission has depression. On the channel maps of the CS ($J = 2 - 1$) line emission (Bally et al. 1987) we find a complex of molecular gas at $V_{\mathrm{LSR}} = -40$ to -60 km s^{-1} which though associated with Sgr C, is positionally shifted toward the south-east by about $5'$. Again we notice that the continuum source does not positionally coincide with the peak position of its associated molecular complex.

The Sgr C molecular complex extends for approximately $0^\circ\!.25$ (35 pc) not only along the galactic plane but also in the direction perpendicular to the plane. In particular, it has a negative-latitude extension at $V_{\mathrm{LSR}} = -50$ to -60 km s^{-1}. The Sgr C region is the root of the western half of the Galactic Center Lobe (Sofue and Handa 1984), and contains nonthermal radio filaments associated with a molecular complex (Liszt 1985; Bally and Yusef-Zadeh 1989). Another molecular feature at high negative velocity, $V_{\mathrm{LSR}} = -100$ to -140 km s^{-1}, is associated with this region. This high-negative velocity feature comprises of two symmetrical plumes extending from G$-$0.50$-$0.05 vertically to the galactic plane for about $\pm 0^\circ\!.2$. This might be associated with possible high-velocity ejection along the Galactic Center Lobe.

2.6. Radio Arc and Bridge

The radio arc at G0.2+00, which is nonthermal, is not particularly associated with molecular features in so far as the present data are concerned. The arc apparently crosses some molecular clouds at positive V_{LSR}, though no particular correlation has been found. The radio bridge at G0.1+0.05, which connects the arc with Sgr A, is associated with a molecular complex at $V_{\mathrm{LSR}} \sim -30$ km s^{-1}. This negative velocity feature was described in detail by Güsten (1989), and may be more related to the galactic center activity than to the star-forming activity.

3. Discussion

We have examined the positional correlation between molecular clouds and H II regions through a comparison of the CO line data with radio continuum maps. It has been found that, while the continuum sources are more or less associated with molecular gas, the peak positions of molecular clouds slightly but definitely avoid the continuum peaks. The molecular shell around Sgr B1 and the molecular arcs surrounding G$-$0.27 are typical cases of such molecular-continuum avoidance. From these observations we conclude that the molecular clouds, at least in the vicinities of star-forming sites in the galactic center region, are distributed in such a way that they comprises shells and/or rings surrounding the central continuum sources.

The shells and rings are probably driven by activities in the star-forming regions, such as stellar winds and/or supernova shocks. In fact, the kinetic energies of the shells, $E \sim 10^{50-52}$ erg, can be supplied by several supernovae (table 1). This picture agrees with that drawn by Tsuboi et al. (1989), who have suggested that the galactic center region is full of expanding (barrel-shaped) bubbles of molecular gas which are driven by explosive events, although their bubbles are not necessarily centered by known star-formation regions. However, it must still be investigated in more detail whether the scenario of an accelerating massive cloud complex by SN explosions etc. is physically feasible. We only suggest that such molecular ring/shell structures might be similar, but less energetic, to molecular rings and shells often found in starburst nuclei like M82 (e.g., Nakai et al. 1987; Sofue 1988). According to the starburst-ring formation scenario (e.g., Sofue 1988), successive SN explosions and stellar winds cause high pressure in the central region of a dense nuclear molecular disk, and a cavity forms near the center. Then, the upper and lower parts of the disk are blown off while forming a cylindrical outflow perpendicular to the disk. Accordingly an expanding molecular ring forms within the disk. It is possible that similar cavity-ring formation takes place within a single massive cloud near the galactic center triggered by interior star formation or mini-burst: namely mini-rings/shells can be formed by mini-bursts associated with individual clouds.

In this scenario the H II region Sgr B2 may still be embedded within or in contact with a dense molecular complex, and star formation (or a mini-burst) in Sgr B2 has possibly been triggered by the expanding Sgr B1 shell. The molecular shell centered by Sgr B1 is in a cavity phase and expanding. The molecular ring around G$-$0.27 is in a late ring phase, in which the upper and lower parts of the cloud had already been blown off. It is thus possible that the G$-$0.27 ring is the oldest, the Sgr B1 shell is moderate, and the Sgr B2 complex the youngest star-forming (mini-burst) regions. The fact that they are not necessarily located close to each other suggests that star-burst sites are wandering around the galactic center.

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