Publ. Astron. Soc. Japan **37**, 697–713 (1985)

The Galactic Center Lobe

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(Received 1985 January 7; accepted 1985 April 30)

Abstract

Radio continuum observations of the central region of our Galaxy have revealed an off-plane, Ω-shaped lobe (the galactic center lobe: GCL) with a diameter 200 pc emerging from the nuclear disk toward the positive galactic latitude. The radio spectrum is flat, indicating either a thermal gas origin or synchrotron radiation due to recently accelerated cosmic-ray electrons. CO line observations show an association of a high-velocity molecular gas with the lobe ridges. The eastern and western lobe ridges are connected to the "radio arc" and Sgr C in which extremely thin filamentary structures are found with the VLA. This fact indicates an influence of a magnetic field on the GCL. The origin of the GCL is discussed in relation to an activity in the central region of the Galaxy. The GCL may be a cosmic jet perpendicular to the nuclear disk under a predominant influence of a strong magnetic field, and a magnetic-twist acceleration model is suggested as a favorable formation mechanism. We point out characteristics of the GCL and some radio lobes in edge-on spiral galaxies common to more energetic jets associated with quasars and radio galaxies based on a statistical plot of a lateral expansion rate of the jet against a radio power of the core source.

Key words: Cosmic jets; Galactic center; Nuclear activity; Radio lobes.

1. Introduction

Kerr and Sinclair (1966) called attention to a "jetlike" feature in the central region of our Galaxy on their low-frequency radio map. Since then, however, no extensive research has been made of a large-scale diffuse radio emission in the off-plane region in relation to the galactic activity. On the other hand, the near-plane extended radio emission has been extensively studied in relation to the extended H II gas disk on the basis of a number of radio surveys (e.g., Mezger and Pauls 1979).

In our recent paper (Sofue and Handa 1984) we briefly reported a discovery of a large-scale, Ω-shaped radio lobe structure above the galactic center through our 10.5-

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* Nobeyama Radio Observatory, a branch of the Tokyo Astronomical Observatory, University of Tokyo, is a facility open for general use by researchers in the field of astronomy and astrophysics.

GHz continuum observations. The lobe is referred to as the GCL (galactic center lobe). We have argued that the GCL may be evidence for a channeled exhaust of matter, or a cosmic jet, perpendicular to the nuclear disk induced by an activity in the central region of our Galaxy. In this paper we describe in detail the radio properties of the GCL based mainly on radio continuum observations (section 2). Some results from our recent CO-line observations are briefly touched upon in relation to the dynamics of the GCL. On the basis of the observational facts, we discuss a possible origin and formation mechanism of the GCL in relation to the galactic center activity.

Recent VLA observations of the "radio arc" near Sgr A (Yusef-Zadeh et al. 1984) have shown the existence of a strong magnetic field in the central region of the Galaxy. In this paper we investigate in detail the relationship of the GCL to the smaller-scale structures in the galactic plane using the 10-GHz continuum data (section 3). We emphasize the importance of the influence of a magnetic field in the active rotating nuclear disk on the formation of the GCL. In fact Uchida and Shibata (1984) have proposed a promising ejection mechanism of matter, or a cosmic jet, perpendicular to the rotating gas disk by a twisting magnetic field running perpendicularly to the disk plane. We discuss the plausibility of this model on the origin of the GCL.

A study of a cosmic jet phenomenon in our Galaxy and those in edge-on spiral galaxies like NGC 3079 (Hummel et al. 1983; Duric et al. 1983) may provide an observational aspect to an understanding of the general cosmic-jet phenomena found frequently in quasars and radio galaxies, and in particular, an understanding of the relationship of the jet to the nuclear disk. We recall that no observational evidence has been given of a "disk" in quasars and radio galaxies, despite the fact that every theory of a jet formation (e.g., Rees 1971; Sakashita 1971) has assumed a priori the existence of a nuclear disk in the central region. An extensive study of the GCL and its relation to the nuclear disk may give an important clue to understand not only a cosmic jet phenomenon in our galactic center, but also those in quasars and radio galaxies (section 3).

2. Radio Properties

a) 10.55-GHz Radio Continuum Observations

The 10.5-GHz observations were made in April 1983 and August 1984 using the 45-m telescope at the Nobeyama Radio Observatory in the course of a radio continuum survey of the galactic plane. The HPBW was 2′.6 at the center frequency of 10.55 GHz and the bandwidth was 500 MHz. The first side-lobe level was below -20 dB, which provided a high-dynamic range measurement of the region near the strong source, Sgr A. We used a cooled parametric amplifier combined with a Dicke switching system. The system noise temperature was about 150 K. We mapped a square area of $4^\circ \times 4^\circ$ centered on the galactic center by scanning in the direction of the latitude at intervals of 1′.2. The integration time per beam area was effectively 1.4 s. Two extreme sides of each scan at $b=-2^\circ$ and $+2^\circ$ were taken as the zero level. Scanning effects were removed using the "pressing" technique developed by Sofue and Reich (1979). The data reduction was made using a radio astronomical reduction

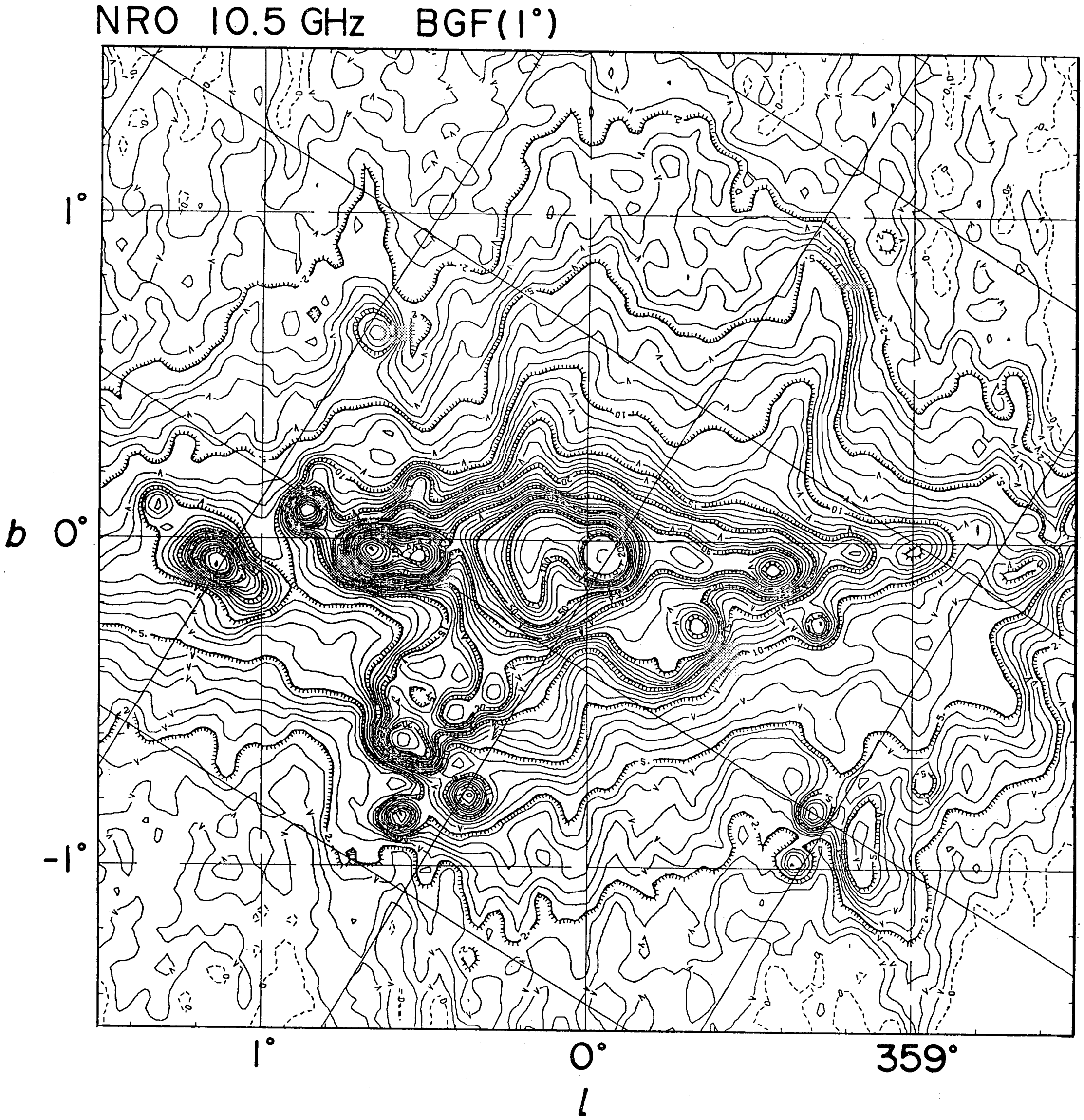

Fig. 1. A BGF (background-filtered) map of the surface brightness at 10.55 GHz of the central region of the Galaxy smoothed to an angular resolution of HPBW 4.′3 (the same resolution as that of the Bonn 2.7-GHz map in figure 4). An extended background structure with a scale size greater than 1.°0 has been removed from the original by applying the BGF method. The unit of the contour numbers is 10^{-21} W m^{-2} sr^{-1} Hz^{-1} in surface brightness.

system at the NRO, which uses partly the NOD 2 reduction package. The effective rms noise on the resultant map in a quiet region is about 30 mK.

Figure 1 shows an obtained 10.5-GHz map for a region of 3°×3° centered on the galactic center and smoothed to a HPBW of 4.′3. In the map an extended, large-scale structure with a scale size greater than 1.°0 has been removed by applying a background filtering (BGF) technique of Sofue and Reich (1979) in order to enhance finer-scale features. The map reveals a number of spur structures emerging from the galactic plane toward high latitudes. Among them the most prominent are the two strong spurs at $l=+0.°2$ and $-0.°6$, both extending toward the positive latitude perpendicu-

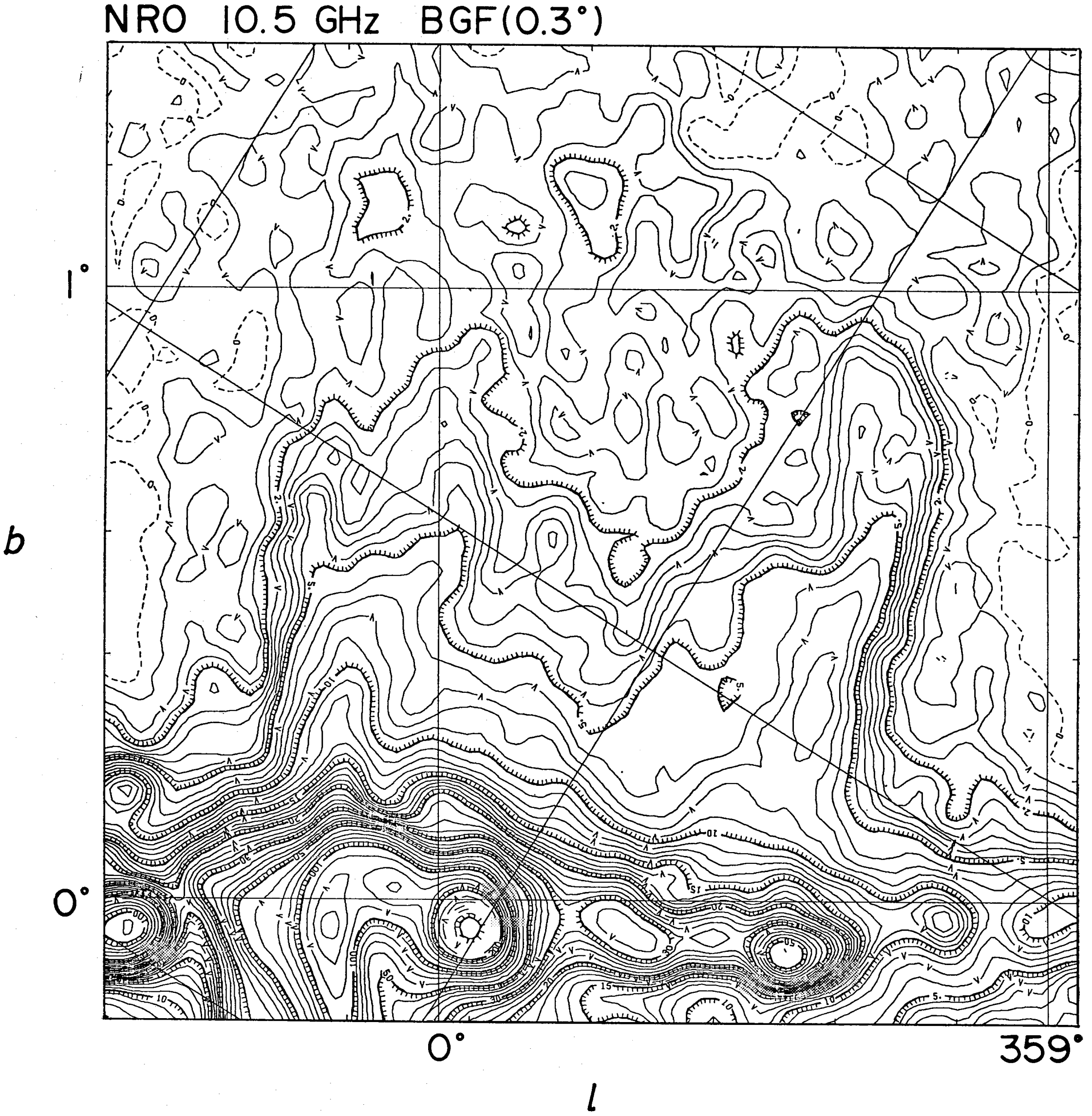

Fig. 2. A close up of the galactic center lobe at 10.5 GHz smoothed to a HPBW of $3'.6$ after a BGF of filtering scale size $0^\circ.3$. The contour unit is the same as in figure 1.

larly to the galactic plane. We emphasize that the two spurs bend convex with respect to the galactic center and are connected with a radio arc at around $b=1^\circ.2$ to form an Ω-shaped lobe structure. Figure 2 is a close up of this structure, or the galactic center lobe (GCL). In the figure the smooth background component with a scale size greater than $0^\circ.3$ has been removed again using the BGF. Figure 2 demonstrates in a clearer way that the two spurs are connected with a broad arc at around $b=1^\circ.2$ to form a giant Ω-shaped loop.

b) 2.7- and 5-GHz Maps

A part of the galactic center lobe already appears in previous radio survey maps at 1.4, 2.7, and 5 GHz of Altenhoff et al. (1970, 1978) and at 5 GHz of Haynes et al. (1978). However, these surveys are not good enough in resolution and sensitivity

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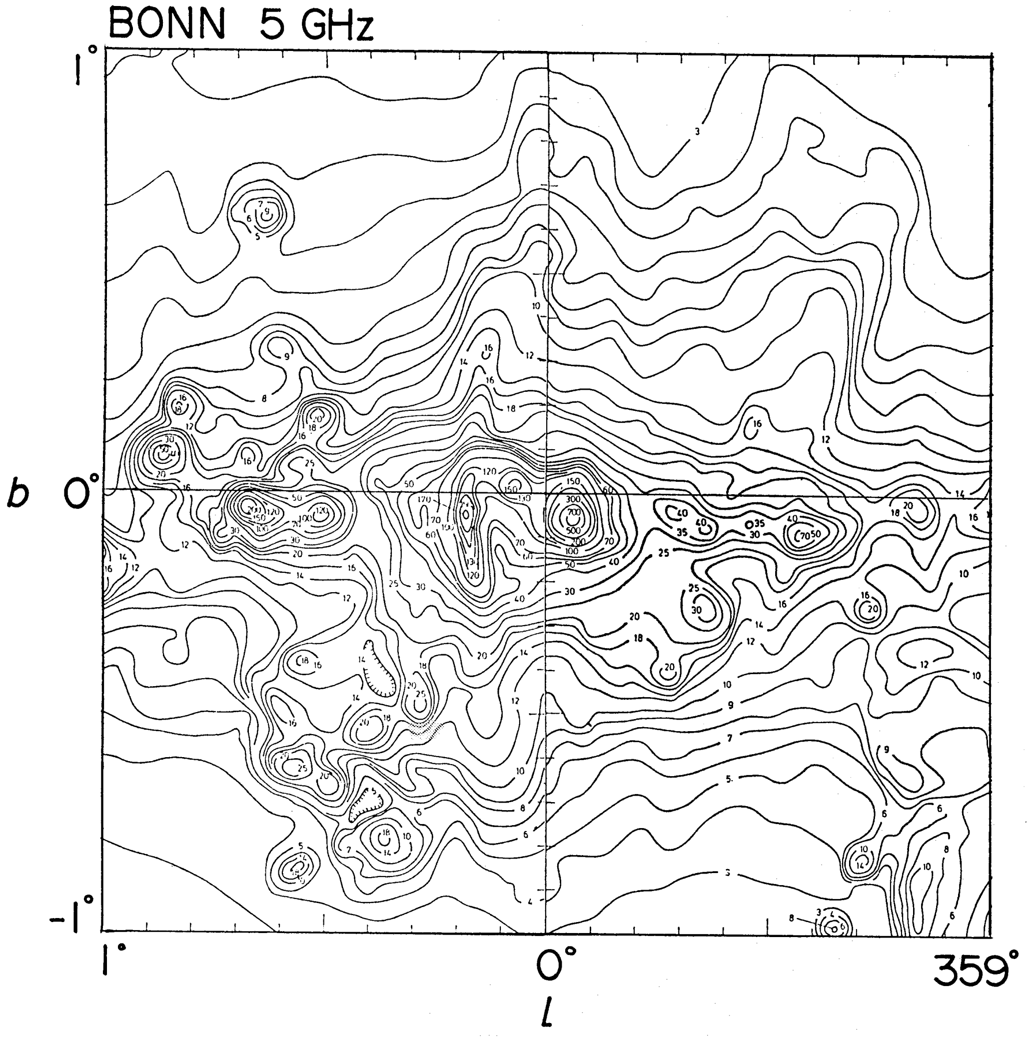

Fig. 3. A reproduction of the Bonn 5-GHz survey map from Altenhoff et al. (1978) for the central region of the Galaxy. We can recognize two spurs running towards the positive latitude, which are the two ridges of the GCL. The contour unit is 0.1 Jy/beam area of $2'\!.6$ HPBW.

to reveal the whole structure of the lobe. Figure 3 is a reproduction of the 5-GHz Bonn survey of Altenhoff et al. (1978) for a $2^{\circ}\times2^{\circ}$ area of the galactic center. Although the map lacks the upper region of the lobe, we can see the two ridges emerging at $l=+0^{\circ}\!.2$ and $-0^{\circ}\!.6$.

The whole lobe structure has been clearly observed in the recent 2.695-GHz Bonn survey with the 100-m telescope (Reich et al. 1984). Figure 4 reproduces the same region as figure 1 from this survey, where the background component with scale sizes greater than $1^{\circ}\!.0$ has been removed with the BGF. As the angular resolution (HPBW $=4'\!.3$) is lower, the ridges are not resolved. However, the figure shows up clearly the connection of the spurs with an arc at $b=1^{\circ}\!.2$ to form an Ω shape.

c) Flux Density and Intensity Distribution across the GCL

Figure 5 shows cross sections of the GCL along a constant latitude, $b=0^{\circ}\!.4$, as

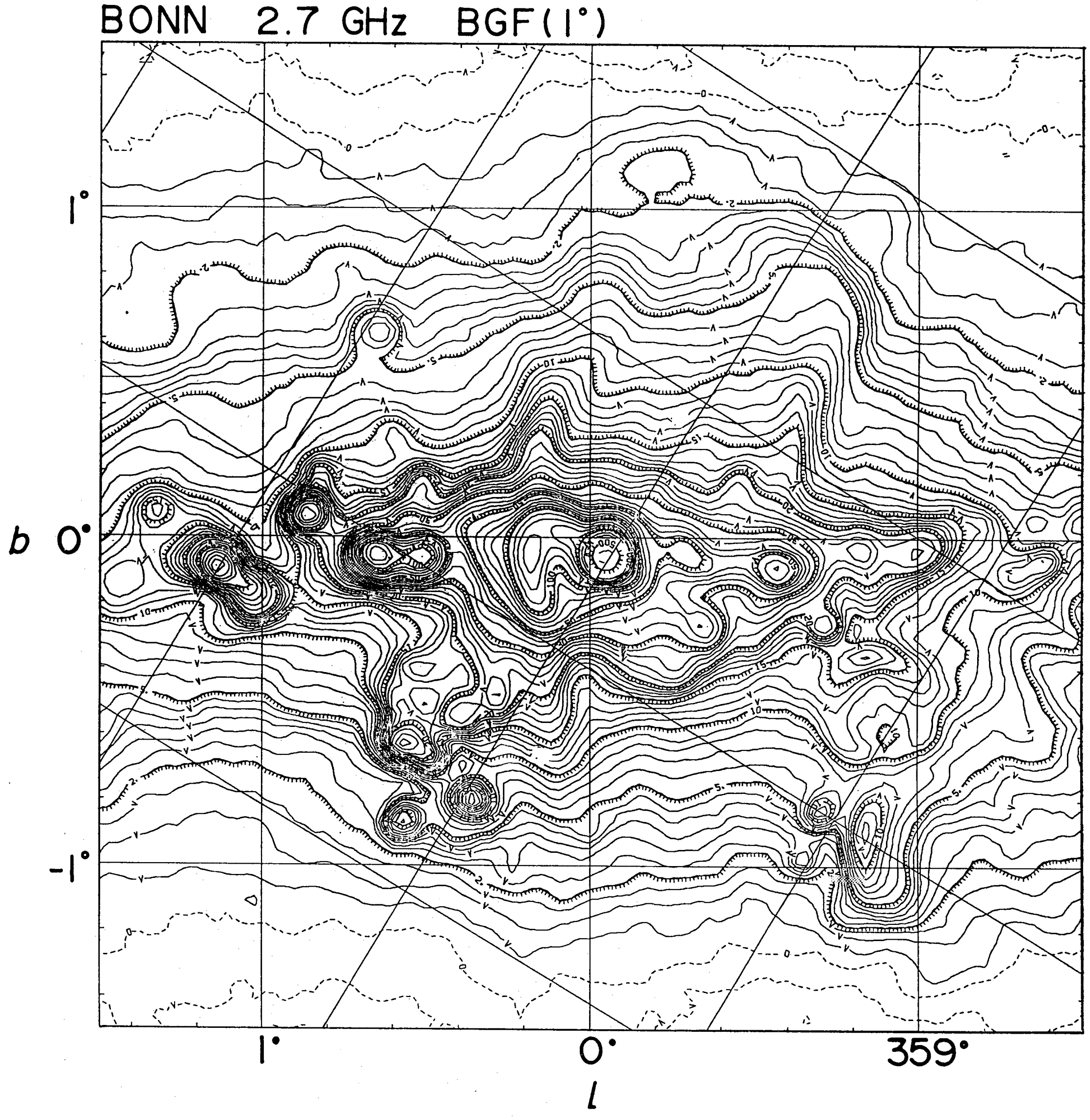

Fig. 4. A BGF map same as figure 1 but at 2.7 GHz from the Bonn survey (Reich et al. 1984). The HPBW of the map is 4!3. A BGF has been applied with the same filtering beam size of 1°0 as in figure 1. The unit of the contour numbers is 10^{-21} W m^{-2} sr^{-1} Hz^{-1}.

obtained from the original 2.7-, 5-, and 10-GHz maps without applying the BGF. The lobe has a steep gradient of radio intensity toward the outer edges, and the two ridges are connected by a diffuse radio emission in between. The cross sections are similar to those typical of a compressed shell like a supernova remnant. This fact suggests that the lobe is a result of an explosive or an energetic outflow phenomenon, probably related to the galactic center activity.

From figure 5 we can see that the radio emission is well represented by a superposition of two components; a lobe component with two sharp peaks at $l = -0°6$

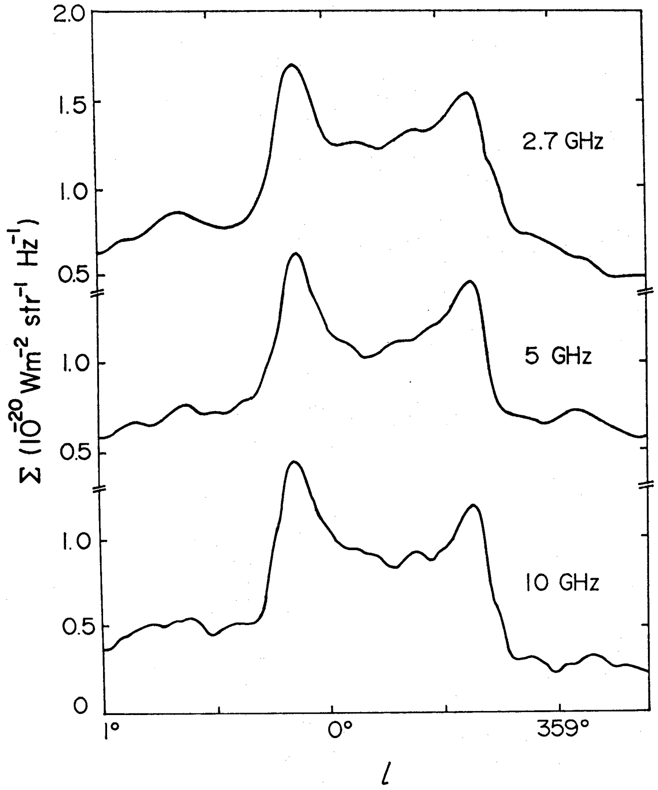

Fig. 5. Radio intensity cross sections of the GCL at a constant latitude, $b=0^\circ.4$, made from the original 2.7-, 5-, and 10.5-GHz survey maps.

and $+0^\circ.2$, and a smooth background component. The latter component is, however, not corrected for the absolute zero level. In particular, the 2.7-GHz map lacks the widely extended nonthermal emission of the background beyond $b=+2^\circ$ and -2° at which an artificial zero level is settled; this causes a relatively small value of the smooth component. By comparing the peak intensities of the lobe component over the background at the three frequencies, we obtain a spectral index of about $\alpha=0$, where $\Sigma \propto \nu^{\alpha}$ with Σ the surface brightness and ν the frequency. The flat spectrum suggests a thermal (free-free) emission from an H II gas. The total flux density of the GCL at 10.5 GHz integrated above $b=+0^\circ.2$ is estimated to be $S=132\pm10$ Jy.

d) Spectral Index Distribution

To get information about the nature of radio emission from the GCL, we obtain a distribution of spectral index for the same region as in figure 1. We use the BGF maps at 2.695 (figure 4) and 10.55 GHz (figure 1) in which the broad, extended component of the background has been removed. By using the BGF maps, we can avoid a systematic error in the spectral index determination which arises mostly from the ambiguous zero levels of the original maps. Figure 6 shows a map of the spectral index thus obtained. The figure shows that most part of the radio lobe has a flat spectrum of $\alpha=0$, which is consistent with our preliminary estimation of the lobe spectrum using the cross sections in figure 5. The flat spectrum suggests strongly the connection of the lobe to an extended nuclear disk, where the spectrum is also flat

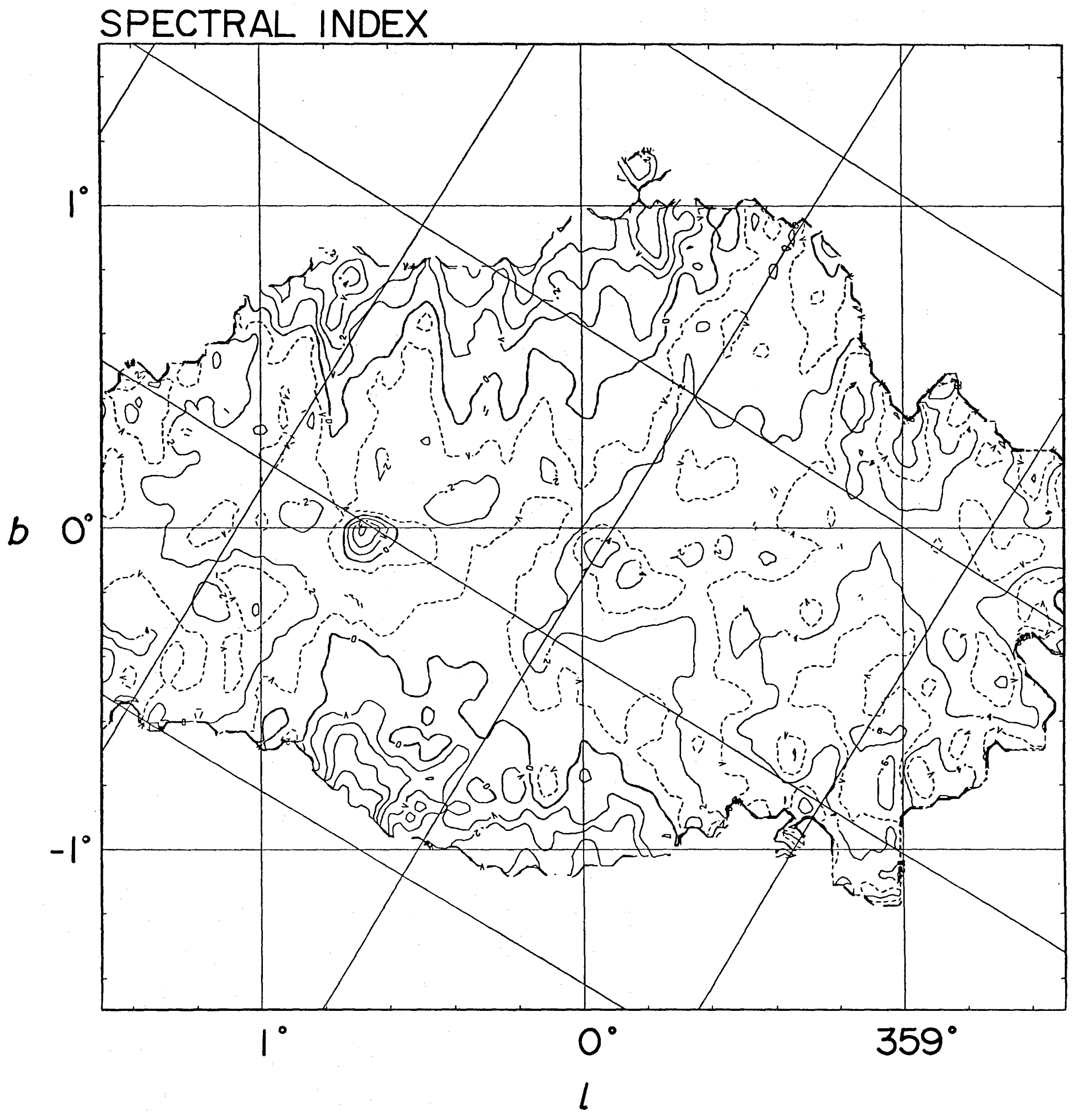

Fig. 6. A distribution of the spectral index α between 2.7 and 10.5 GHz as determined using the BGF maps in figures 1 and 4 ($\Sigma \propto \nu^{\alpha}$). The contour interval is $\Delta\alpha=0.1$.

due to the extended H II gas of temperature 5000 K as derived by Mezger and Pauls (1979). We point out that the lobe may be a thermal gas, which is likely to have been supplied from the extended H II disk (see subsection 3d). However, we mention the recent detection of highly polarized 10-GHz emission from theeastern ridge using the 45-m telescope (Inoue et al. 1984). This fact shows that we cannot still exclude a nonthermal origin of the lobe, at least of the lower part of the eastern ridge.

A region containing many strong sources with flat spectra extends to the southwestern part of the map to $l=0^{\circ}\!.5$ and $b=-0^{\circ}\!.5$, some of which are identified with H II regions by their hydrogen recombination-line emission (Wink et al. 1982; Downes et al. 1980). However, the relationship of this thermal region to the nuclear region remains an open question. We note that there exists a region with a steep spectral index of $\alpha=-0.5$ to -0.6 in the southern (right-bottom) corner of the map. The steep spectrum is due to the two supernova remnants of the shell type, G 359.0−0.5 and G 358.9−0.9 (Sofue et al. 1984).

e) CO Line Observations

The dynamical property is necessary for the understanding of the formation mechanism of the GCL. To get information on the motion in the lobe, CO line observations are in progress using a 4-m millimeter-wave telescope at Nagoya University. We here briefly summarize some of the preliminary results (I. Suwa and Y. Fukui, private communication).

The observations were made in January through April 1984. We observed both ^{12}CO and ^{13}CO line emissions of $J=1$–0 transition. The system noise temperature was about 1500 K for the observations from January through middle March, while it was about 600 K from March through April. We mapped a region of about $1^\circ\!.5\times 1^\circ$ centered on $l=359^\circ\!.6$ and $b=0^\circ\!.2$ with grid intervals of 3′ to 6′. The HPBW of the telescope at 115 GHz was $2'\!.7$, which was almost the same as that of the 45-m telescope at 10 GHz.

In the mapped region we find a significant amount of CO gas at high latitudes, $b\geq 0^\circ\!.3$, with $V_{\rm LSR}$ as high as -150 to $+150$ km s^{-1}. The high velocity gas should be associated with the central region of the Galaxy, but not due either to foreground or blackground disk gas. The velocity profiles of the CO line near the galactic plane are very complicated (e.g., Liszt and Burton 1979). However, those beyond $b=0^\circ\!.2$ show the existence of CO gas at high velocities associated with the GCL ridges. An isovelocity map of the ^{12}CO gas intensity integrated in a velocity range between $V_{\rm LSR}=90$ and 100 km s^{-1} reveals a spurlike extension of CO gas associated with the western ridge of the GCL. It forms a spur starting at $l=-0^\circ\!.6$, $b=0^\circ\!.2$, and reaching $l=-0^\circ\!.6$, $b=0^\circ\!.6$. For the eastern ridge, however, only a slight enhancement is seen. A latitude-velocity diagram along a constant longitude at $l=-0^\circ\!.6$ demonstrates more clearly the extension of the high-velocity gas at $V_{\rm LSR}=100$ to 150 km s^{-1}. The diagram shows also the existence of a high negative-velocity component associated with the ridge at around $b=0^\circ\!.3$.

In comparison with ^{13}CO line data we estimate an optical depth of the western ridge at $l=-0^\circ\!.6$, $b=0^\circ\!.3$ to be about 0.2 and the velocity width is about 30 km s^{-1} with an excitation temperature of $T_{\rm ex}=6$ K, which leads to a column density of H_2 gas as $N(H_2)=6\times 10^{22}$ cm^{-2} by applying the formula of Dickman (1978). The eastern ridge at $l=0^\circ\!.2$, $b=0^\circ\!.3$ has an optical depth of 0.1 and $T_{\rm ex}=9$ K with a line width of about 30 km s^{-1}, which leads to $N(H_2)=1\times 10^{22}$ cm^{-2}. The total mass of the molecular hydrogen gas associated with the GCL at $b\gtrsim 0^\circ\!.1$ is roughly estimated to be $4\times 10^5 M_\odot$.

Recent IRAS observations of the galactic center region by Gautier et al. (1984) cover the GCL. In their maps at 60 and 100 μm we can see a spurlike extension at $l=-0^\circ\!.6$, extending from $b=0^\circ\!.3$ to $0^\circ\!.8$. The position coincides with the western GCL ridge. They have estimated a dust temperature and a dust column density for a selected position at $l=359^\circ\!.6$ and $b=0^\circ\!.84$ (their area 3) as 27 K and 0.6×10^{-3} g cm^{-2}, respectively. This position is exactly on the western ridge of the GCL.

By assuming a dust-to-gas density ratio of 10^{-2} (Spitzer 1978), we obtain a rough estimate of the H_2 column density to be $N(H_2)=2\times10^{22}\,cm^{-2}$ at this position. Considering that the excess in the far-infrared emission associated with the lobe ridge over the extended background emission is about a half of this amount, we may estimate the H_2 column density associated with the ridge to be about $10^{22}\,cm^{-2}$. This amount of H_2 gas is consistent with that obtained from the CO line observations.

3. Discussion

We discuss the characteristic properties and possible origin of the galactic center lobe on the basis of the observational facts described in the previous section.

a) Geometry and Location

The geometrical center of the GCL is at $l=359^{\circ}.7$, $b=0^{\circ}.6$. Its angular diameter across is about $1^{\circ}.06$ and height from the galactic plane is about $1^{\circ}.2$. If the distance is 10 kpc, they correspond to 185 pc and 210 pc, respectively. As discussed in subsections 2c and d, the flat radio spectrum of the lobe excludes the possibility of a foreground or background shell-type supernova remnant. The association of the very high-velocity CO gas along the ridge may indicate a physical connection of the lobe to the nuclear disk: the high velocity cannot be expected from the foreground and background interstellar gas toward the galactic center direction. We also emphasize that the galactic plane region between $l=-10^{\circ}$ and $+10^{\circ}$ is rather a rare region of radio sources and spur structures. No other such strong spurs or extended sources comparable to the GCL are found there. All these facts as well as the geometrical appearance of the GCL indicate its association with the galactic center. We assume hereafter that the GCL is located at the galactic center at a distance of 10 kpc.

b) Energetics and Mass Distribution

We may assume that the lobe contains the H II gas as indicated from its flat radio spectrum. We here assume the electron temperature of 5000 K, which has been derived for an extended low-density H II gas in the nuclear disk (Mezger and Pauls 1979). The total mass of the ionized gas in the lobe above $b=0^{\circ}.2$ is then estimated to be $4\times10^{5}M_{\odot}$ from the total flux density, $S=132$ Jy. The mean electron density in the lobe is about $n_e=5\,cm^{-3}$. Here we assumed a spherical distribution of the H II gas of a uniform density with a radius of 100 pc, and used a formula for the emission measure given by Mezger and Henderson (1967). From the CO line observations we estimate the total amount of the molecular gas involved in the lobe to be about $4\times10^{5}M_{\odot}$ at $b\geq0^{\circ}.1$. Then the total mass of the ionized and molecular gases in the GCL is approximately $10^{6}M_{\odot}$. Since the velocity of the motion of the gas in the lobe is of the order of 100 km s^{-1} as shown from the CO line observations, we can estimate the total kinetic energy to be of the order of 10^{54} erg.

The radio brightness distribution across the GCL at $b=0^{\circ}.4$ (figure 5) suggests strongly that the radio emitting region has a shell or a cylindrical shape. We here assume a cylinder filled by the H II gas with a uniform density and temperature. A simple calculation shows that a cylinder with outer and inner radii of $r_o=82$ pc and

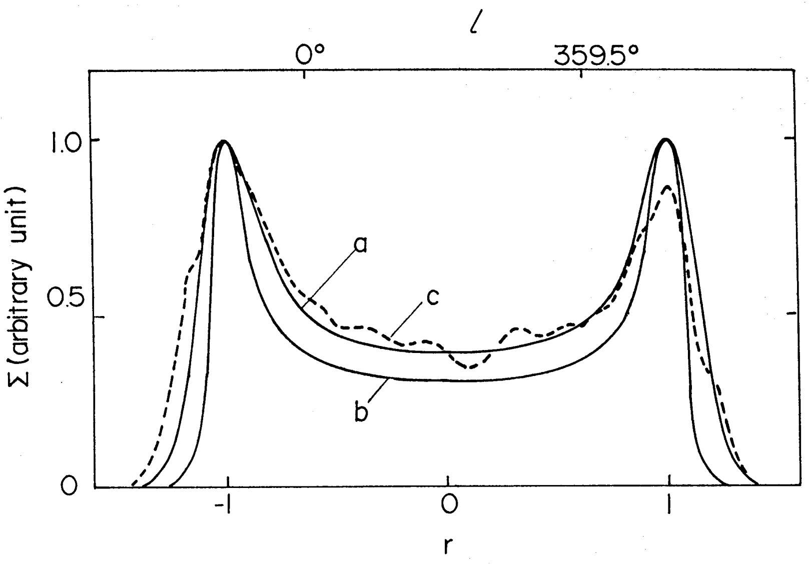

Fig. 7. (a) A calculated brightness distribution for a cylinder of outer and inner radii 82 pc and 65.6 pc, respectively, with a thickness 16.4 pc filled with H II gas of a uniform density and temperature. The result is smoothed to a HPBW of 3′. (b) The same but for a density distribution predicted from Sedov's (1959) self-similar solution for a shocked shell. For a comparison the observed brightness distribution at 10.5 GHz across the GCL at $b=0\overset{\circ}{.}4$ (figure 5) is superposed (line c). All the curves are normalized by the peak intensity at the eastern lobe ridge.

$r_i=65.6$ pc (a thickness of 16.4 pc) well reproduces the observed brightness distribution. Figure 7 shows the calculated brightness distribution smoothed to a 3′ resolution (line a). To fit the peak surface brightness at the lobe ridge, $\Sigma=8\times10^{-21}$ W m^{-2} sr^{-1} Hz^{-1}, the model calculation requires an emission measure of $EM=8000$ pc cm^{-6}. Here we took an electron temperature of 5000 K and used the formula given by Mezger and Henderson (1967). As the line-of-sight depth at the lobe ridge is 98 pc, we obtain an electron density of $n_e=9.0$ cm^{-3}. An approximate estimation of the H II mass contained in the cylinder, assuming the height of 200 pc with the same radii and a uniform distribution of thermal electrons of the above density, leads to a total mass of about $4\times10^5 M_\odot$ of the H II gas.

c) The Connection to Smaller-Scale Structures in the Galactic Plane and Southern Extension

To see the relationship of the lobe structure to smaller structures in the nuclear disk and the southern extension in more detail, we applied the background filtering (BGF) technique to the original map at 10 GHz (resolution of $2\overset{\prime}{.}6$) with a finer filtering beam of $\theta_{\rm BGF}=6'$. Figure 8 shows a BGF map thus obtained at 10 GHz for regions around the Sgr A radio arc and Sgr C. Figure 8a demonstrates a clear connection of the eastern ridge to the radio arc at $l=0\overset{\circ}{.}2$, $b=0°$. Also the figure demonstrates an extension of the eastern ridge to the southern region of the galactic plane, which extends to $l=0\overset{\circ}{.}1$ and $b=-0\overset{\circ}{.}8$ as seen in figure 1. Figure 8b shows that the western ridge has a connection to Sgr C and a small spurlike feature extends from there toward

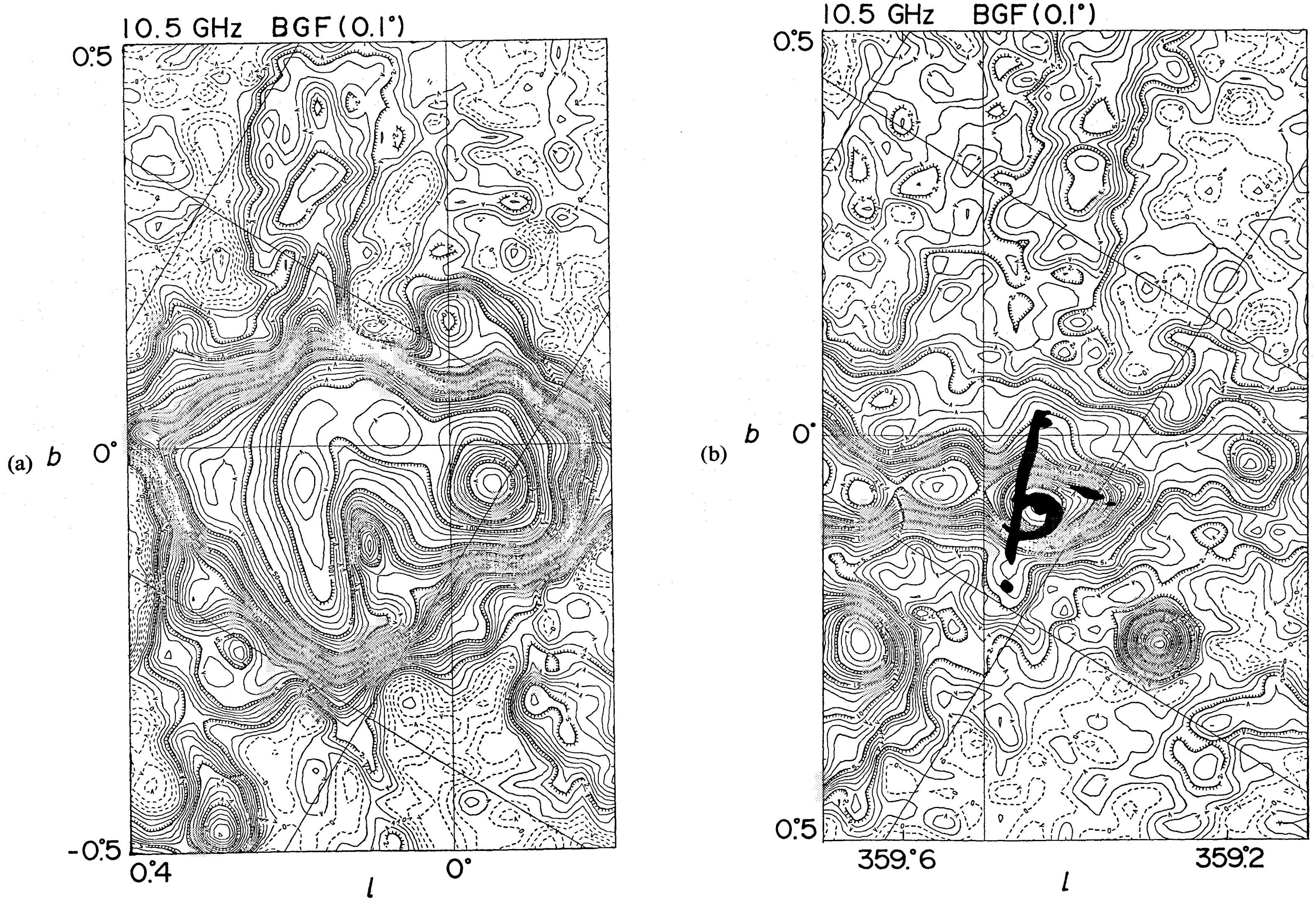

Fig. 8. BGF maps obtained from the original 10.5-GHz data (angular resolution HPBW=2′.6) using a finer filtering beam size of θ_{BGF}= 6′ to demonstrate the connection of the lobe ridges (a) to the "radio arc" at l=0°.2, and (b) to the VLA filament in Sgr C at l=−0°.5 (indicated with the dark area).

the south. In spite of the indication of southern extensions of the ridges, however, we conclude that there exists no complete southern counterpart to the whole lobe structure as found at positive latitudes, and therefore there is a significant north-south asymmetry.

Recent VLA observations of the radio arc near Sgr A (Yusef-Zadeh et al. 1984) and of the Sgr C region (Liszt 1985) have revealed the existence of very thin filamentary structures perpendicular to the galactic plane. Such straight, thin filamentary structures may be an indication of a predominant influence of a magnetic field in these regions. As seen from figure 8, the ridges of the GCL are clearly connected to the radio arc and to the filament in Sgr C; the extensions of the lobe ridges at their roots coincide both in direction and position with these thin filaments. This fact shows that the radio lobe has its roots at the galactic plane, having very similar characteristics both in the eastern and western parts, and is very likely to be predominated by a magnetic field.

d) Origin of GCL—A Cosmic Jet?

As to the origin and formation mechanism of the GCL, we propose the following possible models:

Model A. Explosion at the galactic center: A shock wave produced by an explosion at the nucleus of an active galaxy will be channeled in the direction perpendicular to the disk plane (Sakashita 1971). In fact Sofue (1984) has calculated the propagation of a shock front originating at the nucleus of our Galaxy through an ellipsoidal nuclear disk. We assume a nuclear disk which has a Gaussian distribution of the gas density with a central density of $10\,m_{\rm H}\,{\rm cm}^{-3}$, a half-density radius of 230 pc, and a half-density thickness of 100 pc. The disk is further surrounded by a gaseous halo with a constant density of $0.01\ m_{\rm H}\ {\rm cm}^{-3}$.

The calculation shows that a shock front, caused by a point explosion at the galactic center with an originally spherical shape, becomes elongated in the direction of the z-axis (the rotation axis of the Galaxy) and further makes an omega-shaped lobe structure in the halo. With the above parameters and the expansion velocity at present of the order of $100\ {\rm km\ s}^{-1}$, as suggested by the CO line observations, the shock front well fits the observed shape of the GCL 2×10^6 yr after the explosion. The required explosion energy is about 10^{54} erg. This amount of energy is well within the range of the energy of a nuclear activity in spiral galaxies estimated by Oort (1977).

To compare this model with the observations, we have calculated a brightness distribution across the GCL assuming Sedov's (1959) similarity solution for a shocked shell by a strong point explosion. Figure 7 shows brightness distribution thus calculated, smoothed to a 3′ HPBW resolution, and normalized to the peak brightness at the eastern ridge (line b). Although the calculated curve fits the observations fairly well, the peaks seem to appear too sharply and the maximum-to-minimum brightness ratio is larger than that observed or that obtained for the simple cylinder model in subsection 3b. Also a difficulty arises from this model: such a propagating shock generates synchrotron emission via Fermi-type acceleration of electrons and should have steep spectrum as often quoted for shell-type SNRs, which is not the case in the GCL.

Model B. Galactic loop prominence: An inflation of a giant loop of magnetic tube filled with ionized gas may produce an Ω-shaped lobe above the nuclear disk, similar to the formation of a solar loop prominence. In this case the magnetic energy should be comparable to or greater than the thermal and gravitational energy of the gas involved in the lobe. This leads to a field strength greater than 20 μG.

An intense dynamo action in the nuclear disk due to its steep differential rotation will produce a strong magnetic field as has been observed by Yusef-Zadeh et al. (1984). When the field is amplified to a certain strength, there occurs an inflation of a huge tube of magnetic flux into the halo, forming a loop structure such as the GCL. The inflation may be triggered by a Parker-type instability in a magnetized disk with the existence of cosmic rays. We recall that Duric et al. (1983) suggests a large-scale inflation of a magnetic bubble into a halo from the central region of a spiral galaxy.

Model C. Acceleration by a twisted magnetic field: A channeled acceleration of gas perpendicular to a nuclear disk is produced by the existence of a magnetic field running perpendicular to the disk plane and of an accreting rotating gas disk. Uchida and Shibata (1984) have shown that the accreting gas twists the magnetic lines of force, and the twist propagates toward the halo along the original field direction. The propagating twist accelerates the gas producing a cylindrical outflow perpendicular to the disk. The twisting magnetic field transfers the angular momentum of the disk gas to the halo, which results in a loss of angular momentum in the disk and further causes an accretion and a twist of the field lines. Thus a stationary cylindrical jet appears with an ordered outflow of gas perpendicular to the nuclear disk. The magnetic energy should be of the same order of the kinetic energy of the accelerated gas, or $B^2/8\pi \sim (1/2)\rho v^2$, where B, ρ, and v are the field strength, gas density, and jet velocity, respectively. If we take $\rho \sim 9\ \mathrm{m_H\ cm^{-3}}$ (subsection 3b) and $v \sim 100\ \mathrm{km\ s^{-1}}$, we obtain roughly a magnetic field strength of 10^{-4} G toward the lobe ridge at $b \sim 0\overset{\circ}{.}4$.

VLA observations of the radio arc (Yusef-Zadeh et al. 1984) have shown a predominant influence of a strong magnetic field on the structures in the galactic center. A Faraday rotation measurement by Inoue et al. (1984) has shown that the field direction is along the arc, and the line-of-sight component of the field reverses its direction from the upper part of the galactic plane to the lower part. As shown in the BGF maps in figure 8, the lobe ridges are clearly connected to the radio arc and to the VLA filament in Sgr C at their roots in the galactic plane. These facts indicate a predominant influence of a magnetic field on the formation of the radio lobe. In this respect Models B and C seem preferable to the first model.

Furthermore, Model seems most promising from the following points: According to Uchida and Shibata (1984) a gas in the disk plane can be accelerated to form an ordered bulk motion along a cylinder without suffering from heating, and a "quiet, high-speed jet" is produced. The association of a low-temperature gas as proved by the detection of the CO line emission with a high-velocity bulk motion and of the far-infrared emission along the lobe ridge may support this kind of "quiet" acceleration. The fact that the radio cross section of the GCL at $b=0\overset{\circ}{.}4$ (figure 5) is better fitted by a uniform cylinder model rather than by a shock-compressed shell model (figure 7) also supports this idea. Moreover, the model requires a reversal of the field direction in the upper and lower sides of the galactic plane due to the twisting of the magnetic lines of force by the rotating disk. Such a reversal has been

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really proved to be the case on the eastern ridge by the reversal of the sign of Faraday rotation measure above and below the galactic plane as observed by Inoue et al. (1984). However, we note that the positive high velocities observed in CO on the western ridge is difficult to understand by this model; the model requires a rotation of the cylindrical jet in the same sense as the rotation of the disk.

e) A Common Jet Phenomenon in the Center of a Spiral Galaxy?

VLA observations of the central regions of some edge-on galaxies (Hummel et al. 1983; Duric et al. 1983) have shown that there exist off-plane radio structures emerging perpendicularly to the galaxy disks. In particular, radio lobes found in the central region of NGC 3079 suggests an ejection of a huge magnetic bubble from the nuclear disk into the halo (Duric et al. 1983), and may be of a similar origin to the GCL in our Galaxy, although of a different scale and energy. Such a channeled exhaust, or a "cosmic jet," perpendicular to a disk galaxy of various scales and energy, is likely to be a common phenomenon associated with an activity in the nuclear disk of a spiral galaxy.

We may further speculate that the jet phenomenon in spiral galaxies might have a common characteristics to larger-scale jets often found associated with quasars and radio galaxies. Bridle (1984) has examined the relationship between a lateral expansion rate of a jet and a radio power of the associated core source at 5 GHz, where the expansion rate is defined by the ratio of the width of the jet to its length. Figure 9 is a reproduction of his plot, which clearly shows that the higher the core activity in radio is, the sharper is the produced jet. We plot the same quantities for the GCL and for the radio lobes in NGC 3079 on the same figure by crosses. Here we defined a central core of our Galaxy by a strong radio emitting region within a 6′ radius around Sgr A (Sgr A and its "outskirt") and an integrated flux density at 5 GHz was estimated to be about 200 Jy from the Bonn survey data (figure 3), although the relationship between the lobe and Sgr A is still unclear. This leads to a radio power of the core of about 2×10^{18} W Hz^{-1}. The radio power of the core of NGC 3079 at 5 GHz has been taken from Hummel et al. (1984).

The plot shows that the radio lobes in the spiral galaxies fall just on an extension of Bridle's (1984) plot. This fact suggests a common characteristic of the lobes found in the spiral galaxies to a more energetic cosmic jet associated with an active core in quasars and radio galaxies. We mention the recent detection of highly polarized 10-GHz emission (Inoue et al. 1984), still with a radio spectrum as flat as $\alpha\sim0$. We also recall that the radio arc, which must be nonthermal (Yusef-Zadeh et al. 1984) and Sgr A, which is the "core" of our galactic center, have both flat spectra. If we combine these facts with the fact that extragalactic jets often have flatter spectra toward their cores and that the cores have also flat spectra, too, the similarity of our jet (lobe) to the jets associated with quasars and radio galaxies may be stressed.

We here mention a recent statistical study of a cosmic jet geometry in quasars and radio galaxies by Rudnick and Edgar (1984). They have shown that a jet must occur alternately from one side to the other of a nuclear disk. If such an alternate ejection applies to our galactic center, the north-south asymmetry of the GCL (subsection 3c) could be understood as to be in a one-sided ejection phase.

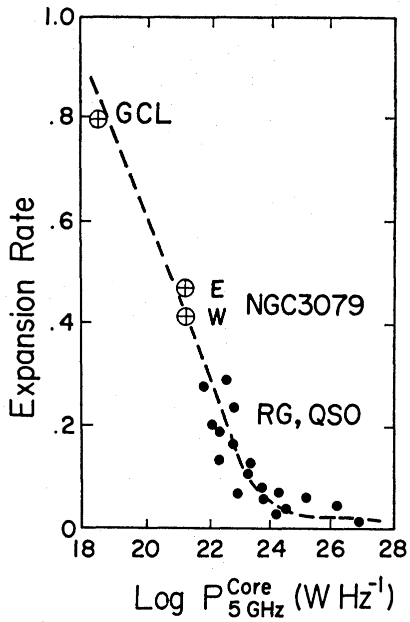

Fig. 9. A plot of the lateral expansion rate of cosmic jets in quasars and radio galaxies (filled circles) against the radio power at 5 GHz of their central core sources (Bridle 1984). The same quantities for the GCL and radio lobes in NGC 3079 are plotted with the crosses, which lie on an extension of the plots for quasars and radio galaxies.

We could further suggest that a sharply collimated energetic jet in quasars and radio galaxies is associated with a very compact nuclear disk rapidly rotating at a relativistic velocity around a very massive central object. Such a compact disk at an extremely large distance is too small to be resolved with the present-day observing technique. On the other hand, the jets found in our Galaxy (GCL) and those in nearby edge-on spiral galaxies are associated with a rather less tight, slowly rotating disk of velocity 100 to 200 km s^{-1} around a less massive central object. Detailed investigation of such broad jets in spiral galaxies by their close-up may provide a promising opportunity to learn about the relationship of the formation and collimation mechanism of a cosmic jet to the structure of a nuclear disk.

The author thanks Mr. T. Handa of NRO, Professor E. Fürst, Dr. W. Reich, and Mrs. P. Reich of MPIfR for the help in the data processing. He is indebted to Dr. Y. Fukui and Ms. I. Suwa of Nagoya University for making the CO line data available prior to publication. He expresses his thanks to Professor Y. Uchida for valuable discussions.

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