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Vertical Radio Structures out of the Galactic Plane and Activities of the Galaxy

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Abstract

In the expectation that our Galaxy may have experienced ejection phenomena of scales of a few kiloparsecs, we searched for structures emanating perpendicularly from the disk. We used a background-filtered whole sky radio map, where the background, the smooth component, has been subtracted so that finer structures are enhanced. Numerous spurs and ridges roughly perpendicular to the galactic plane are found, which are most crowded in the galactic center region. Their origin and implication are discussed in relation to the activity of the Galaxy.

Key words: Galactic activity; Galactic center; Magnetic fields; Radio emission; The Galaxy.

1. Introduction

Radio continuum observations of the galactic center have revealed a number of filamentary structures of various scales from ~ 1 pc to ~ 200 pc. Many of them extend apparently perpendicularly to the galactic plane, and are suggested to be related to strong magnetic fields in the central region. Typical examples are seen in the streamers of ~ 1-pc scale emanating from Sgr A West (Yusef-Zadeh 1986); threads of 10–30-pc scale (Morris and Yusef-Zadeh 1985); the low-energy jet extending from Sgr A East toward the negative latitude for 30 pc (Yusef-Zadeh 1986); the VLA filament in Sgr C (Liszt 1985); the radio arc of 30-pc scale composed of numerous straight filaments (Yusef-Zadeh et al. 1984); polarized plumes showing vertical magnetic field (Tsuboi et al. 1986); and the galactic center lobe of ~ 200-pc scale extending over the galactic plane composed of two vertical ridges (Sofue and Handa 1984).

In external spiral galaxies much larger-scale radio lobes extending perpendicularly to the disk plane are often observed. Examples are seen in the edge-on galaxy NGC 3079, NGC 4388 etc. (Duric et al. 1983; Hummel et al. 1983). These lobes extend for a few kiloparsecs above the galactic plane, and are thought to be the result of the central activity and ejection. Some gas rich spiral galaxies (e.g., NGC 253 and NGC 7331) have vertical dust lanes coherently emerging from the galactic plane over a few kiloparsecs above the disk (Sofue 1987). The vertical structure is thought to be either a trace of a large-scale vertical magnetic field or a coherent ejection of gas by intense

energy release due to active star formation in the inner region of the galaxy.

We may therefore suppose that our Galaxy also possesses a similar vertical structure of a few kiloparsecs scale or more above the galactic plane. Such objects, if exist, may be found at high latitudes as nonthermal radio emitting features. In this paper we present the result of a search for such large-scale elongated features (spurs) on an all-sky radio continuum map.

2. Background-Filtered Maps of the All-Sky Radio Emission

Combining the 408-MHz survey data from the northern and southern hemispheres, Haslam et al. (1982) obtained an all-sky map with a resolution 0°.85. The data are available on a magnetic tape written in the NOD 2 format and consist of 18 maps. In figure 1 we reproduce the original all-sky map in a gray-scale representation in the *l-b* coordinates.

In addition to the bright ridge along the galactic plane, we find a number of fine structures, which are generally elongated in the direction perpendicular to the galactic plane and are called spurs. However, these stretched structures are contaminated by the disk component which has a steep brightness gradient in the direction away from the galactic plane. This makes it difficult to distinguish fine structures from the background diffuse emission particularly in the galactic center directions. In order to enhance such fine structures, we have applied the background filtering (BGF) technique (Sofue and Reich 1979) and subtracted the diffuse emission with scale sizes larger than 5°.

Figure 2 shows the BGF map thus obtained for the same area as in figure 1. Figure 3 shows BGF maps for the region at $|b|<30°$ to show detailed structures near the galactic plane. Figure 4 shows the same but for the regions including the North Polar Spur (NPS) centered on $l=0°$, $b=45°$, its symmetrically opposite region with respect to the galactic plane centered on $l=0°$, $b=-45°$, and for the anticenter regions centered on $l=180°$, $b=\pm 45°$. Figure 4 is displayed on the curved *l-b* coordinates so that the galactic polar regions are not strongly deformed as in figure 1.

3. Continuum Ridges, Spurs, and Arcs

(a) Asymmetry of the Distribution of Spurs

In figures 2–4 we find numerous spurs extending from the galactic plane. Some are straight and perpendicular to the galactic plane, while some are bending and may alternatively be called arcs. The low-frequency (408 MHz) and high-latitude emission in these spurs may reasonably be regarded as nonthermal (e.g., Reich and Reich 1988). Most of the spurs are extending from the strong galactic ridge from $l=-40°$ to 40°. Except for broad spurs extending from the tangential directions of the local arm at $l\sim 80°$ and $l\sim 260°$, no pronounced spurs are found outstide this region. This asymmetry of the distribution of spurs in the central and anticentral regions may indicate that the spurs are not local objects: if they are in such a vicinity of the Sun at distances, say, <1 kpc, the distribution must be more uniform and no significant asymmetry is expected. For example, the distribution of the local H I features of $V_{\rm LSR}=-10$ to 10

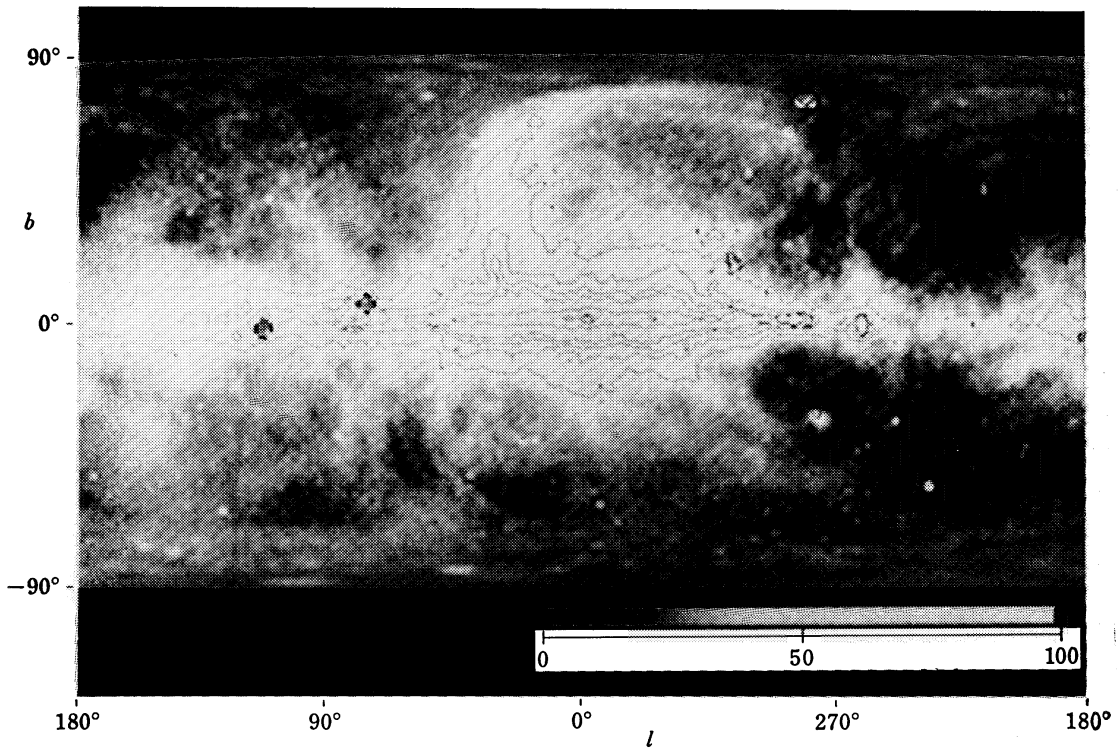


Fig. 1. A gray-scale representation of the all-sky map of the 408-MHz radio continuum emission in the *l*-*b* coordinates reproduced from Haslam et al. (1982). The galactic center is at the center of the map. Top is the north galactic pole and the bottom is the south galactic pole. The numbers on the scale bar are in units of 0.1-K T_b.

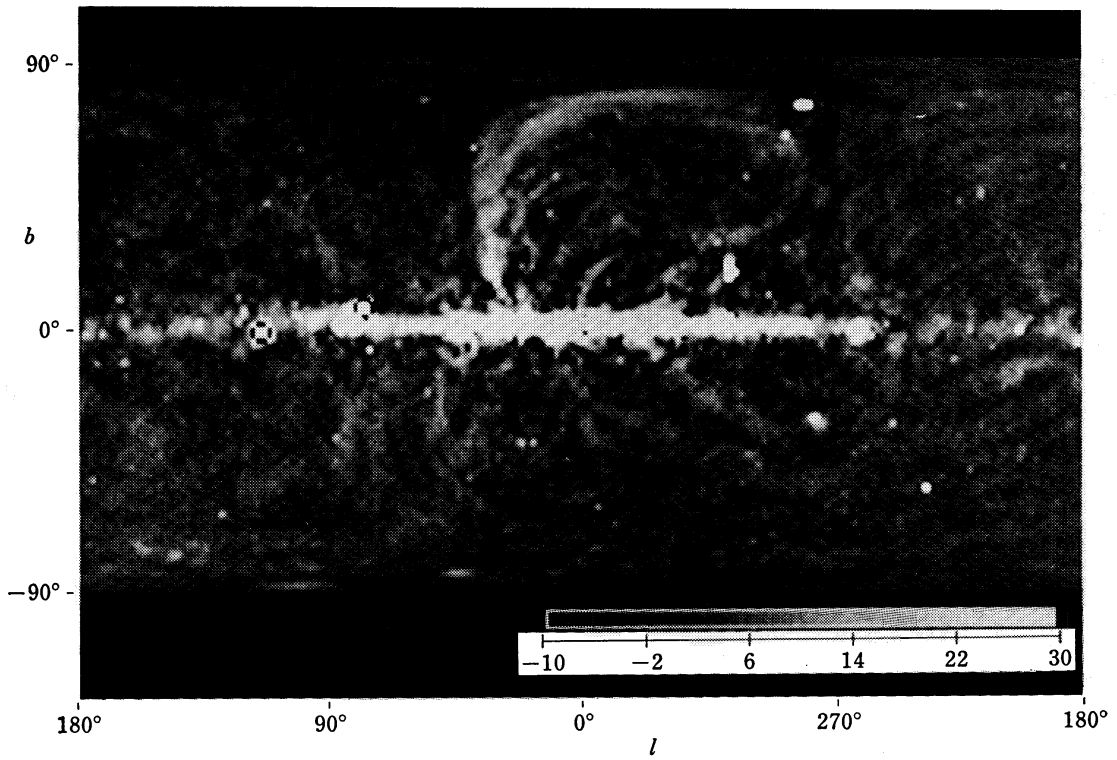


Fig. 2. The same as figure 1, but the smooth background structures with scale sizes greater than 5° have been subtracted using the BGF (background filtering) technique. The numbers on the scale bar are in units of 0.1-K T_b.

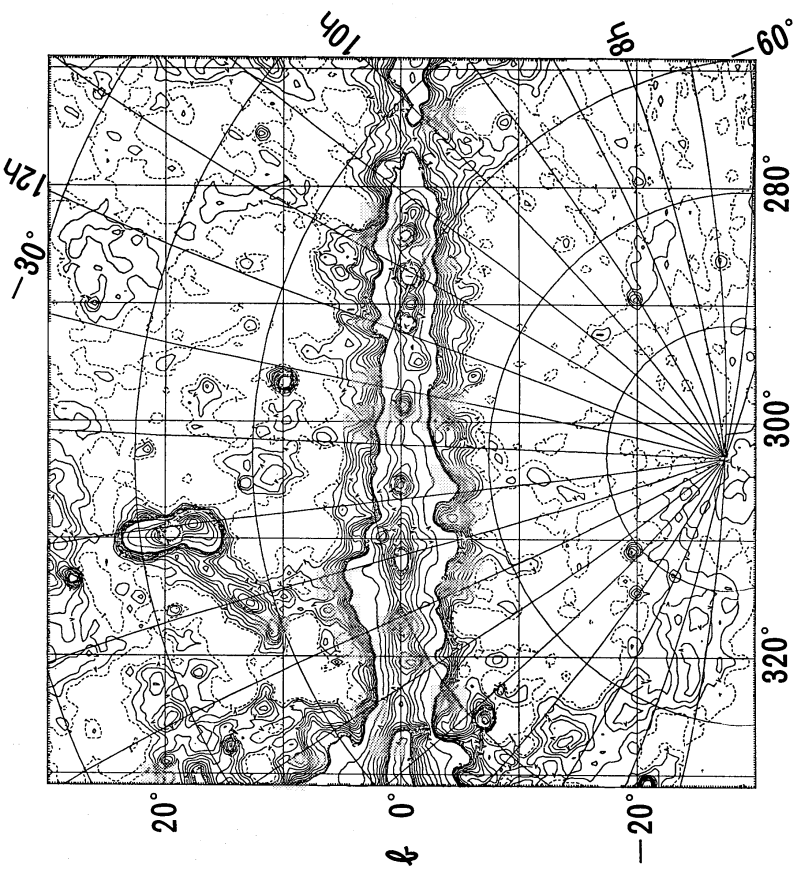


Fig. 3a–2.

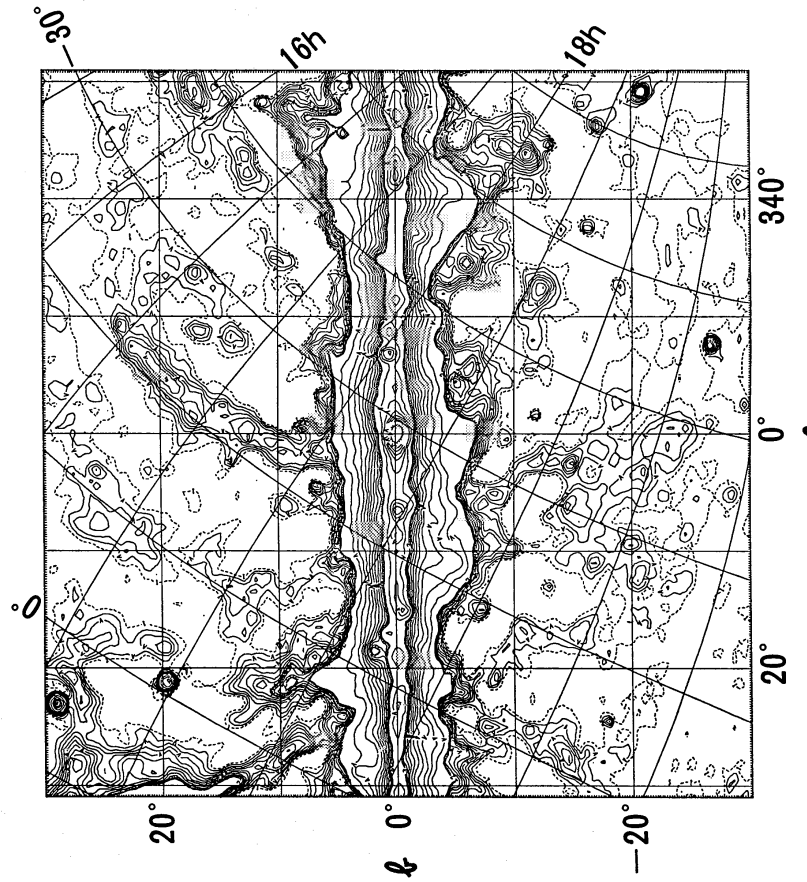


Fig. 3a–1.

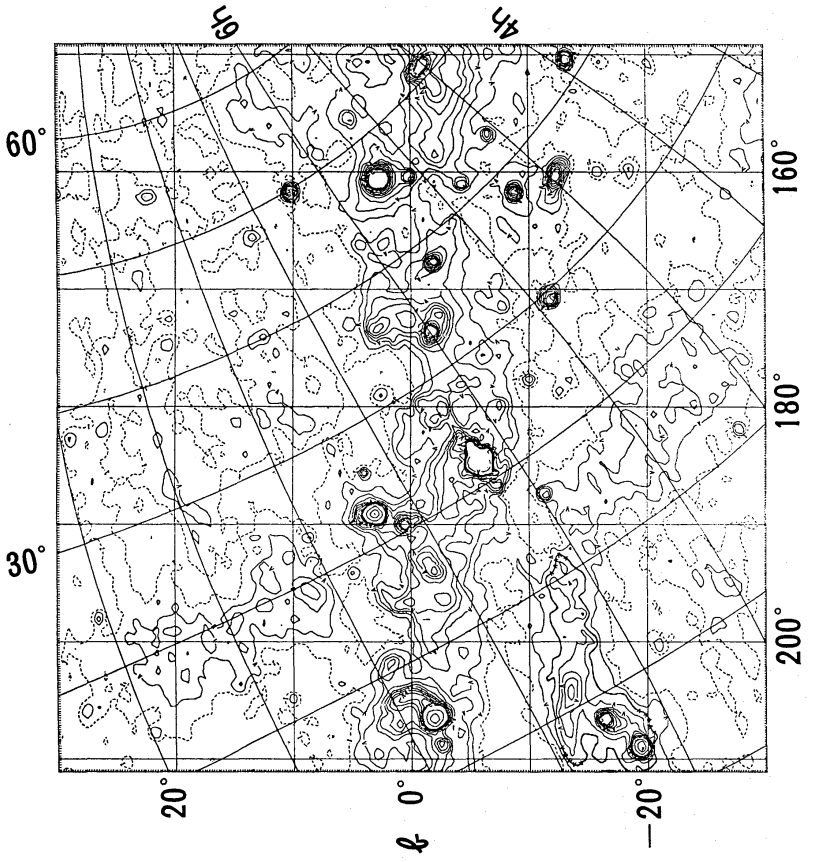


Fig. 3a-4.

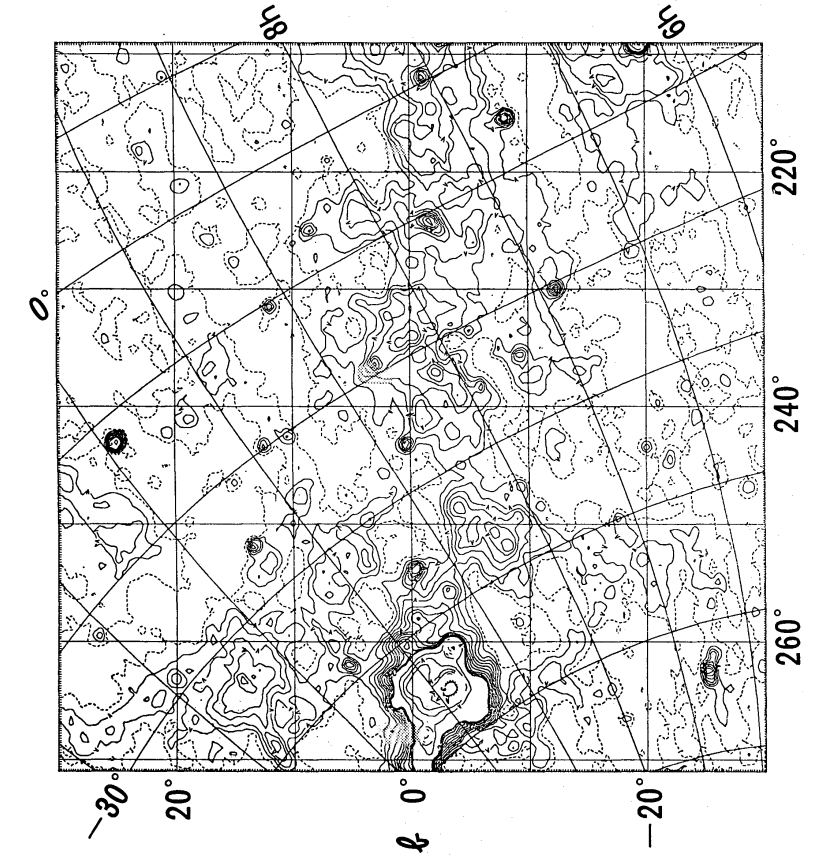


Fig. 3a-3.

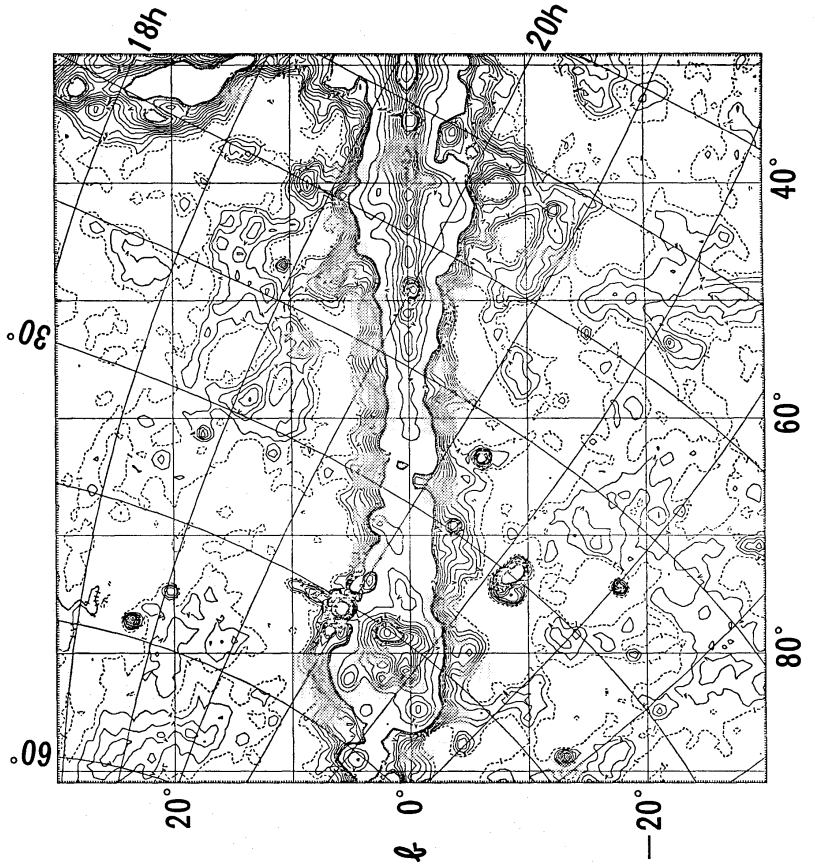


Fig. 3a–6.

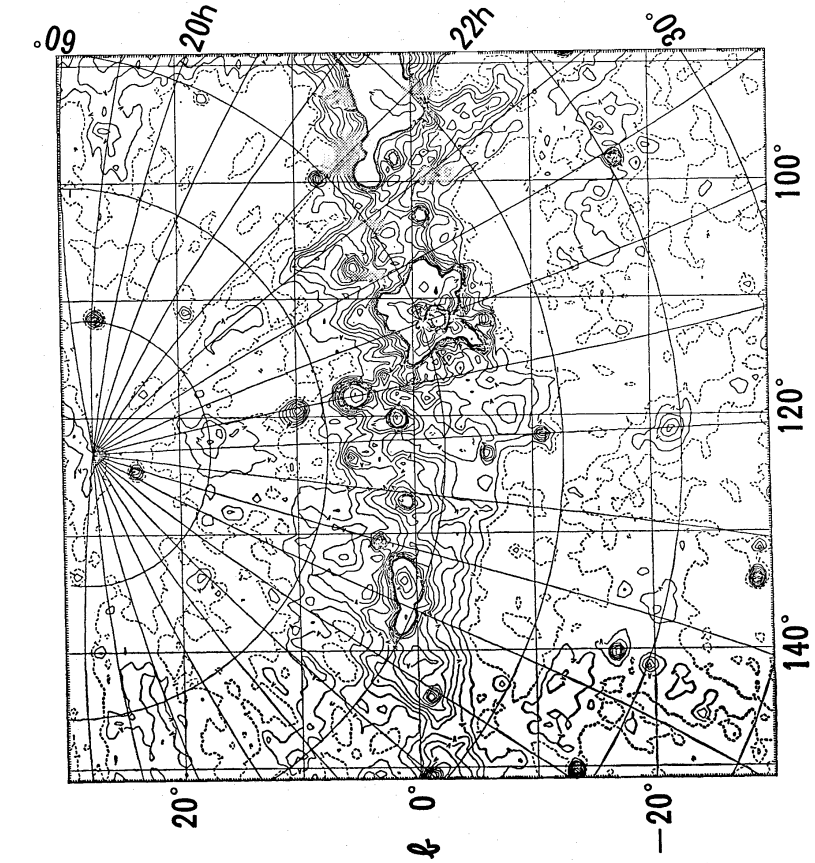


Fig. 3a–5.

Fig. 3a. 1–6: BGF maps of 408-MHz emission for the galactic plane region at $-30° < b < 30°$ represented in the form of contour maps. Labels on the ticked contours, 1 through 5 correspond to 1, 20, 200, 1,000, and 10,000-K T_b, respectively. The intervals between the labeled contours are divided into ten equal steps.

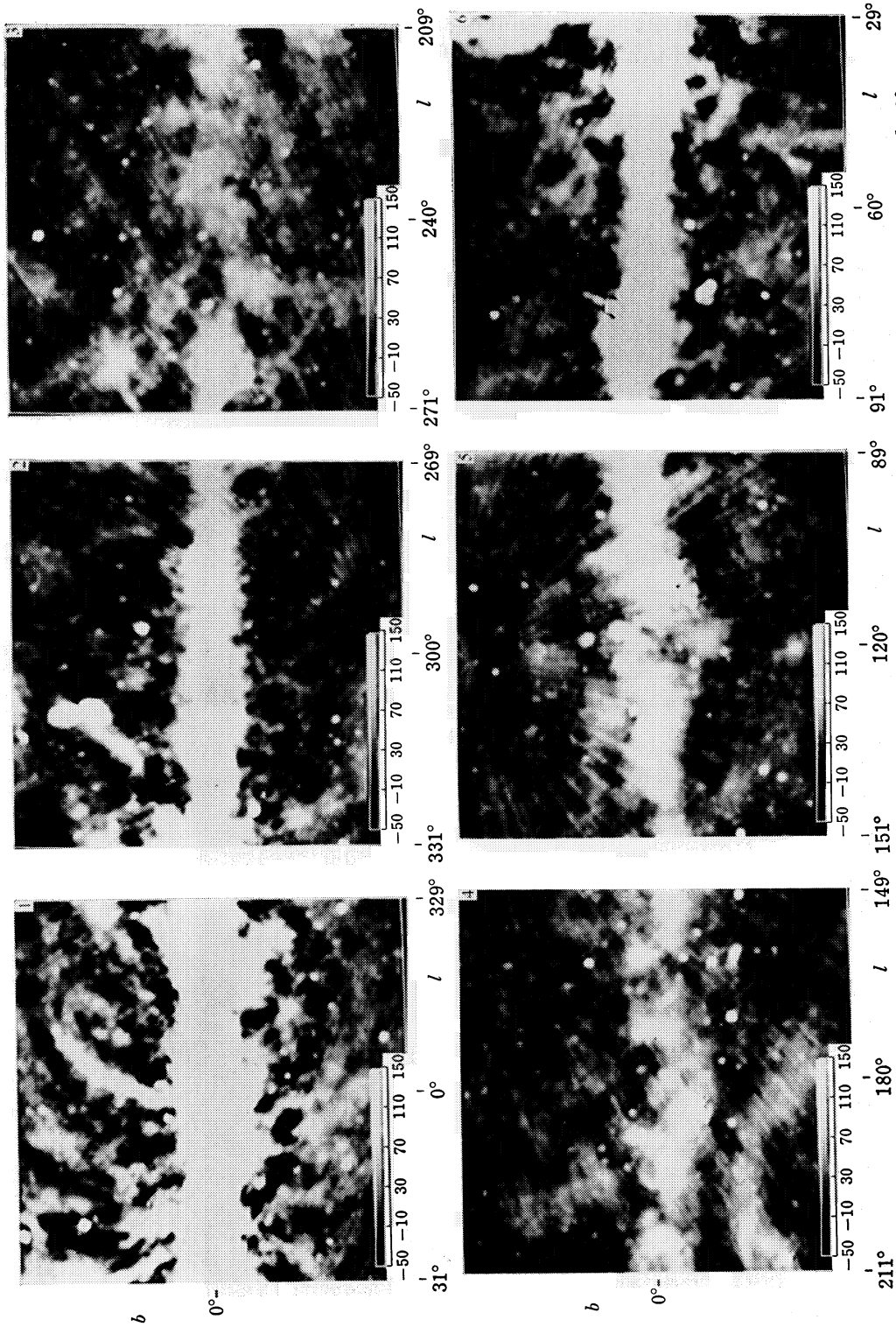
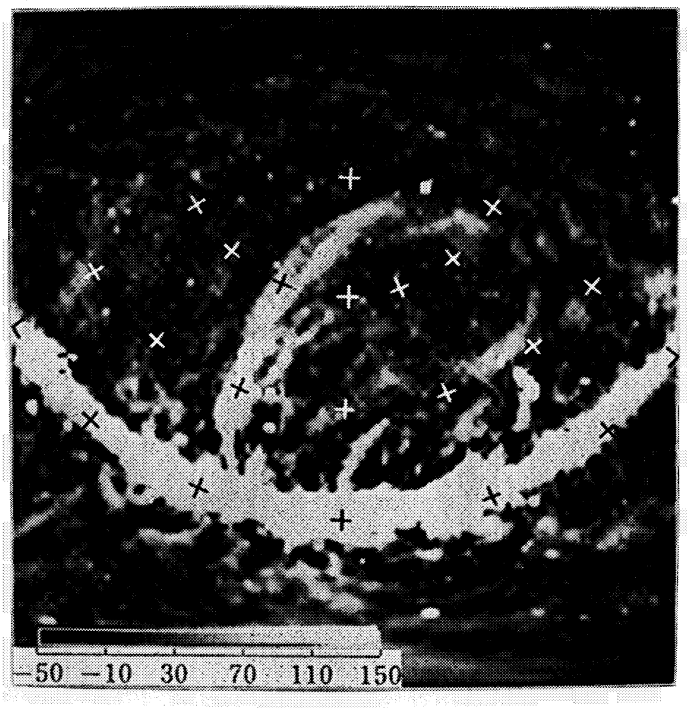
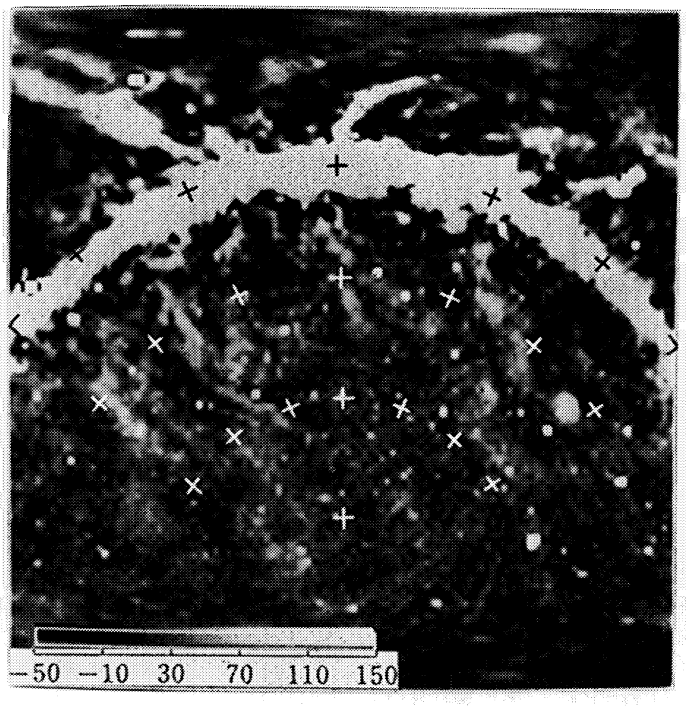


Fig. 3b. 1–6: The same as figure 3a, 1–6, but in a gray-scale representation. The centers of the panels are at $l=0°$, 300°, 240°, ⋯ and 60°, and $b=0°$. Each panel covers an area of 62° along the galactic equator. The bar scales are in units of 0.1-K T_b.

km s^{-1} is almost uniform against the galactic longitude (e.g., Heiles 1984). The present continuum map, however, more resembles the distribution of H I gas with larger velocities located in the inner region of the Galaxy, although individual features do not necessarily have H I or continuum counterparts. We may therefore conclude

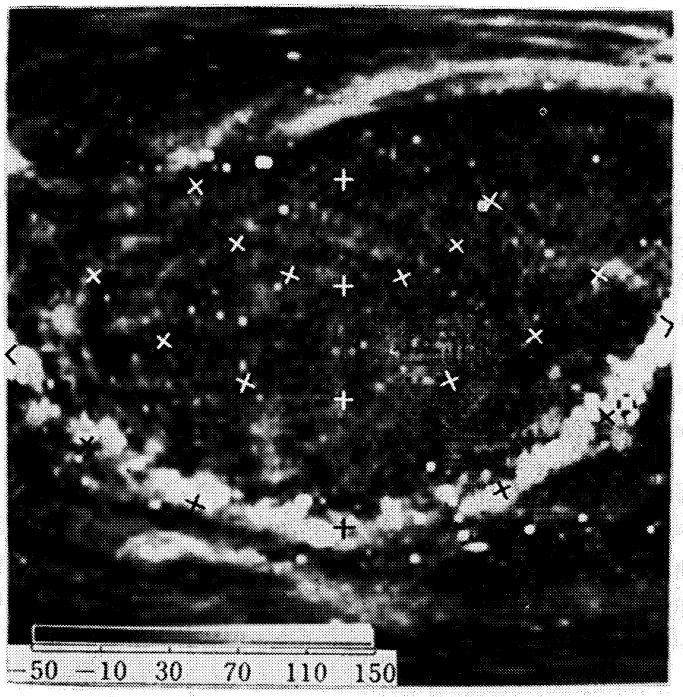


(a)

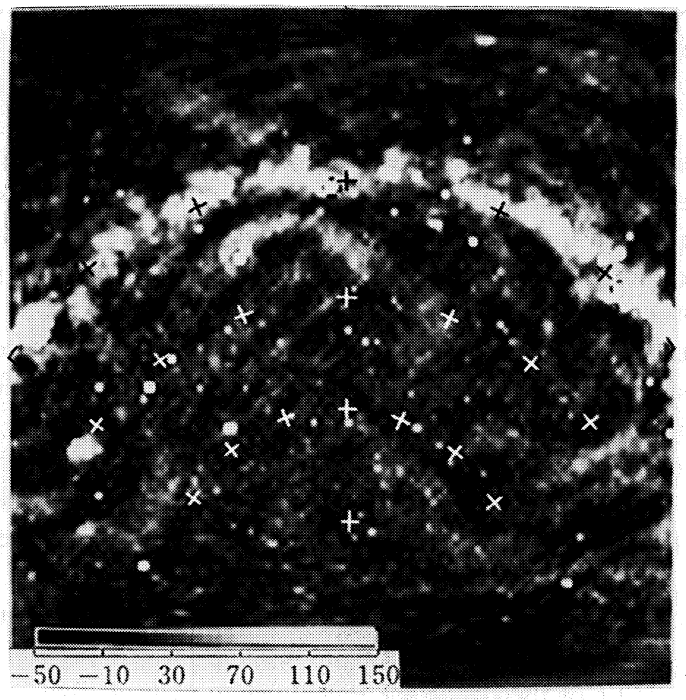


(b)

Figs. 4a and b. See the legend on the next page.



(c)



(d)

Fig. 4. (a) BGF 408-MHz map of the 180° square region including the NPS and its surroundings in a gray-scale representation (the same as in figure 2) on the curved *l*-*b* coordinates so that the galactic polar region is not largely deformed. The bar scale is in units of 0.1-K T_b. The center position is at $l=0°, b=45°$. Grids at every 30° in *l* and *b* are marked by the crosses. (b) The same as (a) but for the southern galactic hemisphere centered on $l=0°$, $b=-45°$. (c) The same as (a) but for the anticenter region with the map center at $l=180°, b=45°$. (d) The same as (a) but for $l=180°$, $b=-45°$.

that most of the spurs crowded near the galactic center ($-40°<l<40°$) are features associated with the structure of the inner Galaxy at galactocentric distances $R<5$ kpc ($=8$ kpc$\times\sin 40°$).

(b) A Giant Arc from the Galactic Center

A sharp prominent arc is found to run from $(l, b)=(2°, 12°)$ toward the positive latitude, reaching as high as $(-10°, 24°)$. Its lower- and negative-latitude extension is not clearly seen. The distance is unknown but from its proximity to the galactic center the arc may be associated with the center. Then the height of the northern arc is as high as 3.6 kpc from the galactic plane ($=8$ kpc$\times\tan 24°$), if it is on a plane perpendicular to the Sun-galactic center line. A detailed description of this prominent feature will be given elsewhere.

(c) Giant Lobes over the Galactic Center

The NPS has its root at $l=20°$ and $b=2°$ in the galactic plane (Sofue and Reich 1979). It extends up to latitude as high as $b=75°$, drawing a giant loop on the sky, called Loop I. Passing near the north galactic pole, it makes another loop, called Loop IV, centered on $l=315°$ and $b=45°$. Loop I has the diameter of about 115°. On one hand there is a hypothesis that attributes these loop structures to nearby, very old supernova remnants (e.g., Berkhuijsen et al. 1971). On the other hand there is a discussion that the spurs may be more distant objects from careful inspection of optical and radio data (Sofue et al. 1974). An alternative hypothesis that attributes the NPS to a more distant lobe structure associated with the galactic center explosion has been also proposed (Sofue 1977; 1984).

The BGF maps obtained in the present work exhibit quite a new aspect of the whole structure around NPS and Loop IV. The relation to the galactic plane region can be more clearly seen than in the previous works concerning the Loops. Now the NPS may be fitted convincingly by an Ω shape with one root in the galactic plane at $l=20°$ and the other root at $l=330°$. The ridge at $(l, b)=(310°, 30°)$ can be traced toward the galactic plane, passing near Cen A (a strong double source at $l=310°$, $b=20°$), and ends near the galactic plane at $l=330°$. The whole Ω is deformed to incline toward the negative longitude.

In the southern galactic hemisphere we may trace a symmetrical lobe structure, although it is not prominent as the northern one. It might be possible that the South Polar Spur (SPS) starts at $(l, b)\sim(40°, -10°)$ as a complex of several segments of radio ridges. It passes $\sim(50°, -30°)$ and extends to $\sim(30, -70°)$. Then its continuation appears to come back at around $\sim(-60°, -35°)$, returning to the galactic plane at $l\sim-20°$, $b\sim-5°$.

If the above tracing of the ridges is allowed, we may draw a pair of symmetrical Ω lobes with the apparent diameter of $\sim 100°$ which are connected at the galactic plane in a dumbbell shape whose axis roughly coincides with the galactic rotation axis ($l=0°$).

(d) Small Spurs

Besides the above prominent spurs and ridge structures, there exist numerous smaller ridges extending from the galactic plane. Most of them are roughly perpendic-

ular to the galactic plane and suggest some ejection and/or inflation from the disk plane. Their concentration toward the central region suggests their physical association with the inner region of the Galaxy. The fact that the spurs are found mostly inside the solar circle, more specifically with $|l|<40°$, suggests that they are associated with the tangential directions of spiral arms. This may imply that the spurs are originating due to the ejection associated with the intense star forming activity in the inner dense spiral arms such as in the 4-kpc molecular ring.

(e) Medium Size Loops

Besides the ridges and spurs emerging from the galactic plane, many filamentary structures are found. The features are best seen in the anticenter region, where the bright galactic ridge is absent. Sofue and Nakai (1983) have extensively studied high-latitude loops of medium size of diameter 5 to 10°, and discussed the detection of the oldest supernova remnants in our Galaxy. They report that very few continuum loops have counterparts in the H I emission.

4. Summary and Discussion

On the premise that our Galaxy may have experienced various ejection phenomena out of the galactic plane, particularly in the inner region near the galactic center, we have searched for radio emitting structures protruding from the galactic plane. The background filtered (BGF) radio maps at 408 MHz of the whole sky (figures 2–4) revealed various spurs and extended ridges perpendicular to the galactic plane. The majority of them are concentrated in the inner region of $l=-40°$ to 40°, and this fact may imply that the spurs are related either to the galactic center region or to the inner spiral arms with intense star formation activity.

(a) Comparison between Optical, H I, and Radio Continuum Data

As is readily expected from the above arguments, the arcs and spurs shown here have no definite correlation whith the stellar polarization distribution (Mathewson and Ford 1970). This is because the spurs are more distant objects than the stars used for the polarization measurements which are mostly within 1 kpc. It should be noted that the direction of the North Polar Spur is almost perpendicular to the direction of the alignment of the nearby star-light polarization. The star-light polarization at around $l=30°$, $b=10°$–$20°$ is better correlated with the direction of the Hydra ridge of local H I gas. The Hydra ridge has its root at $l=35°$ in the galactic plane, while the NPS has the root at $l=20°$. The continuum NPS and the Hydra H I ridge cross each other almost perpendicularly. We have further compared the BGF maps in the continuum with the whole sky H I map (e.g., Heiles 1984). The continuum spurs discussed in this paper seem to have no definite correlation with the H I emission features.

(b) Central Activity and Spurs

The vertical structures closely associated with the galactic center of scales <200 pc mentioned in section 1 might be related to the nuclear activity. Although the vertical features are far from being understood, there have been some suggestions which attribute them (1) to an explosive activity (Sofue 1984; Umemura et al. 1988); (2) to a

large-scale magnetohydrodynamic jet acceleration (Uchida et al. 1985; Shibata and Uchida 1987); or (3) to magnetic inflation from the nuclear disk (Heyvaerts et al. 1988).

The giant galactic center arc and the giant lobes over the galactic center (including NPS) may be related to this kind of energetic phenomenon. An energetic explosion occurring at the nucleus of the order of $\sim 10^{56}$ erg could produce an Ω-shaped shock front in the halo (Sofue 1984). The dense, tightly wound magnetic field in the central region may inflate to produce a large loop (lobe) (Heyvaerts et al. 1988). Alternatively the vertical magnetic field accumulated to the central region (Sofue and Fujimoto 1987) will be twisted by the galactic rotation and result in an ejection of matter as a mild jet (Uchida et al. 1985; Shibata and Uchida 1987). Such a gigantic loop (lobe) structure is really found in external galaxies. The pair of lobes in NGC 3079 (Duric et al. 1983) is particularly similar to the pair of lobes composed of the NPS in our Galaxy. The brightness of NPS is much weaker, while the size (~ 8 kpc) is larger than the lobes in NGC 3079 (~ 3 kpc.)

(c) Vertical Large-Scale Magnetic Field and Spiral Arms

Sawa and Fujimoto (1986) and Fujimoto and Sawa (1987) have shown that the global magnetic field in spiral galaxies can have bisymmetric spiral configuration near the galactic plane, as observed for the majority of spirals (Sofue et al. 1986), while the magnetic lines of force out of the plane are going up vertically, looping in the halo and returning to the galactic plane. It is therefore quite possible that the out-of-plane ($z \sim 1$ kpc) field is vertical. In addition, a larger-scale vertical field as a fossil of the frozen-in primordial field may have been accumulated in the inner region and crosses the galactic plane (Sofue and Fujimoto 1987). Then the coherent, vertical field out of the plane may cause such radio spurs as observed here.

The 4-kpc molecular ring includes numerous star forming regions. A high rate of supernova explosions and injection of themal energy from OB stars will cause expanding motions in the interstellar gas. These energy inputs may enhance the magnetic inflation (Parker 1966) above the spiral arms. As a consequence the vertical ejection features out of the galactic plane will be produced and may be observed as spurs emanating in the direction tangential to the 4-kpc ring and the inner spiral arms.

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