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PROMINENT POLARIZED PLUMES IN THE GALACTIC CENTER REGION AND THEIR MAGNETIC FIELD

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ABSTRACT

We have observed the distribution of linear polarization over the central $2^{\circ}\!.5 \times 3^{\circ}\!.0$ region of the galaxy at 9.05, 9.55, 10.05, and 10.55 GHz with the 45 m telescope of Nobeyama Radio Observatory. We found that the prominent polarized plumes extend over $1^{\circ}\!.6$ perpendicular to the galactic plane. Except for these plumes, we have detected no remarkable polarized feature within 200 pc of the galactic center. The western side (in galactic coordinates) of the Galactic center lobe (GCL), which was noticed by Sofue and Handa, is thus not polarized, while the eastern side of it agrees with the northern polarized plume and is highly polarized up to 40%. This implies that the emission mechanisms of both sides of the GCL differ from each other, and hence suggests no physical connection between them. In the polarized plumes and the central compact feature, the transverse magnetic field is essentially parallel to the axis of the plumes, and the sign of the rotation measure changes twice: at the northern edge of the northern polarized plume and at a gap between the northern polarized plume and the central compact feature on the radio arc. Faraday rotation is responsible for depolarization, in particular on the central compact polarized feature. We propose a model in which the magnetic tube runs perpendicular to the galactic plane at $l \sim 0^{\circ}\!.2$ and polarization gaps are due to a depolarizing thermal medium which exists within and/or around the tube.

I. INTRODUCTION

Recent observations of the galactic center region have revealed some peculiar features, all of which might relate to the activity of the galactic center region. First, filamentary structures were detected in the radio arc with the Very Large Array (VLA) at 6 and 20 cm by Yusef-Zadeh *et al.* (1984). They suggested that magnetic fields play an important role in the formation of these filaments. Second, a large-scale, off-plane feature, which we refer to as the Galactic center lobe (GCL), was noticed by Sofue and Handa (1984). It extends up to 1° from the galactic plane. This was attributed to a magnetic field which was originally oriented perpendicular to the galactic plane and is being wrung out from the medium of the galactic plane (Uchida *et al.* 1985).

Finally, the first linear-polarization observation in this region was made with the 45 m telescope of Nobeyama Radio Observatory (NRO) at 3 cm by Inoue *et al.* (1984, hereafter referred to as Paper I). They revealed the existence of extremely large Faraday rotation at some points. A mapping observation of the linear polarization was also made with the 45 m telescope at 3 cm by Tsuboi *et al.* (1985, hereafter referred to as Paper II). They mapped a small area around the galactic center and detected two polarized plumes located on both ends of the radio arc. Moreover, they found that the transverse magnetic field is oriented along the major axis of these plumes and that there exists a reversal of the line-of-sight component of the magnetic field with respect to the galactic plane. These polarized plumes were confirmed by Seiradakis *et al.* (1985) with the Bonn 100 m telescope. The field of the present observation is so large that the polarized plumes are completely revealed. Furthermore, we improved sensitivity and extended the mapping area in order to search for similarly polarized features in active regions such as Sgr B2, Sgr C, etc., especially at the western part of the GCL. Hereafter in this paper, we use the galactic coordinate system and "north" refers to the direction with increasing galactic latitude and "east" to the direction with increasing galactic longitude.

II. OBSERVATION

We have made a polarization mapping of $2^{\circ}\!.5 \times 3^{\circ}$ centered at the galactic center using a four frequency-channel polarimeter (Inoue *et al.* 1984) at 10 GHz attached to the 45 m telescope of Nobeyama Radio Observatory. The total bandwidth was 2 GHz from 8.8 to 10.8 GHz and divided into four contiguous frequency channels with a 500 MHz bandwidth. This multichannel polarimeter enables us to derive the rotation measure (RM) without $n\pi$ ambiguity.The polarizer consists of a rotatable $\lambda/2$ phase shifter followed by an orthogonal polarization divider. Two orthogonal polarizations were switched by a diode switch to derive differential polarization. The system temperature was 150 K and the HPBW was $2'\!.7$. The instrumental polarization was calibrated to a level of 0.5% using thermal or little polarized sources: DR 21, NGC 7027 and 3C 84. The intensity and polarization were calibrated with 3C 274. We obtained five partial maps: three are centered in the western part of the field and the two others are to the east; and all include the galactic center and the prominent polarized plumes. The standard deviation in

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intensity and polarization of the resultant map are 50 and 10 mJy/beam, respectively.

III. POLARIZED INTENSITY

The gray scale display in Fig. 1 [Plate 42] shows the average polarized intensity over the four frequencies, superposed on the total intensity at 10 GHz with contours. The most remarkable polarized feature in Fig. 1 is a pair of prominent polarized plumes which extends to the north and south sides of the radio arc, and a compact feature on the radio arc. The whole structure of the plumes is completely revealed by the present observation. This observation also shows that there is no phenomenon similar to the plumes within a wide area around the galactic center. The plumes extend a total of up to 1°6 perpendicular to the galactic plane. The plumes and the compact feature all lie on a straight line, the former being symmetrical in shape and location with respect to the central compact feature. This morphology may suggest that the central compact feature ejects the plumes as seen in radio galaxies. However, both in our total intensity map and VLA maps (Yusef-Zadeh *et al.* 1984) there exists no compact object which would suggest something akin to an active galactic nucleus of an extragalactic object at the position of the compact feature. The new features shown in Fig. 1 thus strongly support the previous conclusion that the plumes are physically associated with the radio arc (Paper II). If this is the case, the length and width of the north plume are 85 pc and 30 pc, respectively, with the distance to the galactic center of 8.5 kpc.

Although the two plumes are quite similar in shape, there are a few differences between them. In the north plume the polarized intensity gradually decreases with increasing galactic latitude. Along the major axis of the plume, there is an obvious ridge, which is highly polarized, up to 40% in the highest-frequency channel. The southern edge of this plume, where the polarized intensity shows a peak, bends slightly eastward, while the northern edge of this plume bends slightly westward.

The south plume shows, on the other hand, a rather flat distribution with weak blobs in the polarized intensity. The blobs are not so highly polarized: the average degree of polarization is 10%–15%. The southern edge of the south plume is, on the other hand, polarized as highly as the polarization of the ridge in the north plume.

In Fig. 1, no polarization can be detected on the western side of the GCL: the degree of polarization is typically below 5%. One can even see a shallow dip at this side of the GCL in the degree-of-polarization map in Fig. 2. The polarization gap between the north plume and the central compact feature was ascribed to the depolarization (Paper II). We confirm this and the other previous result that a strong depolarization occurs in the central compact feature: the ratio of the degree of polarization at the highest-frequency channel to that of the lowest one reaches three. Furthermore, we find a fairly large depolarization in the north edge of the south plume.

Contours in Figs. 3(a)–(d) show the distribution of the polarized intensity of the polarized intensity of the central compact feature for each frequency channel. In the lower-frequency channels the central compact feature is elongated parallel to the radio arc, and its elongation changes from parallel to perpendicular to the radio arc with increasing frequency. The shape at the highest frequency agrees well with the result at 10.7 GHz (Seiradakis *et al.* 1985). Furthermore, a VLA observation at 5 GHz (Yusef-Zadeh *et al.* 1986) showed a rather large and complex polarized region along the radio arc. Thus the shape of the central compact feature depends strongly on frequency. If depolarization predominates in this area, the extent of the polarized region should increase with increasing frequency. In this case, however, the size of the polarized region seems to decrease with increasing frequency. So we cannot explain such a frequency dependence only by depolarization. In addition, we should emphasize that the center of the central compact feature does not correspond to G0.16–0.15. The central compact component is located at G0.16–0.13, which coincides with the 160 MHz map (Yusef-Zadeh *et al.* 1986).

Faint polarized emission is spread out over the region to the west of the plumes in Fig. 1. This region has a low noise level due to overlap of the observation, and thus the faint polarization is above 7σ. However, there still remains a little possibility that the emission is spurious due to the strong emission from the galactic center.

IV. STRUCTURE OF THE MAGNETIC FIELD

We determine the intrinsic position angle of the polarization and RM in the plumes, and then derive the direction of the transverse magnetic field, assuming optically thin synchrotron radiation. The orientation and length of bars in Fig. 4(a) show the transverse magnetic field thus derived and polarized intensity, respectively. The transverse magnetic field is essentially oriented parallel to the plumes. Such an ordered field could explain the high degree of polarization in the plumes. Furthermore, a waving pattern of the transverse field can be clearly seen both in the north and south plumes. In the two plumes, this waving pattern is quite similar in wavelength and amplitude: the wavelength is 7′–10′, or 17–25 pc, and the amplitude of the deviation angle is about 30°. This amount significantly exceeds the 3σ level. On the other hand, such a waving pattern is not obvious in either the total intensity or polarized intensity. So the waving might be due to a disturbance propagating in the magnetic field.

Contours in Fig. 4(b) show the distribution of RM in the plumes. This map is convolved into a Gaussian beam with a HPBW of 3′5 in order to improve the signal-to-noise ratio. In the north plume, the RM is positive except for the northeastern edge. This indicates a reversal of the line-of-sight component of the magnetic field at the northeastern edge. In the southern part of the north plume, the RM is ~ 1000 rad/m^2 and its gradient is parallel to the elongation, or the transverse magnetic field. In addition, a large depolarization occurs in this region, and this is attributed to the internal Faraday depolarization (Paper II). The gradient of the RM changes from parallel to perpendicular to the elongation with increasing galactic latitude.

The sign of RM in the central compact feature and the south plume is negative: the line-of-sight component of the magnetic field goes away from the observer. Therefore, there is another reversal of the magnetic field between the north plume and the central compact feature, as noted in Papers I and II. In the central compact feature, the magnitude of RM reaches -2500 rad/m^2 at the peak of polarized intensity and is abruptly increasing at the northern and southern edges. The south plume has some holes (RM$\geqslant -500$ rad/m^2) in RM. The RM in the south plume is several hundred rad/m^2.

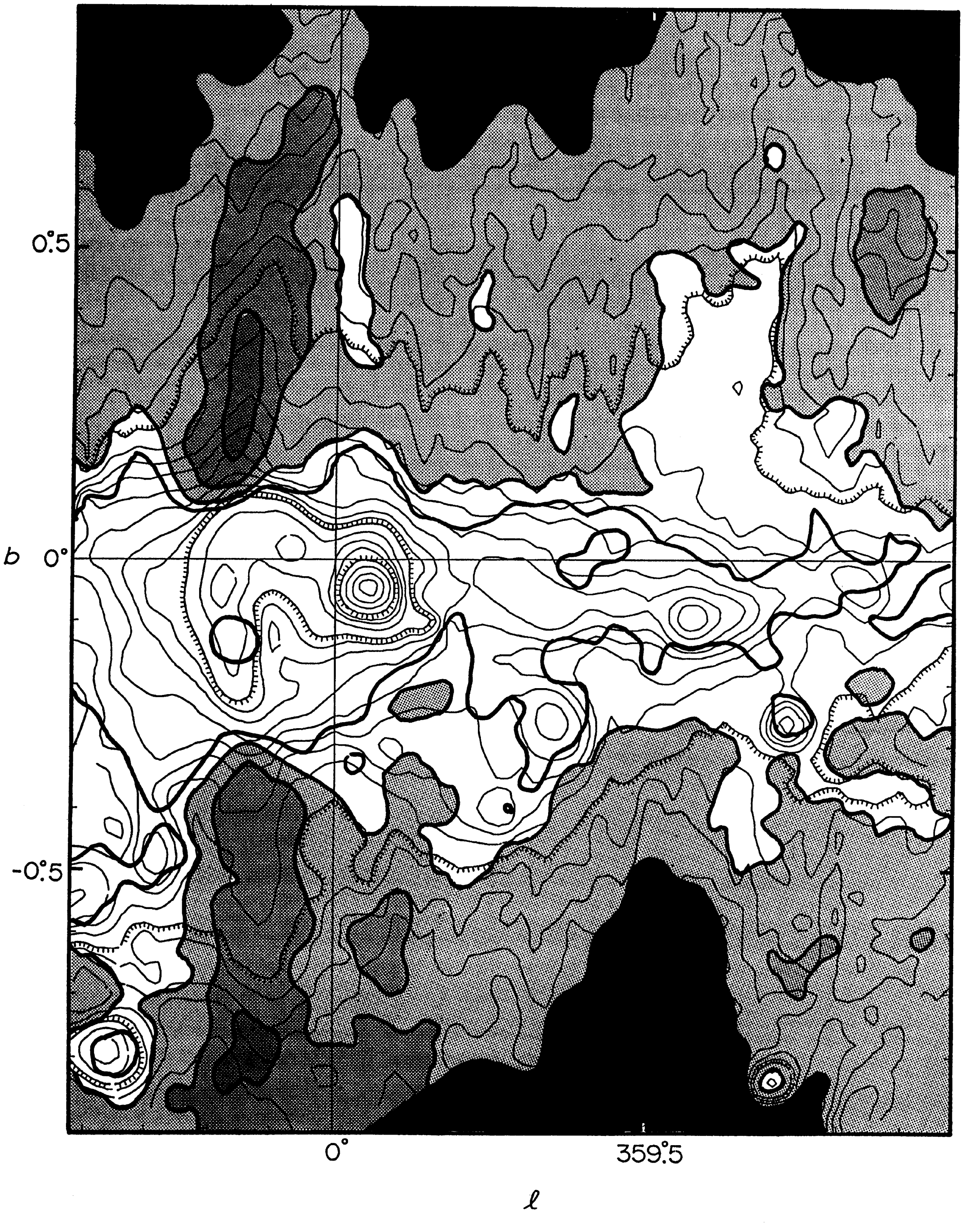

FIG. 2. Thick, shaded contours show the distribution of the degree of polarization superposed on the total intensity. The contour level is 2%, 4%, 10%, 20%. The west side of the Galactic center lobe (GCL) (Sofue and Handa 1984) shows no polarization. The standard deviation of the degree of polarization depends on the total and the polarized intensity. It is less than 1% near the galactic plane. Black area shows where the degree of polarization is less than the 3σ level. Half-power beamwidth (HPBW) of the degree of polarization is 3'.5.

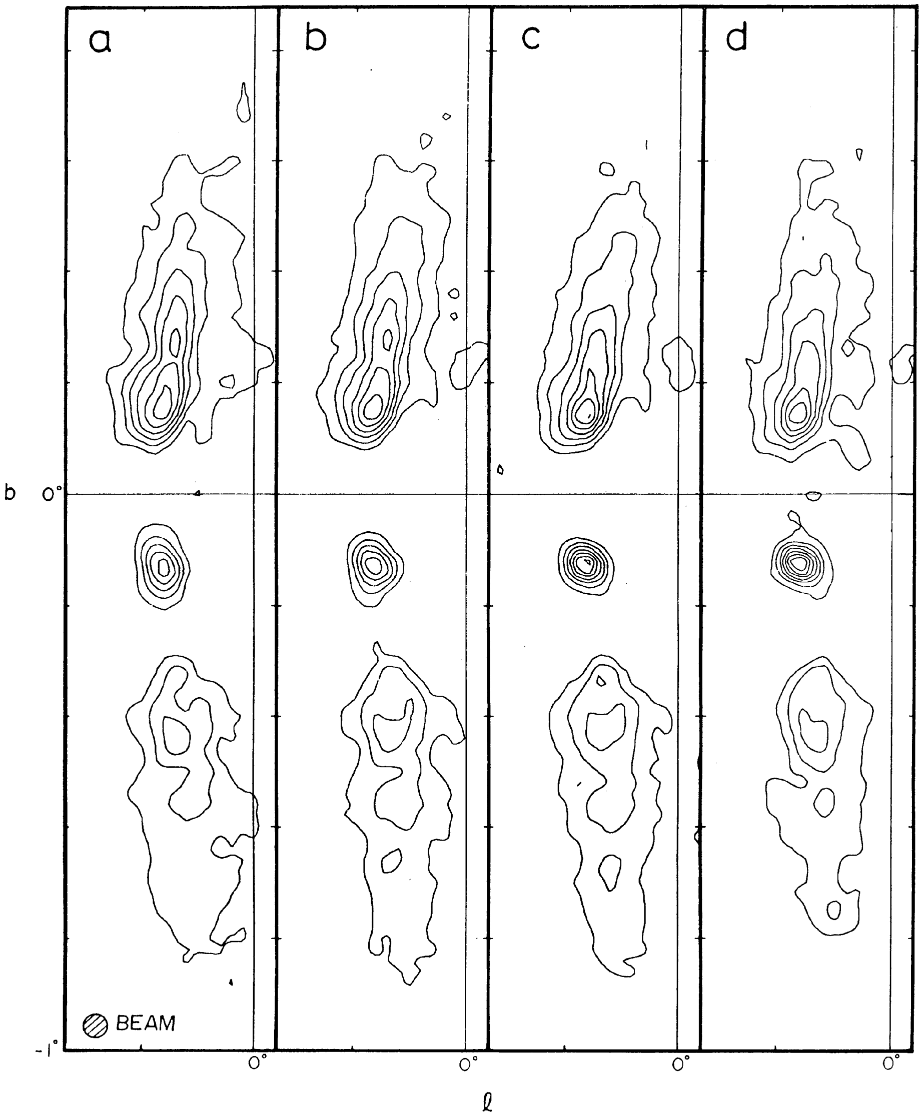

FIG. 3. Change of the polarized intensity distribution with frequency for the central compact feature. The structure of the central compact feature varies with frequency, in addition to showing a large depolarization (Paper I). Contours show the polarized intensity at a center frequency of (a) 9.05 GHz, (b) 9.55 GHz, (c) 10.05 GHz, and (d) 10.55 GHz. Contour interval at each frequency is 70 mJy/beam.

V. DISCUSSION

In spite of the dense thermal medium near the galactic plane (Mezger and Pauls 1979), we can detect the compact polarized feature and two large extended polarized plumes only on the eastern side of Sgr A. Their shape strongly suggests that they are physically related to the radio arc. It is then likely that the plumes are closely related to the radio arc. The luminosity of the plumes is 10^{35} erg/s. Furthermore, assuming equipartition, the strength of the magnetic field is several tens of μG, which is almost the same as that derived from Faraday rotation (Papers I and II).

We propose a model of these polarized structures in which there exists a magnetic tube running across the galactic plane at $l \sim 0\overset{\circ}{.}2$. The tube extends at least 240 pc in spite of the abrupt decrease in total intensity at both ends of the radio arc. The thermal medium which exists within and/or around the tube is responsible for the gaps in polarization near the galactic plane and produces very large Faraday depolarization: internal Faraday depolarization and/or Faraday screen in front of the polarized source. Thus little polarization is detected near the galactic plane (Paper II). The compact polarized feature on the radio arc may be due to a lack of the thermal medium. It was suggested by Yusef-Zadeh *et al.* (1986) that the vertical and the helical filaments are nonthermal and thermal, respectively, and that the thermal medium of the helical filament in front of the vertical ones is responsible for the strong depolarization in the radio arc. However, we suggest internal Faraday depolarization instead of a Faraday screen as the main mechanism for depolarization: Degree of polarization in the compact polarized feature changes from 3% to 9% between the lowest- and the highest-frequency channel (Paper I). We can estimate depolarization using a uniform-slab model of internal Faraday rotation (Burn 1966). Assuming the RM is 2500 rad/m^2 and the spectrum in this region is flat, as reported by Sofue (1985), then the degree of polarization changes from 9% to 27% between the lowest- and the highest-frequency channel. This remarkable agreement between

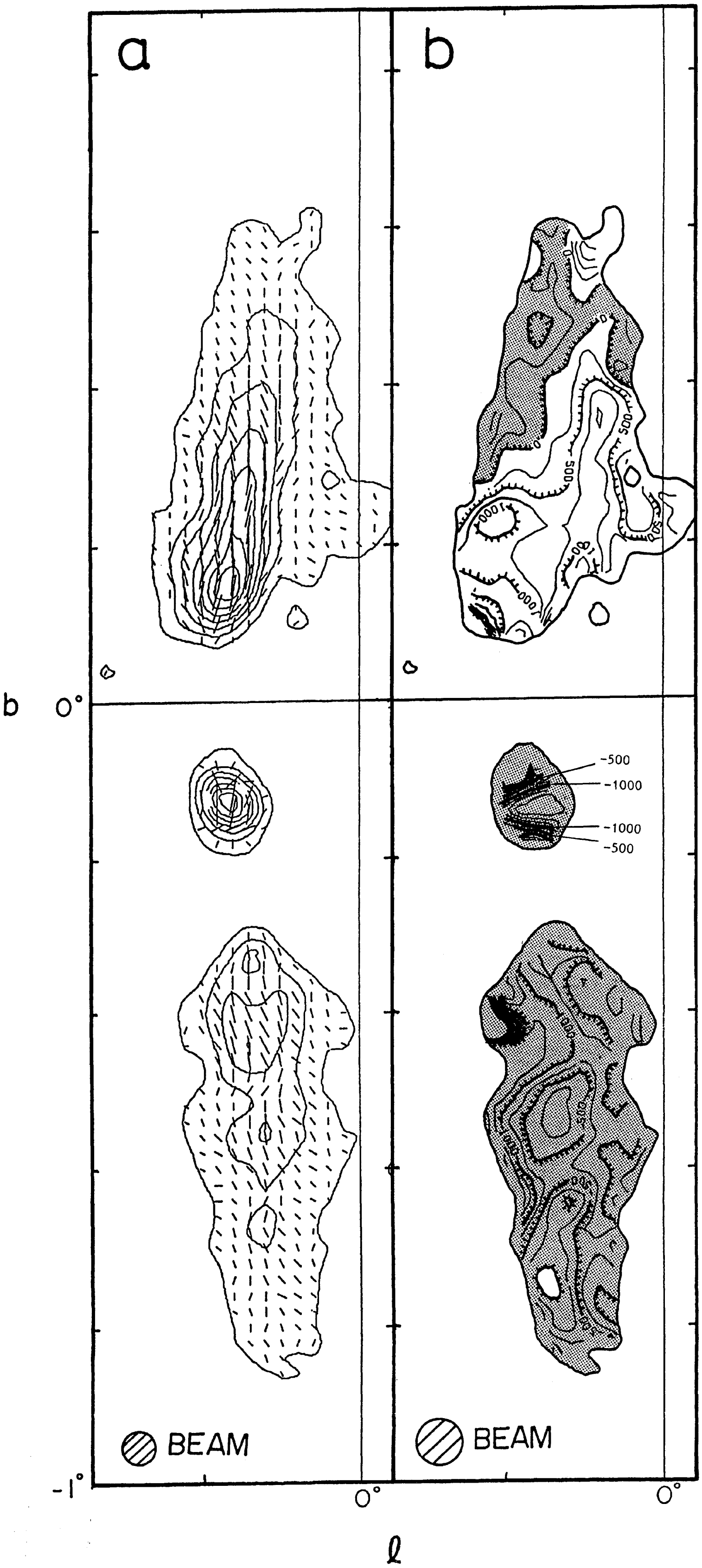

FIG. 4. (a) The orientation of the transverse magnetic field superposed on the polarized intensity in Fig. 1. The magnetic field essentially runs along the plumes with a slight waving pattern. The length is proportional to the polarized intensity. Contour interval is 60 mJy/beam. The standard deviation of the orientation is several degrees for the whole of the plumes and the compact polarized feature. (b) Distribution of rotation measure (RM) over the region where the polarized intensity exceeds 60 mJy/beam with a restoring beam of 3.′5. With original HPBW of 2.′7, the largest magnitude of RM is − 2500 rad/m^2 at the center of the compact feature. Shaded area is for negative RM (the line-of-sight component of the magnetic field goes away from the observer) and nonshaded area for positive RM. Contour interval is 250 rad/m^2. The standard deviation of RM depends on the polarized intensity. It is less than 150 rad/m^2 at 60 mJy/beam and is 30 rad/m^2 at the center of the compact feature.

the model and the observation gives a strong support for the internal Faraday depolarization.

Furthermore, our result of the degree of polarization ($p = 9\%$ with HPBW = 2′.7) in the compact polarized feature does not agree with Bonn's result of $p = 22\%$ with HPBW = 1′.2 (Seiradakis *et al.* 1985). However, their result agrees very well with the model calculation mentioned above. Therefore, we can estimate that the scale size of the uniform polarized region on the compact polarized feature is about 1′. This is consistent with the scale size of the polarization, which can be seen in the VLA polarization map at 5 GHz (Yusef-Zadeh *et al.* 1986). This also suggests that internal Faraday rotation is dominant in the region. So this system may be a complexity of thermal and nonthermal media in addition to the magnetic field.

The distribution of RM changes smoothly in the north plume with very large gradient: the sign of RM reverses within a scale of ~ 100 pc along the axis of the plume. There seems to be no correlation between distributions of RM and polarized intensity in the north plume, and similarly with the relation between distributions of RM and total intensity. This implies the distribution of RM is mainly due to the change of line-of-sight component of the magnetic field. On the other hand, there is a weak correlation between RM and polarized intensity in the southern half of the south plume, although the gradient of RM in the south plume is also large. Some blobs in polarized intensity agree with holes in RM. This again shows that the RM in the plume is, to some extent, due to internal Faraday rotation.

Assuming that the main part of the Faraday rotation is caused by the thermal medium within the magnetic tube and/or its thermal sheath, the plume should have some inclination with respect to the z direction (perpendicular to the galactic plane). We found the waving pattern of the magnetic field in the plumes [see Fig. 4(a)]. It is unlikely that such a waving is confined only to the plane of the sky. If the magnetic tube runs perpendicular to the galactic plane, we would see more complicated changes in the sign of RM owing to the wave pattern, as illustrated in Fig. 5(a). Consequently, the inclination of the magnetic tube should be larger than the angular amplitude of the waving. The model expects that the reversal of the sign in RM is attributed to the bending of the magnetic tube between the north and the south plumes, and the bending angle to the line-of-sight should be considerably sharp. We show the schematic display of this situation in Fig. 5(b).

This bending of the magnetic field may be due to local structures such as molecular clouds. These clouds might interact with the magnetic tube and bend it. However, the problem is still open: the bendings might be due to the galactic rotation because of a rough symmetry of the sign in RM with respect to the galactic plane.

There are alternative hypotheses which interpret the structure of the polarized features and the GCL. The magnetic structure of the galactic center region related to the GCL was discussed by Uchida *et al.* (1985). They proposed a magnetic-cylinder model in which a magnetic field is running perpendicular to the galactic plane with a radius of

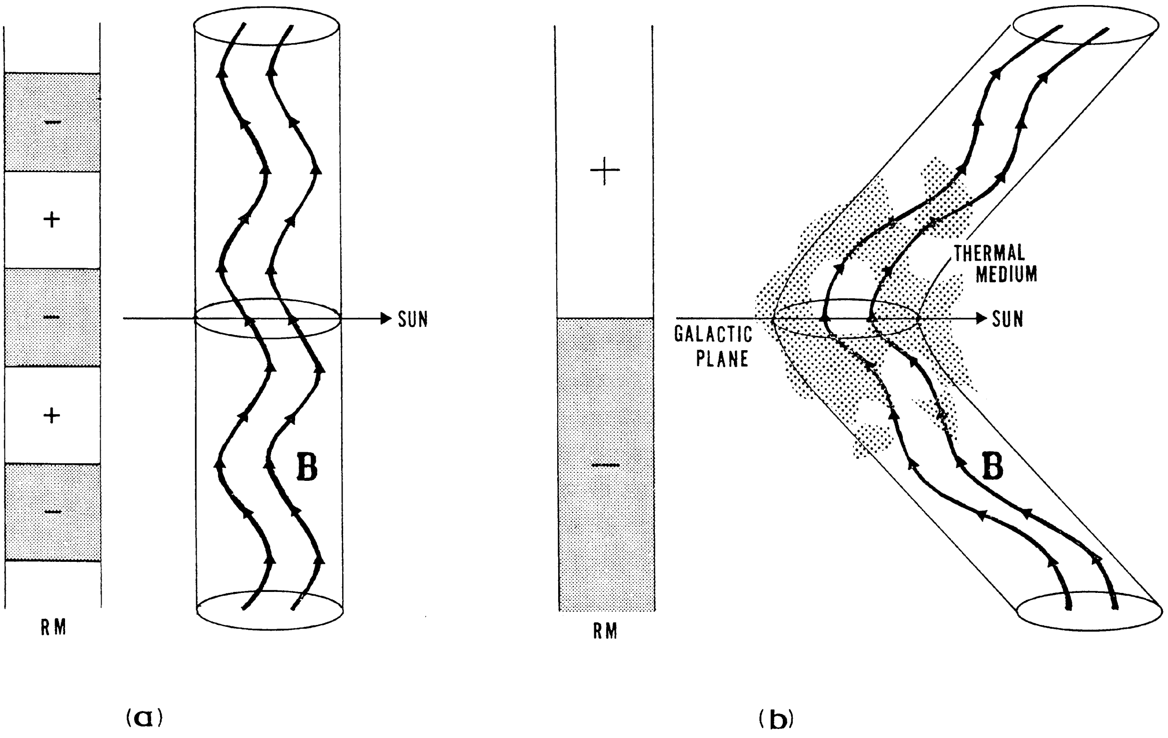

FIG. 5. Schematic display of the magnetic tube. (a) The waving of the magnetic field produces inversion in the sign of the line-of-sight component of the magnetic field, if the magnetic tube runs perpendicular to the line of sight. Thus the fact that there is no such inversion despite the waving indicates an inclination of the magnetic tube with respect to the plane on the sky. (b) The magnetic tube sharply bends near the galactic plane and this bending is responsible for the reversal of RM [see Fig. 4(b)]. This bending may be due to interaction with molecular clouds, or the galactic rotation, and might explain apparent bending between two plumes. Furthermore, the magnetic tube is associated with a thermal medium, resulting in the observed large RM (Papers I and II).

~100 pc. The symmetric axis of the cylinder is the rotation axis of the galaxy. However, as mentioned in the previous section, each side of the GCL has completely different polarized properties from each other. Thus the large-scale asymmetry of the polarized feature between the western and eastern sides of the galactic center invokes a serious difficulty on this model.

The problem of whether both sides of the GCL relate physically to each other, or whether the east side of it is really polarized or not, is essential to investigate a model. So we will examine this in detail. First, the distance to the galactic center from the west side of the GCL is almost twice that of the eastern one, and hence the depolarization in the west side should be smaller than that in the east side provided that the thermal electron density decreased as a function of distance to the galactic center. Second, in 57.5 and 80 MHz maps (LaRosa and Kassim 1985) we can see an emission and an absorption which correspond to our polarized features and the west side of the GCL, respectively. The optical depth of the thermal medium becomes thick at these low frequencies, and hence this absorption is ascribed to the thermal medium within and/or around the west side of the GCL. The similar absorption can be detected in the middle of the south polarized plume. There is, however, no remarkable difference between the north and south plumes in Fig. 1. Thus the thermal medium cannot screen the south polarized plume at 10 GHz. If the thermal medium within and/or around the west side of the GCL is as thick as that in the radio arc and it screens the polarized emission, the expected surface brightness at 10 GHz is larger than the observational one. Finally, recent IR observations show that IR emission in the west side of the GCL is remarkable at 20 and 27 μm (Little and Price 1985) and 50 and 100 μm (Gautier *et al.* 1984), while not so prominent in the east side of it (Sofue 1985), although the emission from the radio arc can be seen. Moreover, little IR emission can be seen at the south polarized plume. All these factors imply that the west side of the GCL is thermal.

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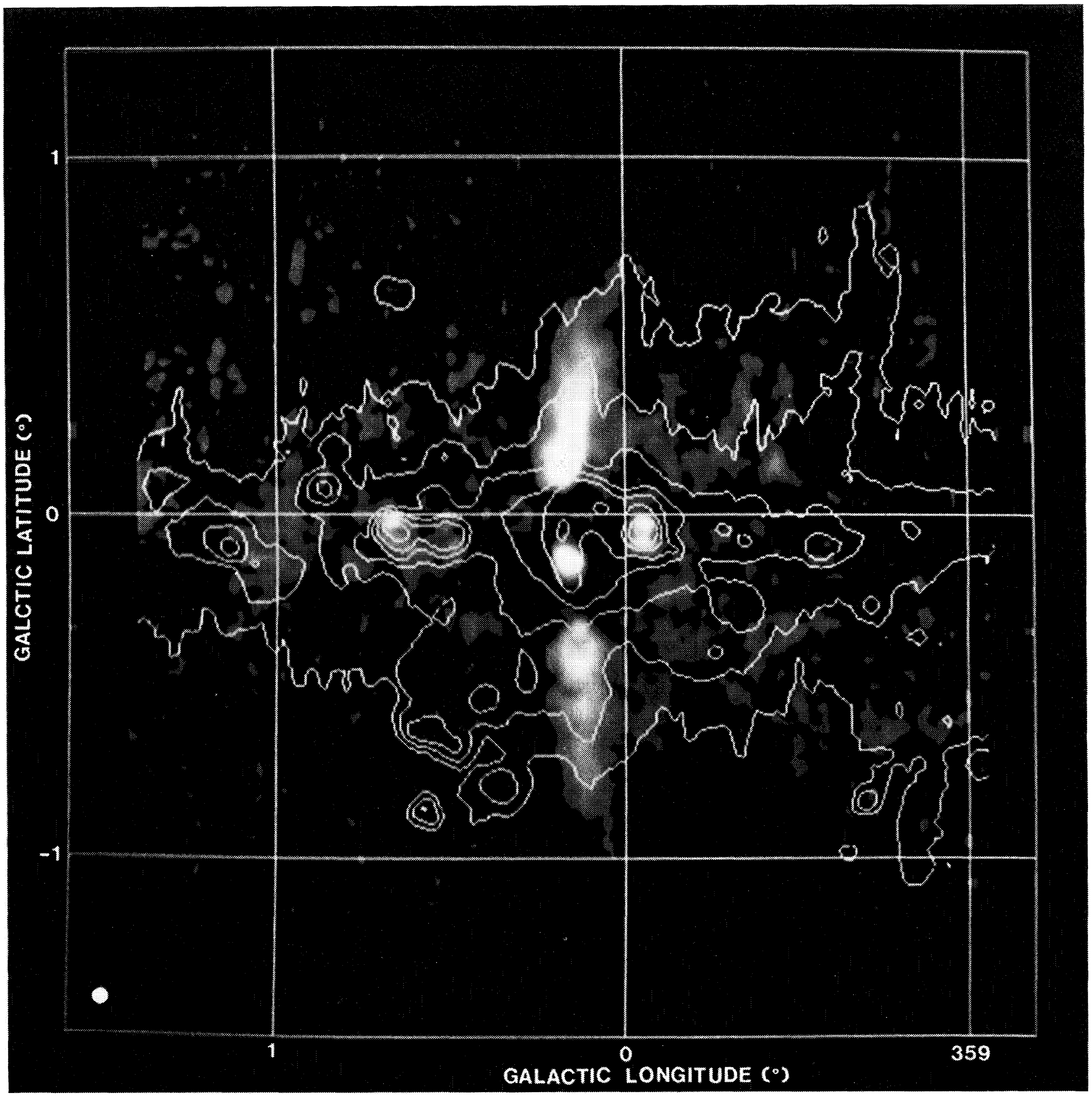

FIG. 1. Gray scale shows the average polarized intensity over all four frequency channels, superposed on the contours of the total intensity at 10 GHz. This wide-field-of-view map (2°.5 × 3°) reveals the whole structure of the extended polarized plumes, and also shows that there is no other remarkable plume in this area at all. Contour levels of the total intensity are 400, 800, 1600, 3200, 6400, 12 800, 25 600, and 51 200 mJy/beam at 10 GHz. Half-power beamwidth (HPBW) of both the polarized and total intensity of 2'.7 is shown in the bottom left-hand corner.

Tsuboi *et al.* (see page 819)

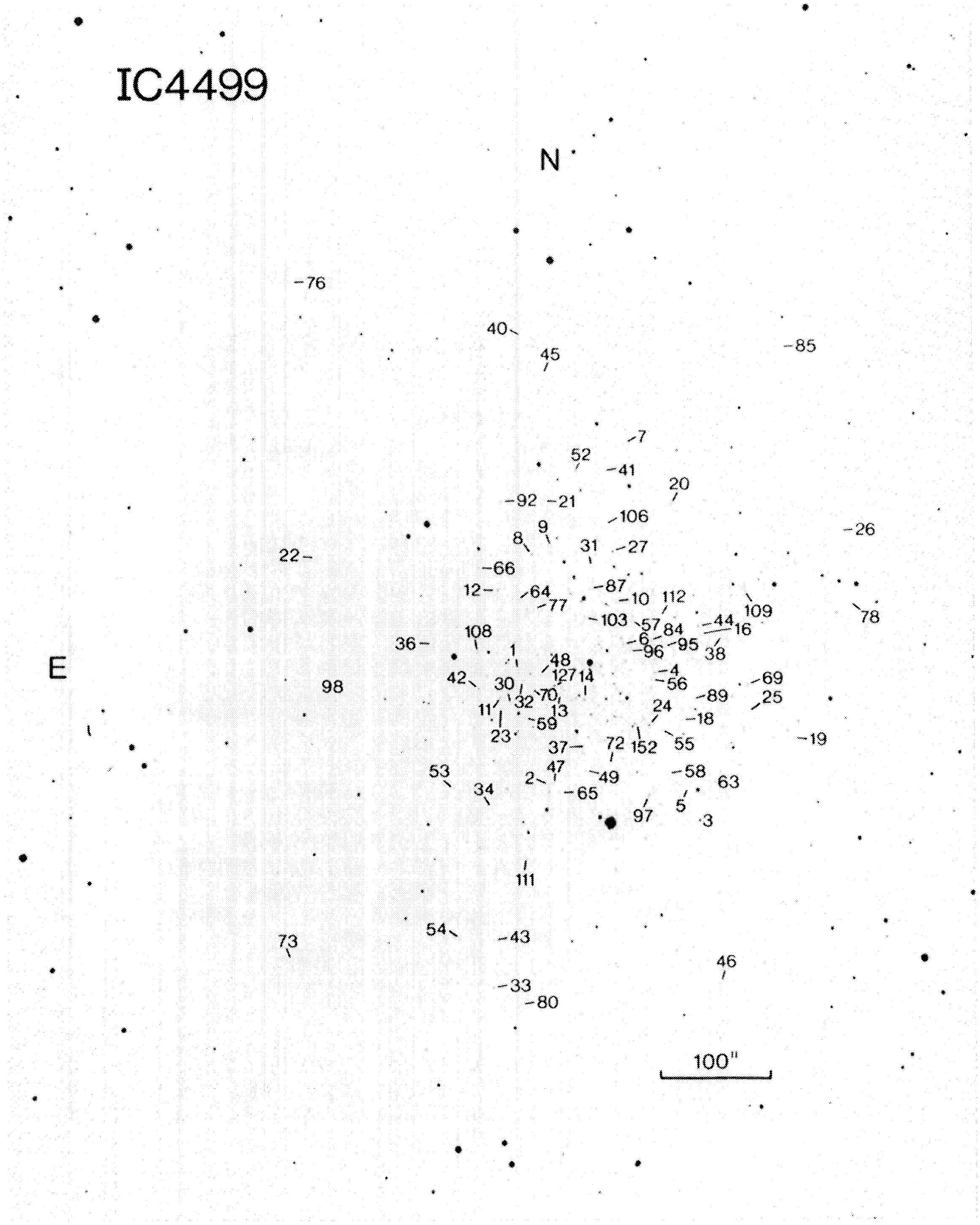

FIG. 1. Identification of 80 variable stars in IC 4499. The star numbers of Fourcade, Laborde, and Arias (1974), which were adopted by Sawyer Hogg (1973), are used. The print was made from plate No. 5778, a 60 min exposure taken with the University of Toronto 24 in. telescope on 103a0 emulsion behind a GG385 filter.

Clement *et al.* (see page 826)