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Bisymmetric Open-spiral Confignration of Magnetic Fields in the Galaxies M 51 and M 81

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Summary. Positional variations are studied of the Faraday rotation measure (*RM*) of linearly polarized radio waves from the spiral galaxies M 51 and M 81. A double periodicity is found in the *RM* distribution round the center of the galaxy, which indicates the presence of a bisymmetric and open-spiral magnetic field in the galactic plane. The field configuration suggests a primordial origin of the galactic magnetic fields. The field strength is estimated as $5\,10^{-6}$ G in the disk of M 51, and $3\,10^{-6}$ G in M 81, if the electron density and the distribution law of magnetic fields are similar to those in our Galaxy.

Key words: Faraday rotation – magnetic fields – linear polarization – spiral galaxies

1. Introduction

Tosa and Fujimoto (1978) proposed an analysis to determine the overall configuration of magnetic fields in spiral galaxies by using the distribution of polarization planes of radio emissions. They have shown that the magnetic lines of force in the spiral galaxy M 51 are parallel to the local spiral arms and the field direction is bisymmetric with respect to the rotation axis: the magnetic lines of force spiral in along an arm and spiral out along a diametrically-opposite one, satisfying the condition of divergence-free. They suggested also that the spiral magnetic field in M 51 is topologically consistent with the frozen-in of large-scale intergalactic magnetic field to the protogalaxy, being mildly twisted by differential rotation and maintained in a steady state by some hydromagnetic mechanism. They stressed that the field configuration can be explained neither in terms of the local compression of circular fields in the spiral shock waves nor in terms of twisting up of random (turbulent) magnetic fields by differential rotation.

If such a large-scale, mildly wound magnetic field really exists in a spiral galaxy, the frozen-in hypothesis seems to break down on some phase of the evolution of the galaxy and too many problems are put forward to the hydromagnetics of galactic gaseous disk in differential rotation. Before searching for dynamical models of magnetic fields in spiral galaxies, we have therefore to examine more critically the radio polarization data to get more evidence for or against the presence of the bisymmetric open-spiral fields.

2. Characteristic Distributions of Faraday Rotation Measure in the Spiral Galaxies M 51 and M 81

2.1. M *51*

A photograph of the spiral galaxy M 51 is reproduced from Tosa and Fujimoto (1978) in Fig. 1 where are superposed the magnetic field components transverse to the line of sight. These components have been determined by using the polarization vectors at $\lambda=6$ cm and 21 cm observed by Segalovitz et al. (1976). We find that the magnetic fields are predominantly parallel to the spiral arms. Tosa and Fujimoto (1978) suggested that the rotation measure (*RM*) has a double periodicity in its distribution along a circle round the center of M 51. From these results they concluded that the overall magnetic field is not circular but rather bisymmetric, spiraling with respect to the galactic center at a pitch angle equal to that of the spiral arm. However, their conclusion about the double periodicity in the *RM* distribution seems still inconclusive, because the number of the data points of *RM* is not enough.

In the present paper we assume sufficiently reasonably, as suggested by Fig. 1, that the magnetic fields are in the galactic plane and parallel to the local (or nearest) spiral arms, although their directions (towards us or away from us) still need to be determined. This assumption means that the intrinsic polarization planes are perpendicular to the nearest arms. Therefore the angle ϕ between the plane of the "intrinsic" polarization and that at any wavelength, say at 21 cm for example, can yield a local rotation measure. Then we can fully make use of the 21 cm data (Segalovitz et al., 1976) which are distributed on 111 points on the disk of M 51 (Fig. 2).

Figure 3 shows the variation of the rotation angle ϕ as a function of θ, where θ is the azimuthal angle of the data position measured from the north to east round the M 51 center. The data are divided into two groups: open circles are those for inner region of 1.'8 (5 kpc at a distance of 9.7 Mpc) of the galactic center and filled circles for outer region. Note that the data in regions I to IV in Fig. 2 are excluded from our analysis: the magnetic fields in region I seem to be much disturbed by the interaction with the companion galaxy; the field directions in regions II–IV are not clear for the lack of 6 cm data but seem to deviate largely from the directions of the local spiral arms. We note also that the rotation angle ϕ in region V scatter more largely than those in other regions, which causes an apparent hump at $\theta\approx 350°$ in Fig. 3 (open circles). We do not take into account the data in region V so seriously in the following analysis, because the region is located so close to the galaxy center that

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Fig. 1. Photograph of M 51 (Palomar Observatory) on which are superimposed the components of magnetic fields transverse to the line of sight as determined through a Faraday effect analysis (reproduced from Tosa and Fujimoto, 1978)

both the thermal electron density and the magnetic field strength may have large fluctuations from the mean values.

Taking all these situations into account, we can now recognize a double periodicity in the ϕ distribution in Fig. 3 with two maxima at $\theta \approx 110°$ and 260°, and the peak-to-peak amplitude is $\phi_{\max} - \phi_{\min} = 40° \pm 8°$. When the double periodicity is compared with that predicted from the model configuration by Tosa and Fujimoto (1978), we can conclude reasonably the existence of a bisymmetric, mildly-twisted magnetic field in M 51: the field lines flow-in on one half of the disk and flow-out on the diametrically-opposite half.

2.2. M *81*

The galaxy M 81 is one of the nearby spirals well investigated by radio observations at several wavelengths, which exhibits two well-defined logarithmic spiral arms in radio continuum (e.g. Segalovitz, 1976). Although not so many data are available as in M 51, if we apply the same analysis method to M 81, we can use 33 data points of polarization at 1420 MHz obtained by Segalovitz (1976).

We here define the rotation angle ϕ as an angle between the observed polarization plane at 21 cm and an assumed intrinsic polarization vector which is perpendicular to the local spiral arm. Figure 4 shows the plots of ϕ against the azimuthal angle θ of the data position. The data are again divided into two groups: the open circles are those within $r < 6'$ of the M 81 center (or < 5.6 kpc at a distance of 3.2 Mpc) and the filled circles are those at $12' > r > 6'$, where r is the "true" radial distance from the center corrected for the inclination of the disk, $i = 60°$.

In Fig. 4 we recognize clearly a double periodicity with two maxima at around $\theta = 40°$ and 220°, and two sharp minima at $\theta = 140°$ and 320°. We note that the positions of the minima are near the node of the galactic plane at $\theta_{\mathrm{node}} = 150°$ and 330° which are determined from the radial-velocity distribution of H I

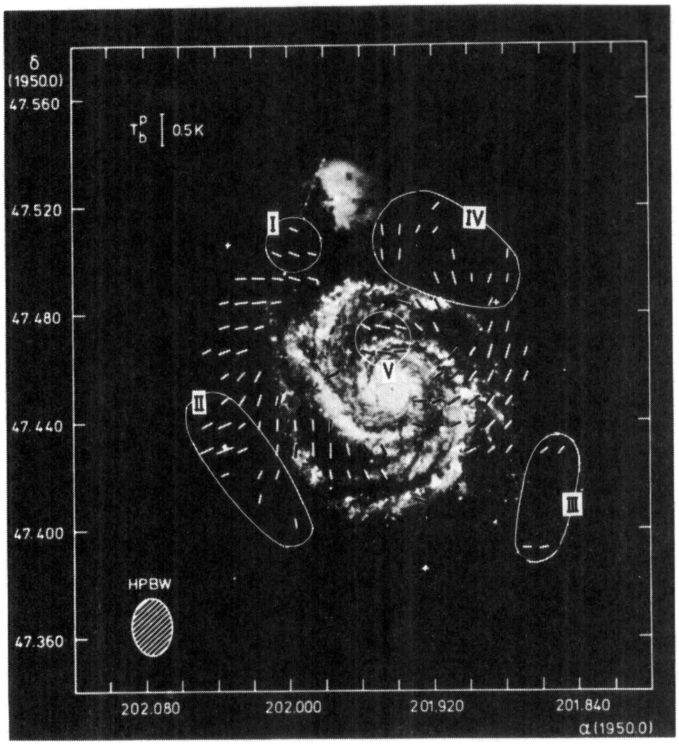

Fig. 2. Distribution of observed polarization planes of radio emission at $\lambda=21$ cm (reproduced from Segalovitz et al., 1976). See the text as to regions I to V

gas (Segalovitz, 1976). The peak-to-peak amplitude of the deflection angle is $\phi_{\max}-\phi_{\min}=160°\pm20°$. The absolute zero level of the rotation measure cannot be determined from the present data alone without knowing the foreground Faraday effect.

3. Bisymmetric Magnetic Fields in Spiral Galaxies

We now consider in more quantitatively the meaning of the double periodicity in the *RM* distribution obtained in M 51 and M 81 in the premise that they are due to a large-scale bisymmetric configuration of magnetic fields in the galactic disk. We denote the inclination angle of the disk by i, the pitch angle of the spiral by α along which the field is directed, and the position angle of the locus of maximum strength of the bisymmetric field by μ measured from the node on a certain circle concentric to the center of the galaxy in its equatorial plane (Fig. 5). Then the Faraday rotation angle ϕ varies with apparent position angle θ_0 measured from the node as follows:

$$\phi=\tfrac{1}{2}RM_0\lambda^2\tan i[\cos(2\Theta+\alpha-\mu)+\cos(\alpha+\mu)], \tag{1}$$

with

$$\Theta=\tan^{-1}(\tan\theta_0/\cos i), \tag{2}$$

where λ is the radio wavelength and Θ is the "true" azimuthal angle from the node on the plane of the galaxy (Fig. 5). The characteristic rotation measure, RM_0, of the galactic disk is defined as

$$RM_0=0.81\int_0^\infty n_e(z)B_0(z)dz(\mathrm{rad\ m^{-2}}). \tag{3}$$

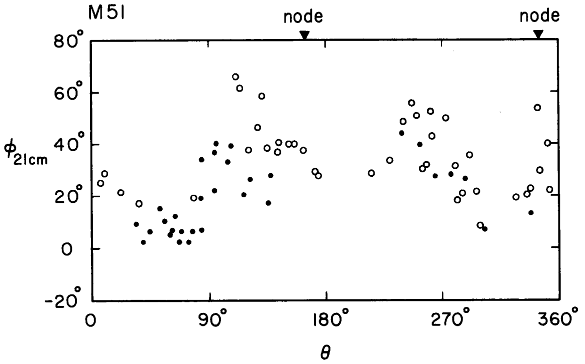

Fig. 3. Rotation angle ϕ between the polarization plane at $\lambda=21$ cm and the intrinsic polarization plane which is assumed to be perpendicular to the local spiral arm in M 51. They are plotted against the azimuthal angle of their position θ as measured from the north. Open circles are those for inner region of 1'.8 from the galaxy center, and filled circles for outer region

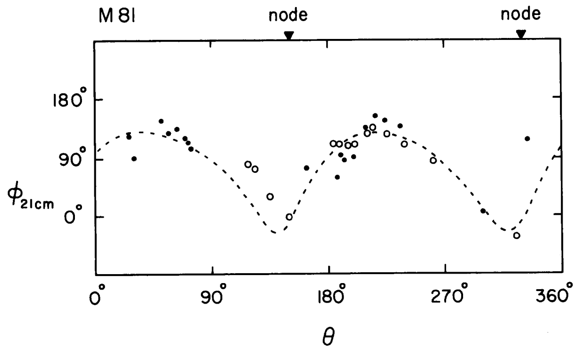

Fig. 4. Rotation angle ϕ between the polarization plane at 21 cm and a line perpendicular to the local spiral arm of M 81. The dashed line is the same as the theoretical line b in Fig. 6, but the amplitude is set to $-80°$ and $\alpha-\mu=30°$. The node position is at $\theta_{\mathrm{node}}=150°$. Open circles are those for $r\leqq6'$; filled circles for $r>6'$, where r is the "true" angular distance from the center corrected for the inclination

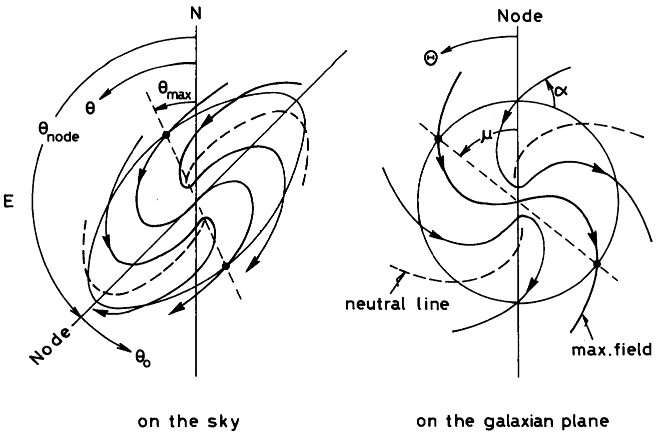

Fig. 5. Schematic configurations of the bisymmetric, open-spiral magnetic fields in the galaxian plane (at right) and those projected onto the plane of the sky (at left). Definitions of parameters and arguments are indicated

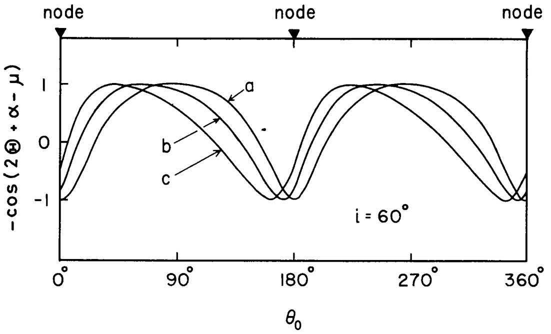

Fig. 6. Calculated θ_0 dependence of ϕ normalized by $1/2\,RM_0\lambda^2 \cdot \tan i$, or $\cos(2\Theta+\alpha-\mu)$ in Eq. (1), in case of $i=60°$ for (*a*) $\alpha-\mu=0°$, (*b*) 30°, and (*c*) 60°

Here $B_0(z)$ is the maximum value of the field strength in 10^{-6} G on the circle under consideration, which is an even function of the height z in pc from the equatorial plane, and $n_e(z)$ is the electron density in cm^{-3}. We assume that the scale heights of $B_0(z)$ and $n_e(z)$ are sufficiently small compared to the galaxy size.

3.1. M *51*

The inclination angle of M 51 is $i=15°$. In this case Eq. (1) can be approximated by a doubly sinusoidal variation by putting $\theta_0 \approx \Theta$

$$\phi \approx \tfrac{1}{2} RM_0\lambda^2 \tan i[\cos(2\theta_0+\alpha-\mu)+\cos(\alpha+\mu)]. \tag{4}$$

This is an expression similar to Eq. (4) in Tosa and Fujimoto (1978). (Their expression involves a slight error about the definition of the angle β: their angle β should be read as an angle from the node to the maximum-field position, here denoted as μ, instead of the neutral-line position as they defined.)

The eye fitting of Eq. (4) to the *RM* distribution in Fig. 2 gives the amplitude of the rotation angle as $1/2\,RM_0\lambda^2 \tan i = 20°\pm4°$. Recalling that $\lambda=0.21$ m and $i=15°$, we obtain $RM_0 = 60\pm12$ rad m^{-2}. From the positions of the two maxima in ϕ at $\theta \approx 110°$ and 260° in Fig. 3, we obtain $\alpha-\mu\approx60°$ for the first maximum and $\alpha-\mu\approx90°$ for the second maximum. We take a typical pitch angle of $\alpha\approx20°$ for the spiral arms of M 51. Then we have $\mu\approx-40°$ for the first maximum position and $\mu\approx-60°$ for the second maximum position with a discrepancy of 20°. By taking $\theta_{\text{node}}=166°$ and 346° (e.g. Segalovitz, 1976), we obtain approximate positions of the bisymmetric loci of maximum magnetic field to be at around $\theta_{\max}\approx126°$ and 286° measured from the north. We note that the two maximum positions of the field do not appear completely symmetric to each other, which may be due to a large-scale deformation of the field configuration probably caused by the interaction with the companion galaxy.

3.2. M *81*

In Fig. 6 we show some calculated curves of $-\cos(2\Theta+\alpha-\mu)$ which appears in Eq. (1), for $\alpha-\mu=0°$, 30°, and 60° in case of $i=60°$. We find that the curve of $\alpha-\mu=30°$ fits the observed ϕ distribution at 21 cm in Fig. 4. We can approximate the amplitude of ϕ by $1/2\,RM_0\lambda^2 \tan i = -80°\pm10°$ with $\alpha-\mu=30°$, which leads to $RM_0=-37\pm5$ rad m^{-2}. Since the pitch angle of the spiral arms of M 81 is determined as $\alpha\approx23°\pm4°$ using Segalovitz's (1976) radio map at 21 cm, we obtain the maximum field position as $\mu\approx7°$. By taking into account the inclination of the galaxy, $i=60°$, and the position angle of the node, $\theta_{\text{node}}=150°$, we have $\theta_{\max}\approx147°$ and $\approx327°$. We are thus confident that the magnetic field in M 81 is also mildly twisted and bisymmetric. The logarithmic spiral may hold of the field configuration.

3.3. Magnetic Fields and Faraday Rotation in M 51 and M 81

We have obtained $RM_0=60\pm12$ rad m^{-2} for the M 51 disk and $RM_0=-37\pm5$ rad m^{-2} for M 81. We now discuss these quantities in more details together with that in our Galaxy. We assume that the distributions of electron density in the z-direction in both galaxies are similar to that in our Galaxy as determined from observations of pulsars (Manchester and Taylor, 1977):

$$n_e(z)=0.03\exp(-|z|/h_e)\ \text{cm}^{-3}, \tag{5}$$

where the scale-height h_e is taken as 1 kpc. For the magnetic field we assume the same distribution law:

$$B_0(z)=B_0\exp(-|z|/h_m), \tag{6}$$

and the same scale-height, $h_m=h_e=1$ kpc.

In our Galaxy the large-scale and uniform component of the magnetic field has the strength of $B_0\approx3\ 10^{-6}$ G in the solar neighbourhood. Substitution of Eq. (5) and (6) with $B_0\approx3\ 10^{-6}$ G into Eq. (3) gives $RM_0\approx36.5$ rad m^{-2} for our Galaxy. We note that the RM_0 obtained for M 51 and M 81 agree with this value within a factor two.

The RM_0 for M 51 is 1.5 times as large as that for M 81. This difference in RM_0 may be attributed to differences of B_0 and n_e in the two galaxies. If the electron density and the scale-heights of $n_e(z)$ and $B_0(z)$ are the same for both galaxies as those in our Galaxy, we have $B_0\approx5\ 10^{-6}$ G in the M 51 disk and $B_0\approx3\ 10^{-6}$ G in M 81. We may then expect higher synchrotron emission from M 51 than from M 81, which is indeed observed. Below we compare surface brightness temperatures at $\lambda=49$ cm in M 51 and M 81 using the radio continuum maps of Segalovitz (1976).

The typical brightness temperatures of the outer arms in the SW quadrants of M 51 and M 81, corrected for the inclinations, are respectively $T_{\text{M}51}=32.6\pm6.5$ K and $T_{\text{M}81}=4.8\pm0.7$ K at $\lambda=49$ cm. The ratio of the brightness temperatures is 6.8 ± 1.4. Since the radio waves at 49 cm is due mainly to synchrotron radiation, if we assume a local equi-partition between cosmic-rays and magnetic field, the surface brightness should be proportional to $\sim B^{3.5}$ with B the field strength. If the scale height of the distribution of magnetic fields is the same for both galaxies, we can estimate the ratio of the field strengths by equating $(B_{\text{M}51}/B_{\text{M}81})^{3.5}$ to $(T_{\text{M}51}/T_{\text{M}81})_{49\,\text{cm}}=6.8\pm1.4$, or $B_{\text{M}51}/B_{\text{M}81}=1.7\pm0.1$. This ratio is consistent with the ratio of B_0 derived from $RM_0: B_{0,\text{M}51}/B_{0,\text{M}81}\approx1.7$. It is thus plausible to attribute the *RM* difference between M 51 and M 81 to that in B_0.

4. Discussions

We have analysed the polarization data at $\lambda=21$ cm for M 51 and M 81, and have shown that the *RM* on the galactic plane varies systematically with the azimuthal angle round the center, having a double periodicity. Such a characteristic distribution can be accounted for by the Faraday rotation due to thermal

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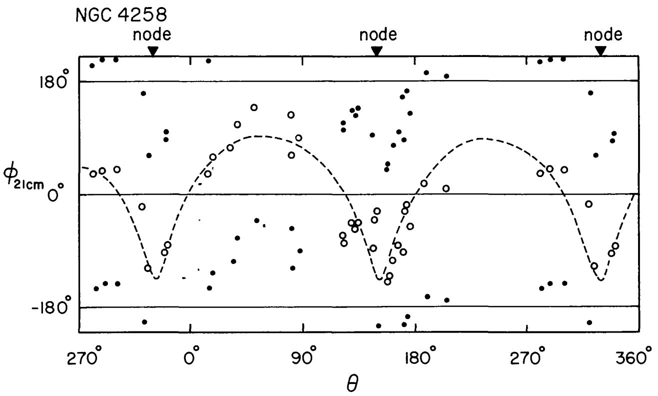

Fig. 7. The same as Fig. 4, but for NGC 4258 allowing for $\pm n \times 180°$ ambiguity in each ϕ value. A possible double periodicity (dashed line) may be obtained, if we trace only those denoted by open circles

electron and bisymmetric magnetic fields in the galactic disk (Tosa and Fujimoto, 1978). We suggest that such a field configuration could be produced, if large-scale intergalactic magnetic fields (i. g. Sofue et al., 1979) were trapped into the protogalaxy, twisted by differential rotation and maintained in a steady open-spiral state by some hydromagnetic mechanism in the disk.

If this is the case, we have to abandon the frozen-in hypothesis of magnetic fields and have to search for some new hydromagnetic mechanism to maintain the field in a slightly wound state in the differentially rotating medium. In this respect Sawa and Fujimoto (1980) have found a steady state solution that the field lines are maintained in an open-spiral configuration, provided that the galactic disk is surrounded by a huge halo of diffuse gas and magnetic fields. Thereby they assumed turbulent diffusion of magnetic fields within the disk of finite thickness and mixing of the magnetic fields between the halo and disk.

We have so far obtained evidence for the existence of bisymmetric and open-spiral magnetic fields in the disk galaxies M 51 and M 81. The number of sample galaxies is only two in the present study. Further observations of radio polarization are needed for other spiral galaxies. The following two arguments about the Galaxy and NGC 4258 seem to be related to our study of open-spiral bisymmetric magnetic fields. We comment on these two galaxies in order to stress the importance of further observations of polarization from spiral galaxies. (Note that they do not show a very clear evidence for our field configuration but only a suggestion.)

4.1. The Galaxy

It is well established that a large-scale magnetic field is present in the solar neighborhood over a few kpc (e.g. Heiles, 1976). Simard-Normadin and Kronberg (1979) have shown from their analysis of Faraday rotation measures of extra-galactic radio sources that there exists a reverse component to the nearby uniform field, directed towards us from $l \approx 50°$, $b \approx 0°$: a neutral field region is expected in the direction of $l \approx 70°$.

Recently Thomson and Nelson (1979) have shown from an analysis of pulsar Faraday rotations that the local systematic field has a reverse component in the direction of the inner spiral arm (Sagittarius arm) region. The *RM* distribution of pulsars are best fitted with a model that a neutral line of magnetic field lies in the direction of $l \approx 74°$ at a distance of 170 pc from the sun on the galactic-center side. On the anticenter side of this neutral line the uniform component is directed from $l \approx 260°$ towards $l \approx 80°$, and vice versa on the other side.

It is remarkable that the two results, independently derived from pulsars and extragalactic radio sources, agree with each other. The above facts suggest that the magnetic fields in our Galaxy are not wound so tightly but wound at a pitch angle of $\alpha = 15° - 20°$. The presence of the neutral line of magnetic field is not inconsistent with our conclusion about the bisymmetric open-spiral structure.

4.2. Other Galaxies

The spiral galaxy NGC 4258 is known to exhibit anomalous nonthermal radio arms (van der Kruit et al., 1972). Except for the nonthermal radio structure, the galaxy has quite a normal morphology both in optical and H I observations (van Albada, 1978). We here try to apply our method of *RM* analysis to the polarization data at 21 cm of this galaxy obtained by van Albada. We use only the data apart from the anomalous radio ridges by more than two beam widths. In the same way as in M 51 and M 81, we plot the rotation angle ϕ of polarization plane with an ambiguity of $\pm n \times 180°$, where n is an arbitrary integer. Although we can recognize some wavy feature in the ϕ distribution, it seems difficult to identify a periodicity at a first glance. However, if we recall that the inclination of NGC 4258 is large, $i = 72°$, a much larger Faraday rotation is expected than in M 51 and M 81: the amplitude of the deflection angle, $\phi_{\max} - \phi_{\min}$, would be on the order of 200° and it seems reasonable to include the ambiguity of $\pm 180°$. Then our proposed double periodicity is seen in the figure, when we trace the open circles which are approximately fitted with the dashed line. The corresponding amplitude of the variation in ϕ is approximately $1/2|RM_0\lambda^2 \tan i| \sim 100°$, which yields $|RM_0| \sim 26$ rad m^{-2}. We note that this result is still inconclusive. We need more data, in particular apart from the anomalous arms, in order to distinguish the double-periodicity from many other characteristics in the ϕ distribution.

In conclusion we would like to emphasize that the method presented in this paper will be promising to determine the field configurations in extragalactic spiral galaxies even from single-frequency observations of polarization. In addition to M 51, M 81, and NGC 4258, other spirals of mild inclinations like M 31, M 33, M 101, NGC 2403, NGC 7331, and NGC 253 are candidate galaxies for the determination of the overall structure of the magnetic field, for which the polarization observations are highly desired with radio synthesis telescopes and/or large single dishes.

Very recently Beck et al. (1979) and Beck (1979) have performed radio observations over the entire extent M 31 and M 33 at several frequencies, including polarization at 1.4 and 2.7 GHz. Their data provide extensive means to investigate the field configuration in these galaxies. An analysis of *RM* using their data is under way by applying the presently proposed method of determining the field configuration. The results will be published in a separate paper (Sofue and Takano, 1980).

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