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The Configuration of Magnetic Fields in the Spiral Galaxies M31 and M33

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Abstract

The configuration of magnetic fields in the spiral galaxies M31 and M33 is studied through an analysis of the positional variation of the Faraday rotation measures for linearly polarized radio waves from the galaxies. The systematic magnetic field in M31 is predominantly oriented along the bright radio "ring," and no large-scale reversal of the field is found in the region between 8 and 15 kpc from the galaxy center. The strength of the systematic component of the magnetic fields is estimated to be 2.2×10^{-6} G in M31. The magnetic field in M33 is in an open-spiral configuration, and a bisymmetric distribution of the field directions is suggested.

Key words: Faraday rotation; Magnetic field; Radio polarization; Spiral galaxies.

1. Introduction

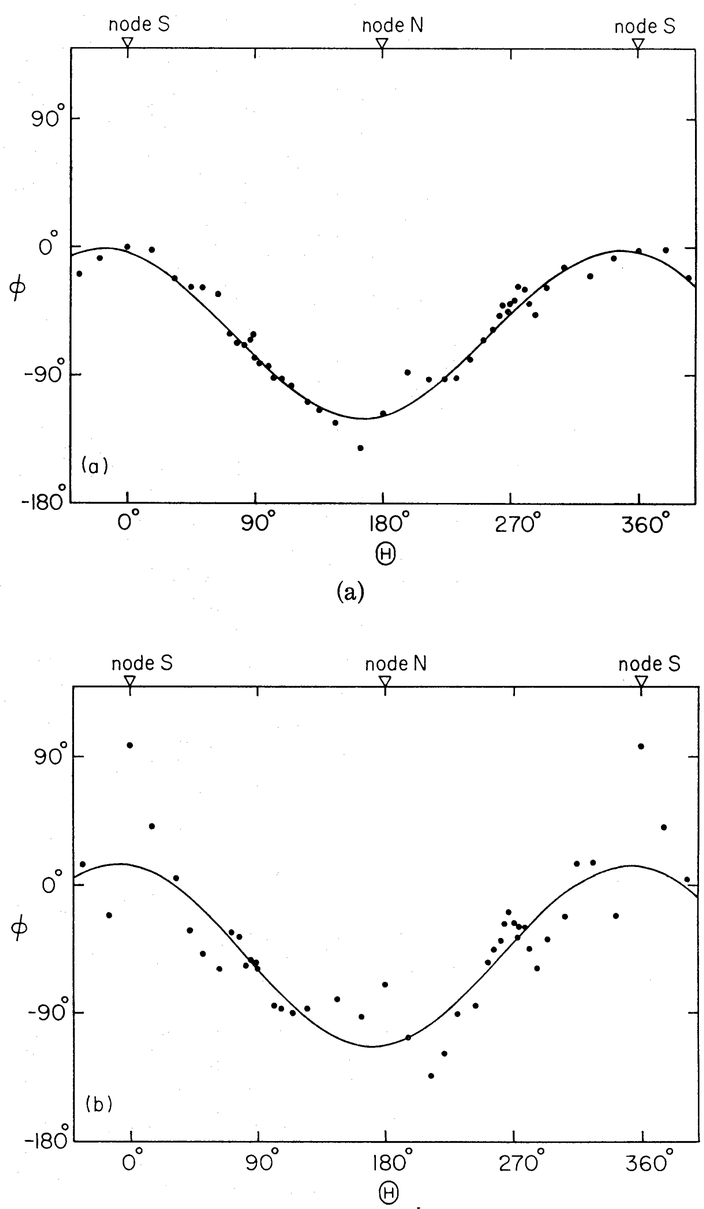
Observations of linearly polarized radio waves from galaxies provide information on their magnetic fields. In particular, the Faraday rotation measures (RM) may yield the orientation of the magnetic fields. Tosa and Fujimoto (1978) and Sofue et al. (1980; this is referred to hereafter as Paper I) have shown the existence of open-spiral, bisymmetric magnetic fields in the disks of the spiral galaxies M51 and M81 by analyzing the data of radio polarization by Segalovitz (1976) and Segalovitz et al. (1976). The necessity has been stressed for further observations of the distribution of the polarization plane in other galaxies in order to see whether or not the bisymmetric and spiral field configuration is a characteristic of spiral galaxies. Recently Beck et al. (1980) and Beck (1979) have observed the radio polarization across the spiral galaxies M31 gnd M33 at 1420 MHz and 2700 MHz. In the present paper we analyze their data to study the configurations of magnetic fields in these galaxies.

2. M31: A Magnetic Field Oriented along the Bright Radio "Ring"

From their observations of linear polarization at 2.7 GHz Beck et al. (1980) have suggested an orientation of the magnetic field in M31 along its bright radio "ring." To examine the field configuration in a quantitative way, we apply the method of RM analysis proposed in Paper I to this galaxy. We make use of the polarization data at 2.7 GHz presented by Beck (1979).

We divide the disk of M31 into three rings, each 15′ wide: Rings I, II, and III, centered at the radii 43′ (8.6 kpc at a distance of 690 kpc), 58′ (11.6 kpc), and 73′ (14.7 kpc), respectively. When projected onto the plane of the sky, their minor-to-major axial ratio is taken to be $\cos i=0.28$, where $i=74°$ is the apparent inclination of the rotation axis of M31 to the line of sight (Beck 1979). Ring I coincides with the loci of maximum radio emission, or the bright radio "ring" (Beck et al. 1980). We assume that the magnetic fields are oriented along the rings which are concentric to the galaxy center. We can then define the Faraday rotation angle ϕ counterclockwise as the angle of the observed E-vector (polarization plane) to a vector perpendicular to the projected ring on the sky.

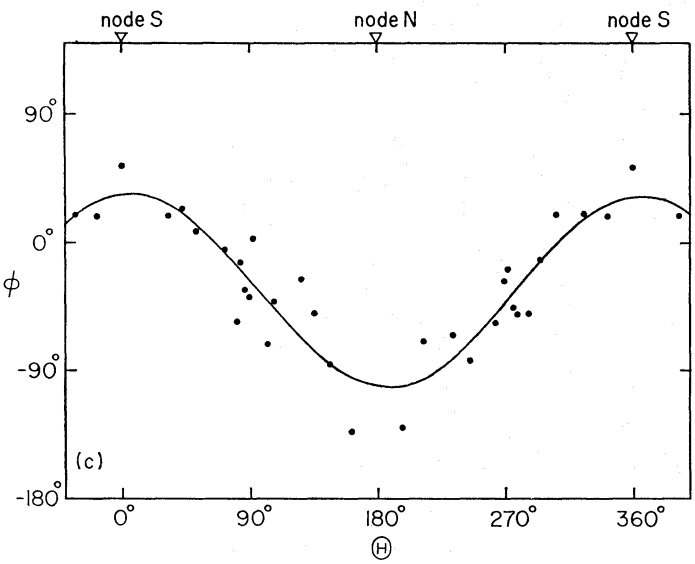
We further divide the rings into cells of 10°-interval of Θ and average



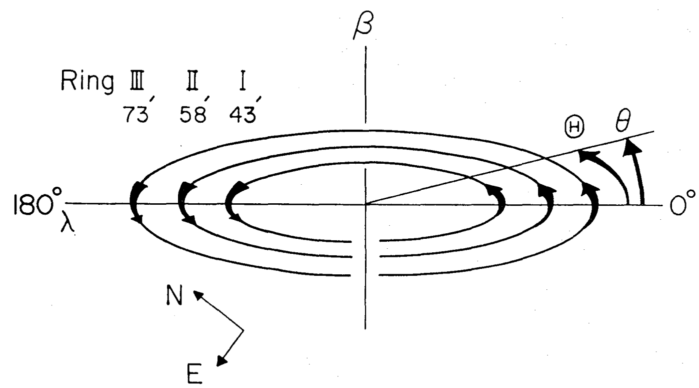
(a)

(b)

Fig. 1a–b. See the legend on the next page.



(c)



(d)

Fig. 1. Rotation angle ϕ of the observed polarization plane at 2.7 GHz of M 31 measured from a vector perpendicular to Rings I–III (see the text), plotted against the true azimuthal position angle Θ: (a) along Ring I (43′ radius); (b) Ring II (58′); (c) Ring III (73′). The systematic variation in ϕ is fitted with a sinusoidal function of Θ in equation (2), which indicates the existence of a magnetic field oriented along the ring. The orientation of the magnetic field and the angles θ and Θ are shown in figure d.

the polarization vectors in each cell. Here Θ is the "true" azimuthal position angle in the plane of the galaxy of the data point and is defined by

$$\Theta = \tan^{-1}(\tan\theta/\cos i)\ , \qquad (1)$$

where θ is the position angle of the point on the sky from the node referred to the galactic center (see figure 1d).

Figures 1a–c show plots of ϕ thus obtained against Θ for Rings I to III, respectively. The errors in the polarization angle observed by Beck (1979) are typically 6° for Ring I and 12° for Rings II and III. Our reading errors from his map are about 5°. Then the errors in ϕ in figure 1a are typically 8°, and they are 13° in figures 1b and c.

We can clearly recognize a singly sinusoidal periodicity in each of the figures.

The ϕ distribution in figures 1a–c can be fitted by the following equations:

$$\left.\begin{array}{ll}\text{Ring I}: & \phi=(-61^\circ\pm1^\circ)+(59^\circ\pm3^\circ)\cos(\Theta+15^\circ)\ , \\ \text{Ring II}: & \phi=(-50^\circ\pm2^\circ)+(64^\circ\pm7^\circ)\cos(\Theta+8^\circ)\ , \\ \text{Ring III}: & \phi=(-34^\circ\pm2^\circ)+(68^\circ\pm7^\circ)\cos(\Theta-7^\circ)\ . \end{array}\right\} \quad (2)$$

If our assumption of the circular magnetic field is correct, the constant term in these equations, -61°–-34°, may be attributed to the foreground Faraday rotation originating outside the M31 disk. These rotations at 11.1 cm correspond to rotation measures of $RM_{fg}=-87$–-49 rad m^{-2}. These values are well within the range of large negative RM obtained for extragalactic radio sources near M31 ($l=121^\circ.2$, $b=-21^\circ.6$; Tabara and Inoue 1980). We note further that the constant term in the above equations increases significantly from Ring I to III. Such a radial variation in the constant term is difficult to attribute either to RM in the disk of M31 or to the foreground RM. It might suggest an influence of the magnetic halo surrounding M31.

The sinusoidal component in equation (2) may be attributed either to a gradient of the foreground RM in the absence of an internal RM in M31, or to an RM by the circular magnetic field in M31 in the absence of a gradient of the foreground RM. From the fact that the maximum and minimum positions of ϕ in figures 1a–d coincide just with the nodal positions of M31 ($\Theta=0^\circ$ and 180°), we may more naturally attribute this component to a circular field in the disk of M31 (Tosa and Fujimoto 1978). Then the mean amplitude of the sinusoidal variation in Rings I–III, $\phi_0=63^\circ\pm5^\circ$, can be related to the characteristic rotation measure RM_0 through

$$\phi_0=RM_0\lambda^2\tan i\ , \quad (3)$$

with $RM_0\tan i=91\pm8$ rad m^{-2} and $RM_0=26\pm3$ rad m^{-2}. Here RM_0 is defined by

$$RM_0=0.81\int_0^\infty B(z)n_e(z)dz\ \ (\text{rad m}^{-2})\ , \quad (4)$$

where z is the height from the equatorial plane of the galaxy in parsecs, $B(z)$ is the strength of the field in microgausses which is an even function of z, and $n_e(z)$ is the thermal electron density in cubic centimeter.

We assume the following forms for the z-dependences of B and n_e:

$$B(z)=B(0)\exp(-|z|/h_m) \quad (5)$$

and

$$n_e(z)=n_e(0)\exp(-|z|/h_e)\ , \quad (6)$$

where h_m and h_e are the z-scale heights of the distributions of B and n_e, respectively. As typical values of h_e and $n_e(0)$ we take the same values as those obtained in the local region in our Galaxy: $h_e=1$ kpc and $n_e(0)=0.03$ cm^{-3} (Manchester and Taylor 1977), and further assume that $h_e=h_m$. Then we obtain $B(0)\sim2.2\times10^{-6}$ G as the strength of the circular component of magnetic fields in the plane of M31. This value is consistent with that for the ordered field in M31 derived from the polarized radio intensity on the assumption of equipartition between energy densities of magnetic field and cosmic-ray electrons (Beck 1979).

We have shown that the observed ϕ variation in equation (2) can be consistently interpreted by the Faraday rotation due to the assumed circular magnetic field in M31 and the uniform foreground rotation; we may conclude that the magnetic field in M31 is predominantly oriented along the "ring" and its direction is toward us at $\Theta=0°$ and in the opposite direction at $\Theta=180°$. We have so far regarded the z-scale heights of B and n_e to be small compared to the galaxy size. This assumption may be valid if the field has a large-scale configuration and a moderate strength as in M31. In addition to the above sinusoidal variation, small-scale variations are seen in figures 1a–c. They may be due to local irregularities of RM or to deviations of the field direction from the circular orientation, which cannot be distinguished from each other. The amplitudes in ϕ of these components are less than $\sim\pm20°$ (±28 rad m^{-2} in RM), or less than one third of the circular component.

Our result about the circular field orientation is consistent with that of Beck et al. (1980). However, they assumed the absence of both the internal and foreground Faraday rotations on the SW half of M31, on which their result about the field orientation is based; whereas they found a large negative Faraday rotation of -127 rad m^{-2} (or $\phi=-90°$) on the NE half, which they thought to be due to a foreground RM. Figure 1 shows that the apparently zero Faraday rotation on the SW half ($\Theta\sim270°$–$90°$) is due to a cancellation of the internal rotation of 60–90 rad m^{-2} in M31 by the foreground rotation of $RM_{fg}=-65$ rad m^{-2}. Moreover, it is clear that the large negative RM on the NE half should be attributed to the sum of the internal RM of -60–-90 rad m^{-2} in M31 ($\Theta\sim90°$–$270°$) and the foreground RM of -65 rad m^{-2}.

3. M 33: An Open-Spiral Magnetic Field

Beck (1979) has observed linearly polarized radio waves from M33 at 1.4 and 2.7 GHz. We made use of his data to determine RM and intrinsic E-vectors at points where polarization angles are available at both frequencies. We used a grid whose grid points coincide with the data points of the 1.4-GHz polarization map. The E-vectors at 2.7 GHz around each grid point are averaged over cells of $3'\times3'$ square arc-minutes yielding a mean polarization angle at that point. On determining RM we take into account that the foreground RM will have a large negative value ($RM\sim-20$ to -100 rad m^{-2}) as expected from RM of extragalactic radio sources near M33 ($l=133.^\circ6$; $b=-31.^\circ3$; Tabara and Inoue 1980). The errors in the observed polarization angle are about 15° to 4°, corresponding to polarization temperatures 4 to 16 mK. In the northern part of M33, where the polarization temperature is about 10–20 mK and polarization vectors are considerably ordered, our estimated errors in ϕ are typically 7° which corresponds to an error in RM of about 10 rad m^{-2}. In the southern part of the galaxy, the errors in ϕ reduce to about 15° or the errors in RM of 20 rad m^{-2}, because of the large scatter of polarization angles and the low polarization temperatures. The obtained RM distribution in M33 is in agreement with that obtained by Beck (1979) except for the region from $\theta_0\sim110°$ to 190° ($\Theta\sim100°$ to 200°), where he gives no RM values because of larger uncertainties due to small polarized intensities. We used the data of RMs in the southern part to discuss the overall configuration of the magnetic fields.

Figure 2 shows the directions of the magnetic field, which are taken to be perpendicular to the intrinsic E-vectors, projected onto the plane of the sky

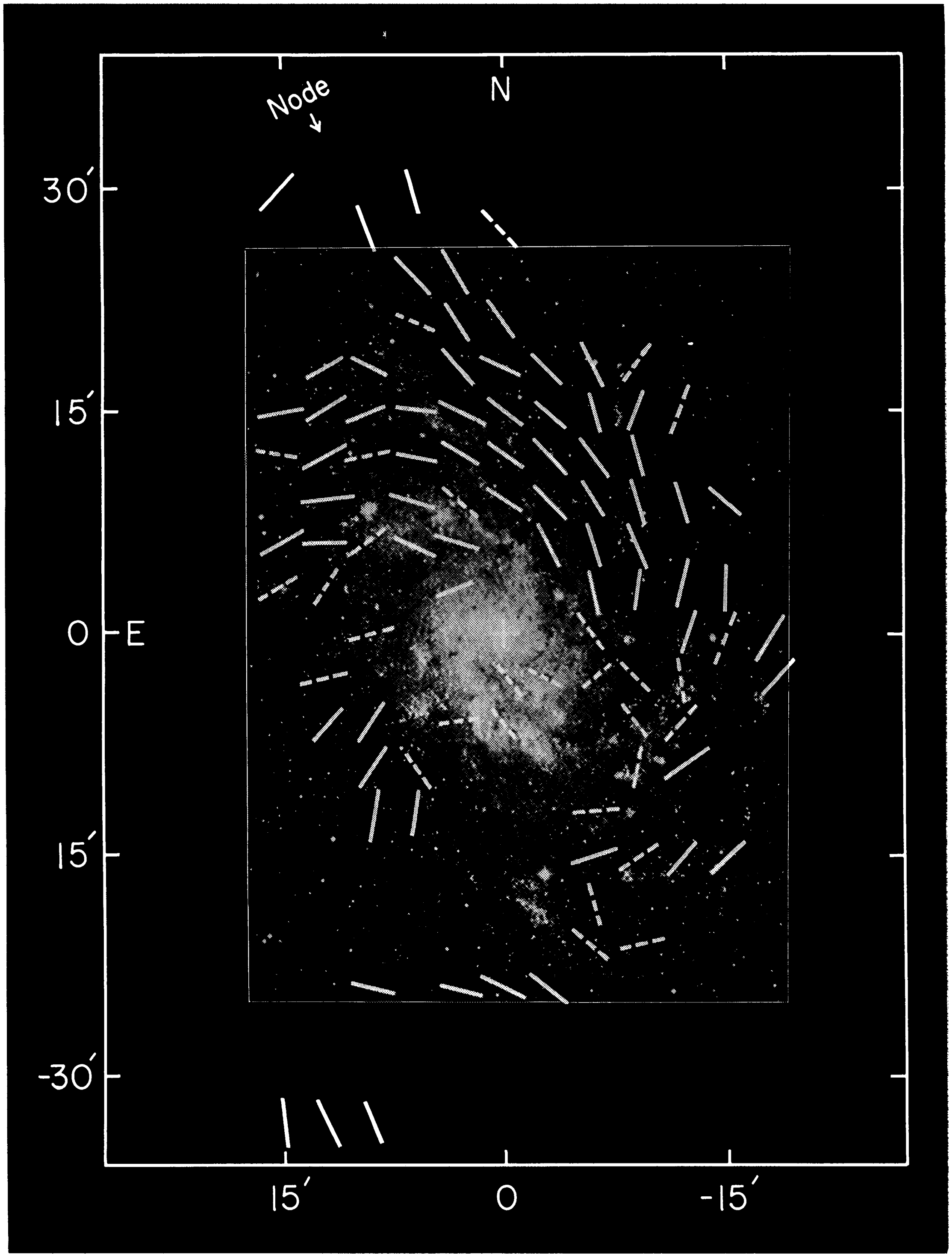


Fig. 2. Distribution of the projected directions of the magnetic field in M 33 superimposed on a photograph [copyright by the Carnegie Institution of Washington; reproduced from Sandage (1961)]. The field directions have been determined by an RM analysis of the linear polarizations at 1.4 and 2.7 GHz. Dashed lines are those with less accuracy because of low polarized intensities. The field is predominantly parallel to the optical arms. Note that the field is more open in the northern-most region.

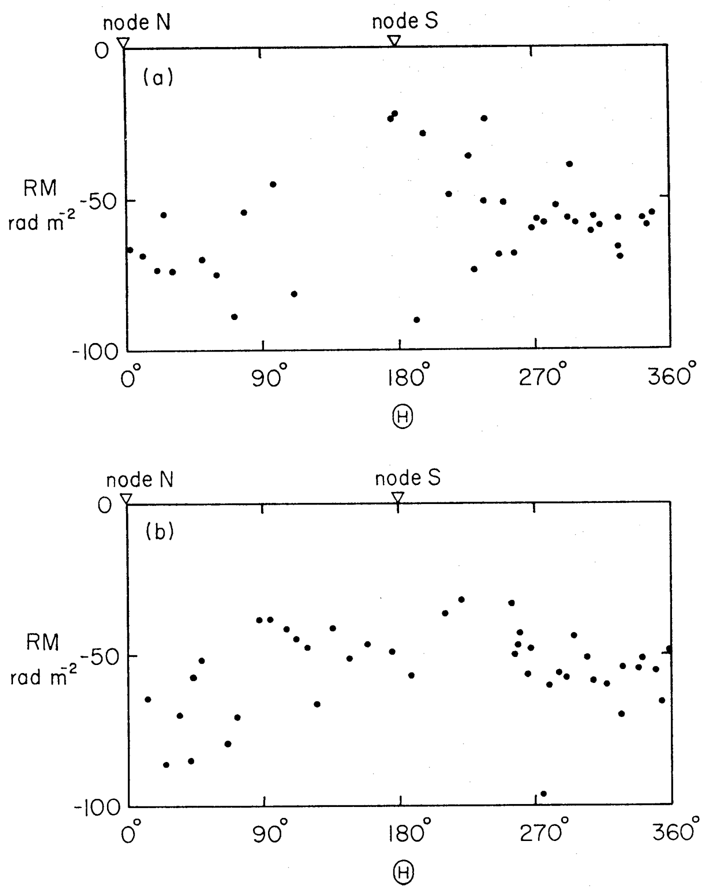


Fig. 3. Faraday rotation measures RM for linearly polarized waves from M 33 as derived from observed polarization planes at 1.4 and 2.7 GHz, plotted against the true azimuthal angle Θ: (a) RM for the inner region of radius 10′–20′ and (b) for the outer region of 20′–30′. The errors in RM are typically 10 rad m^{-2} in the northern part ($220° \lesssim \Theta \lesssim 90°$) and 20 rad m^{-2} in the southern part ($90° \lesssim \Theta \lesssim 220°$) of the galaxy.

superimposed on an optical photograph of M33. The field directions are preferentially parallel to the spiral arms. The large fluctuations in the southern region may be due to the large uncertainty in the RM determination. We note that in the northern-most region ($\Delta\alpha$=0′–10′, $\Delta\delta$=20′–30′), the pitch angle of the field direction is much larger than that in the inner regions. An indication of such a more open structure in the outer region of galaxies is also seen in M51 (Tosa and Fujimoto 1978; Paper I).

In figure 3 we plot the rotation measure as a function of the azimuthal position angle Θ, separately for the inner region of radius 10′–20′ (2–4 kpc) and the outer region of 20′–30′ (4–6 kpc). For the inner region (figure 3a) it is still difficult to recognize any periodicity because of the large scatter in data points at $90° \lesssim \Theta \lesssim 270°$. For the outer region (figure 3b) we find a possible indication of a double-hump variation in RM against Θ: two maxima appear at $\Theta \sim 90°$ and $\sim 240°$, and two minima at $\sim 0°$ and $\sim 170°$; this may be superimposed on a singly periodic component of small amplitude. Such a characteristic pattern, combined with the open spiral field shown in figure 2, is not inconsistent with the existence of a bisymmetric field orientation in the disk of the galaxy (Paper I); the magnetic line of force flows in one half of the disk and flows out on the diametrically opposite half. However, because of scatter and large errors in the data, the strength of the field is still difficult to determine.

4. Discussion

We have shown the existence of a circular magnetic field in the M31 disk (figure 1), and an open-spiral field in M33 (figure 2). Table 1 summarizes the results and compares with those obtained for other galaxies.

The field direction of the circular component in M31 does not change over the Rings I–III as seen from figures 1a–c. This fact implies that the magnetic lines of force run systematically towards us on the SW half of M31 and away from us on the opposite half without any large-scale reversal in between radii 8 and 15 kpc of the galaxy center. Such a large-scale, uniform configuration poses a new problem for the dynamo theory on the origin of magnetic fields; the frozen-in nature as required in the dynamo theory (e.g., Parker 1971, 1979; Stix 1975) predicts a frequent reversal of the field direction due to the differential rotation of the gaseous disk. We note that the circular orientation has only been found in the tightly wound spiral galaxy M31 (table 1). The significance of such a field configuration for the distribution of the H I gas, H II regions, and radio emission in M 31, which are strongly concentrated in the "ring" of radius ~9 kpc (Berkhuijsen 1977), remains open to question.

The open-spiral configuration obtained for M33 is similar to those in M51 and M81, and probably to that in our Galaxy. This fact is in agreement with the hypothesis of the primordial origin of magnetic fields (Ôki et al. 1961, 1964; Zel'dovich 1965; Piddington 1964). We suggest that the intergalactic fields (e.g., Sofue et al. 1979) were frozen into the protogalaxy and have been maintained in

Table 1. Configurations of magnetic fields in spiral galaxies.

Galaxy	Morphological type	Field configuration	Pitch angle α of field lines	RM_0 (rad m^{-2})	Field strength (G)	References*
Our Galaxy ..	Sb	Parallel to the spiral arm	$-15°$	37	3×10^{-6}	(1), (2), (3)
M31..........	Sb tightly wound with an H I ring	Circular along the bright radio ring	$0°$	27	2.2×10^{-6}	(4)
M33..........	Sc	Open-spiral and possibly bisymmetric	$-20°$	—	—	(4)
M51..........	Sc	Bisymmetric and open-spiral	$+20°$	60	5×10^{-6}	(5), (6)
M81..........	Sb	Bisymmetric and open-spiral	$+23°$ (assumed)	37	3×10^{-6}	(6)

* (1) Simard-Normandin and Kronberg 1979; (2) Thomson and Nelson 1980; (3) Manchester and Taylor 1977; (4) Present work; (5) Tosa and Fujimoto 1978; (6) Sofue et al. 1980.

a steady state in its gaseous disk in differential rotation by such a mechanism as proposed by Sawa and Fujimoto (1980) and Fujimoto and Tosa (1980). In fact the field directions in the outermost regions of M33 and M51 seem to have larger pitch angles than those in the inner regions. This might suggest that the magnetic lines of force are connected to intergalactic field lines outside the galaxies. The open-spiral fields are obtained for mildly wound spiral galaxies of morphological types Sb–Sc like M33, M51, and M81 (table 1). The origin of the spiral arms in relation to the magnetic fields in such a spiral configuration is subject to future studies.

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