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Large-scale configuration of magnetic fields in spiral galaxies

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Summary. We propose a simple method to derive the large-scale configuration of magnetic field in a disk galaxy from the characteristic variation of linear polarization angle along major and minor axes. The method tests two assumed models of field distribution, a bisymmetric-open spiral or a ring field configuration, by inferring a Faraday rotation distribution along major and minor axes of the galaxy at a single frequency.

Deep measurements of linear polarization at 5 GHz were made for ten spiral galaxies using the 100-m telescope. Distributions of the polarized intensity and polarization angle along the major and minor axes were obtained for three galaxies NGC 253, NGC 2903, and IC 342. By applying the method proposed we derive that the large-scale field in NGC 2903 is predominant in a bisymmetric and open spiral configuration, while IC 342 has a more ring-like field configuration. Adding to the data in the literature, we conclude that spiral galaxies seem to have either a ring or a bisymmetric spiral magnetic field.

Key words: Faraday rotation – galaxies – magnetic field – linear polarization – radio emission

1. Introduction

The configuration of magnetic fields in spiral galaxies has a significant implication for the magneto-hydrodynamic behavior of interstellar gas and is deeply related to the formation of gaseous spiral arms and magneto-ionic halos (Sawa and Fujimoto, 1980). As to the origin of the magnetic field in galaxies, there seem to exist two controversial points of view: The dynamo theory requires a circular magnetic field whose lines of force may frequently reverse their direction from a circle to another in a galaxy. On the other hand, the primordial-origin hypothesis of the field predicts a bisymmetric spiral field configuration.

To clarify the problem, efforts have been devoted to measure linear polarizations of radio emission from several nearby galaxies. Analyses of the Faraday rotation in the galaxies so far give different answers to the problem: The galaxy M 31 seems to have a circular field configuration, while some galaxies (M 33, M 51, NGC 6946, etc.) have spiral configurations (Beck, 1982; Klein et al., 1982; Tosa and Fujimoto, 1978; Sofue and Takano, 1981; Sofue et al., 1980). Since the sample of galaxies for which the magnetic configuration has been determined so far is limited, we are still in a preliminary stage of knowledge about the large-scale magnetic field of galaxies. Further observations are urgently to shed more light on this problem.

We propose here a new simple method with which we may be able to obtain information about the large-scale field configuration in rather a short time so that we can increase the sample of test galaxies to increase our knowledge about the universal field configurations in spiral galaxies (Sect. 2). The method tests two assumed models of field distributions, a bisymmetric-open spiral or a ring-like field, by inferring a Faraday rotation distribution from polarization measurements at a single frequency along major and minor axes of a disk galaxy.

We performed observations of linear polarization at 5 GHz for several spiral galaxies to determine their field configurations by applying this method (Sects. 2 and 3). A discussion of the general field configuration in spiral galaxies is presented in Sect. 4.

2. The method and observations

We assume that the large-scale magnetic field in spiral galaxies is either in a circular ring or in a bisymmetric open spiral configuration. Then the following simple method of analysis of the linear polarization data will clarify one of the two possible configurations.

Suppose a circularly oriented magnetic field in a disk galaxy as shown in Fig. 1a. Then the line of sight component of the field along the major axis varies asymmetrically with respect to the galaxy centre. The Faraday rotation measure (RM) and position angle of the linear polarization will correspondingly vary antisymmetrically along the major axis as illustrated in the figure, and no change is expected along the minor axis. On the other hand, if the galaxy has a bisymmetric, open spiral magnetic field, these quantities will vary symmetrically along the major as well as along the minor axis with respect to the galaxy centre as shown in Fig. 1b. Thus, if we measure the variation of polarization angle along the major and minor axes, we may be able to distinguish between the two possible field configurations, even if we observe only at one frequency. For that purpose, however, we have to choose an appropriate frequency at which the Faraday rotation is neither too small nor too large. Remembering that the typical "proper RM" ($=\mathrm{RM}_0$) in galaxies is about $10\,\mathrm{rad\,m^{-2}}$ and the observed rotation measure is given by $\mathrm{RM}=\mathrm{RM}_0 \tan i$ with i the inclination of the galaxy, the most appropriate frequency is at around 5 GHz. Here RM_0 is defined through $\mathrm{RM}_0 = 8.1\,10^5\, n_e B_0 L\,\mathrm{rad\,m^{-2}}$, where n_e ($\mathrm{cm^{-3}}$) is the mean

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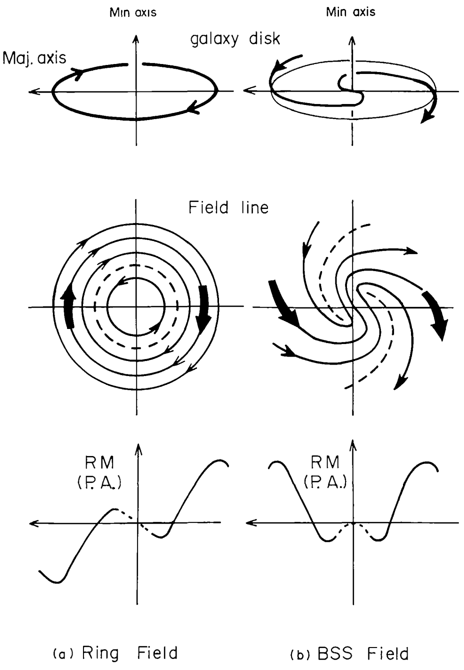

Fig. 1. Two types of the large-scale configuration of magnetic field in disk galaxies. If the field is circularly oriented (**a**), the variation of the polarization angle, the Faraday rotation measure (RM), and rotation angle at a certain frequency along the major axis is anti-symmetric with respect to the galaxy centre. On the other hand, for a bisymmetric, open spiral configuration (**b**), the variation is symmetric

electron density, B_0 (Gauss) is the mean magnetic field strength and L (pc) is the thickness of the disk.

If in addition we have measurements along the minor axis, we can evaluate the amount of Faraday rotation in the disk. Suppose that the polarization angle on the major axis is θ_x and on the minor axis θ_y at the same galactocentric distance. If there were no Faraday effect in the galaxy, we may expect that $\theta_x - \theta_y$ is about 90° in either cases of a ring or spiral field configuration with a small pitch angle. If Faraday rotation occurs, the rotation angle is obtained through $\phi = \theta_x - \theta_y - [\pm 90° \pm 180° \times n]$, with n an integer, and ϕ related to RM and the wavelength λ through $\phi = \lambda^2$ RM. At 5 GHz we may take the smallest absolute value for ϕ as the "most probable" rotation angle, namely $|\phi| = 90° - |\theta_x - \theta_y|$, although we would need more data at different frequencies to get a "true" RM value.

From the scans along the minor axis we can get information about the maximum polarization degrees in the galaxies, as the depolarization due to Faraday rotation within the beam is almost negligible along the minor axis. Furthermore, a comparison of the scans along the major and minor axes give some information about the two-dimensional distribution of the polarization.

The observations were made in August 1983 using the Effelsberg 100-m telescope. The centre frequency and bandwidth were 4.75 GHz and 500 MHz, respectively. The receiver is a 3-channel cooled parametric system which allows the simultaneous observation of Stokes parameters I, Q, and U. The system noise temperature was 70 K. The HPBW was 2.′47. We scanned a galaxy along the major and minor axes for 30 to 60 times at a scan speed of 30′/min. After summation of all scans the effective integration time per beam area was about 200 s resulting in an rms noise of the measurement of about 0.5 mJy/beam. Both ends of each scan were taken to be zero levels and a linear baseline was subtracted from the scan. Because of variations of the baselevels, mainly due to atmospheric emission, the rms noise for the total intensity was higher than the calculated noise. However, an rms of 0.5–1 mJy was attained for the linear polarization measurements which are hardly affected by the atmosphere. The flux values and polarization parameters were calibrated using the radio sources 3C 286 and 3C 48, assuming flux densities of 7.54 Jy and 5.50 Jy, polarization percentages of 11.3% and 4.2% and polarization angles of 33° and 106° respectively for these sources at 4.75 GHz.

3. Results

The observed galaxies are listed in Table 1 together with scan lengths, inclinations, position angles of the major axis, and galaxy types. Figure 2 shows plots of the polarized intensities and position angles of the electric vector measured from the north as functions of distance along the major and minor axes, or X and Y axes, respectively. The errors in the polarized intensities are typically 0.5 mJy. The errors in the position angles can be estimated roughly as $\Delta\theta \cong \Delta S_p / 2S_p$, where S_p is the polarized

Table 1. Parameters for observed galaxies

Galaxy		α_{1950} (h m s)	δ_{1950} (° ′ ″)	Type	Distance (Mpc)	Apparent size (′)	Position angle (°)	Inclination (°)	Scan length X (′)	Scan length Y	arc min per 10 kpc (′)
NGC 253		00 45 05.2	−25 33 48	Sc	4.0[a]/2.4[b]	24.′0	52°	78.°6	34′	15′	8.′6/14.′3
NGC 628	M 74	01 34 00.7	15 31 55	Sc	9.2/7.8	12.1	0	34.9	23	21	3.7/ 4.4
NGC 925		02 24 16.6	33 21 20	Sc/SBc	6.3/6.8	14.8	115	56.0	25	19	5.5/ 5.1
NGC 2903		09 29 19.9	21 43 19	Sbc	7.9/7.0	13.9	17	56.0	25	19	4.4/ 4.9
NGC 4236		12 14 19.2	69 45 00	Sc	2.5/3.3	26.0	162	74.0	37	17	13.8/10.4
NGC 4736	M 94	12 48 32.4	41 23 28	Sb	10.0/4.0	15.0	105	35.1	25	23	3.4/ 8.6
NGC 4826		12 54 16.9	21 57 18	Sb	8.5	12.3	115	59.5	23	19	4.0
NGC 5033		13 11 09.7	36 51 30	Sc	0.0/9.5	12.3	170	58.5	23	17	0.0/ 3.6
NGC 5055	M 63	13 13 34.9	42 17 55	Sb	7.4/4.6	16.0	105	58.6	27	19	4.7/ 7.5
IC 342[c]		03 41 57.6	67 56 24	Sc	4.5	18	40	25	30	30	7.3

[a] Burbidge and Burbidge (1975)
[b] Roberts (1975)
[c] Taken from Gräve et al. (private communication)

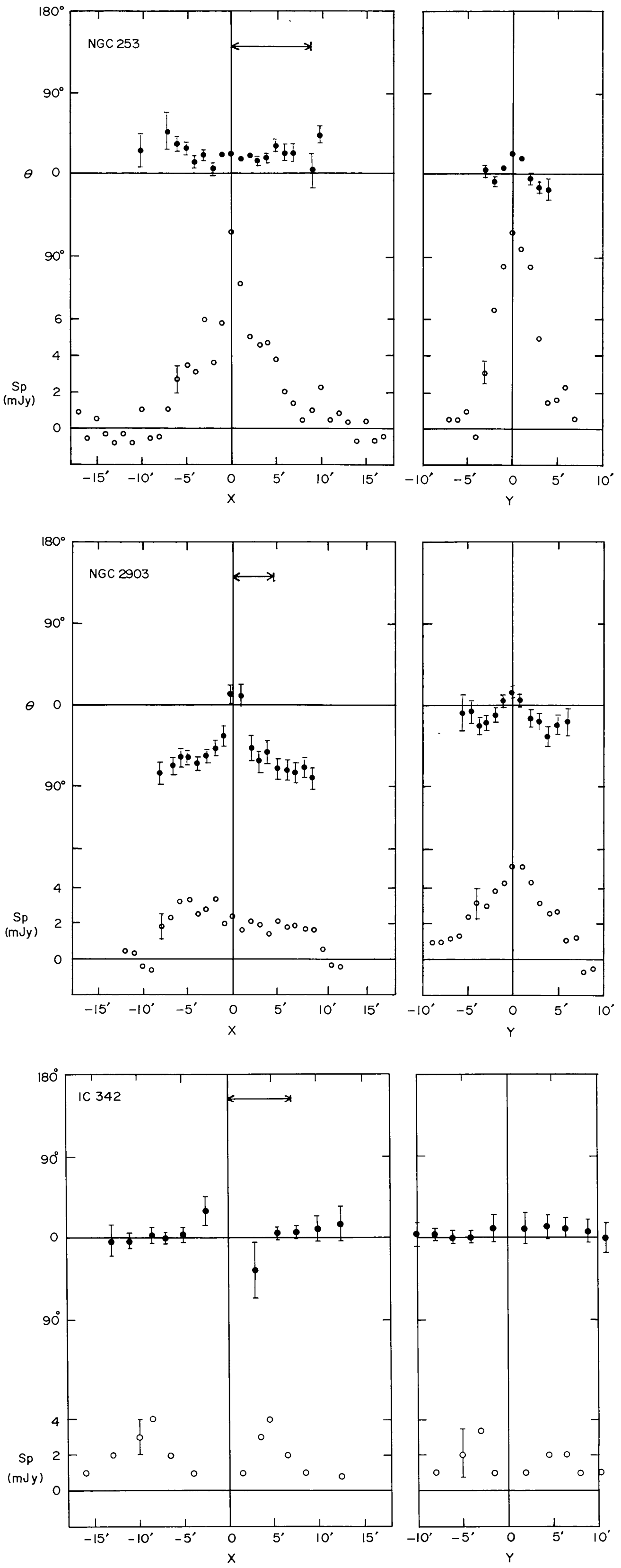

Fig. 2. Measured polarization intensity (S_p in mJy/beam) and polarization angle plotted against the distance along the major (X) and minor (Y) axes for the observed galaxies. The X axis is in the direction of increasing declination and the Y axis is perpendicular to it, composing a right-hand coordinate system on the sky. The arrow indicates a 10 kpc distance along the major axis

intensity and ΔS_p its rms error, and is typically $\pm 10°$ for $S_p = 2$ mJy. Below we describe the individual galaxies.

NGC 253: This very inclined galaxy shows strong nuclear radio emission which might cause spurious polarization near the central region. Therefore we exclude the polarization data for $|x|, |y| < 2'$ from the present discussion. The disk component ($|x|, |y| > 2'$) is detected in polarization with $S_p \sim 5$ mJy/beam, and their polarization angles are well defined. The variation of θ_x along the major axis (X) is small but possibly symmetric with respect to the galaxy centre. This indicates that the ordered magnetic field is rather weak but its configuration is possibly bisymmetric. By comparing with the 10.7 GHz data published by Klein et al. (1983) we obtain a rotation angle of the polarization between 10 and 5 GHz of about 30° for $X = 3$–$5'$ which yields $\mathrm{RM} \approx 150\,\mathrm{rad\,m^{-2}}$. Taking into account that the inclination is 78°.5 and the foreground RM in our Galaxy is small because of the high galactic latitude of the galaxy, we obtain $\mathrm{RM}_0 \approx 30\,\mathrm{rad\,m^{-2}}$.

NGC 628: No significant polarization is detected.

NGC 925: ibid.

NGC 2903: The polarization intensity of the disk is as bright as 2–3 mJy/beam. The polarization angle along the major axis shows a clear symmetric variation and indicates a bisymmetric spiral configuration of the magnetic field. From the comparison of the angles along the major and minor axes we obtain $\mathrm{RM} \sim 130\,\mathrm{rad\,m^{-2}}$ for $|x| = 3$–$7'$ (or 7–15 kpc) and $\mathrm{RM}_0 = 90\,\mathrm{rad\,m^{-2}}$.

NGC 4236: A polarization intensity of 1.5 mJy/beam was detected along the minor axis but no significant polarization along the major axis.

NGC 4735: A polarization intensity of ~ 2 mJy was detected. The polarization angle varies symmetrically along the minor axis, suggesting a possible bisymmetric field configuration.

NGC 4826: No significant polarization is detected.

NGC 5033: Weak polarization of ~ 2 mJy/beam was detected. However, the large scatter in the data makes it difficult to discuss the field configuration, although the plot of θ suggests a bisymmetric spiral field.

NGC 5055: A polarization intensity of 2–3 mJy/beam was detected. The variation of θ_x is symmetric, again suggesting a bisymmetric spiral magnetic field.

IC 342: Gräve and Beck (1984, private communication) have mapped this galaxy at the same frequency with the 100-m telescope. Their data are used to obtain plots of the polarization angle and intensity against X and Y as shown in Fig. 2. Significant polarization of about 4 mJy is detected in a ring-like region at a radius of 5′–8′. The plots of θ_x and θ_y show a clear antisymmetric variation. This fact shows that the field configuration in this galaxy is ring-like.

4. Discussion

The results of the observations are summarized in Table 2. Three galaxies out of ten have significant polarization emission. The variation of the polarization angle along the major axis of NGC 2903 is predominantly symmetric with respect to the galaxy centre. The fact indicates that the galaxy has a magnetic field with a bisymmetric, open spiral configuration. On the other hand, IC 342 shows a clear antisymmetric variation of the polarization angle, which implies a ring-like orientation of the magnetic field. The remaining galaxies show very weak linear polarization and/or a small variation amplitude of the angle, and it is difficult to discuss their field configurations.

Table 2. Observed polarization intensity and field configurations

Galaxy	Polarized intensity (mJy/beam)		Variation of θ along maj. axis	Field configuration[a]
	Maj. axis	Min. axis		
NGC 253	3–5	5	Symmetric?	BSS?
NGC 628	<1.5	<1.5		
NGC 925	<1.5	<1.5		
NGC 2903	2–3	2–4	Symmetric	BSS
NGC 4236	<1	1.5		
NGC 4736	1–2	2		
NGC 4826	<1.5	–		
NGC 5033	1–2	<2		
NGC 5055	1–2	2		
IC 342	4	4	Antisymmetric	Ring

[a] BSS stands for a bisymmetric spiral field configuration

Table 3. Magnetic field configuration in spiral galaxies

Galaxy	Field configuration	Ref.
Our Galaxy	BSS	1
M 31, NGC 224	Ring	2, 3
M 33, NGC 598	BSS	2
M 51, NGC 5194	BSS	4, 5
M 81, NGC 3031	BSS	5
NGC 253	BSS?	Present work
NGC 2903	BSS	Present work
IC 342	Ring	Present work
NGC 6946	BSS?	6

References: 1. Sofue and Fujimoto (1983), 2. Sofue and Takano (1981), 3. Beck (1982), 4. Tosa and Fujimoto (1978), 5. Sofue et al. (1980), 6. Klein et al. (1982)

Table 2 lists all galaxies for which the field configurations have been so far derived. Two galaxies, M 31 and IC 342, have a ring orientation of the magnetic field. We note that M 31 is known for its prominent ring structure at 10 kpc galactocentric distance composed of H I gas and radio emission (Berkhuijsen, 1977; Nakai and Sofue, 1983; Brinks, 1984).

The present observations were made with a 2.'4 beam which gives a linear resolution of ~700 pc at 1 Mpc distance. Since most of our galaxies are ~5 Mpc away we "see" only magnetic field structure at 3.5 kpc resolution. This additional constraint must be remembered when discussing the present data.

We conclude that at present both types of magnetic field structure (closed ring-like and open bisymmetric) seem to be found in nearby galaxies. However, some other simple field model with higher-order variation of Faraday rotation distribution cannot be excluded. The sensitivity of the measurements and the angular resolution must be improved urgently to allow further insight into the exact nature of magnetic fields in galaxies.

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