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The Bisymmetric Spiral Magnetic Field in M31

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Abstract

The radio polarization data of M31 taken with the 100-m telescope at 2.7 GHz (λ 11 cm) are reanalyzed to investigate the magnetic field structure. Variation of polarization angle along an azimuthal circle in the galactic plane can be described as a superposition of a single- and a double-periodic variation. This variation is interpreted as due to a Faraday rotation caused by a bisymmetric open spiral (BSS) magnetic field superposed on the predominant ring field. The coexistence of the two modes (ring and BSS) of magnetic field configurations poses a new aspect on the origin and maintenance of the large-scale magnetic field in a disk galaxy.

Key words: Faraday rotation; Galaxies; Magnetic fields; Radio polarizations; Spiral arms.

1. Introduction

Observations of the linearly polarized radio emission at 2.7 GHz (λ 11.1 cm) of M31 (Beck et al. 1980) showed a large-scale alignment of the magnetic field in the plane of this galaxy. Faraday rotation analyses further have shown that the distribution of the polarization angles is well interpreted by a magnetic field with an axisymmetric ring configuration (Sofue and Takano 1981; Beck 1982) which may follow the spiral arms locally (Berkhuijsen et al. 1987; Loiseau et al. 1987). The ring field appears to be present over a wide range of the radius without any large-scale reversal.

On the other hand, radio polarization observations and Faraday rotation analyses for more galaxies have shown that the majority of the spiral galaxies contain a large-scale magnetic field in a bisymmetric open spiral (BSS) configuration (e.g., Sofue et al.

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1986; Beck 1986). The field flows into the galaxy disk from one end of a spiral and flows out at the diametrically opposite side. The BSS configuration seems most pronounced in the majority of galaxies.

From a theoretical point of view the ring configuration is understood as a result of a dynamo operating in the ground mode which amplifies a weak seed field (Parker 1970; 1971). On the other hand, the BSS field seems to favor a primordial origin hypothesis that an intergalactic magnetic field was trapped by a protogalaxy and wound up by the differential rotation (Piddington 1964, 1981). In fact a large-scale BSS field can be maintained in a steady state, if turbulent diffusion and an exchange process with the halo are taken into account (Sawa and Fujimoto 1980, 1986; Fujimoto and Sawa 1981, 1987). Recently Ruzmaikin et al. (1985) and Ruzmaikin (1987) showed that a disk galaxy can possess a superposition of several fundamental configurations of dynamo modes $m=0, 1, 2, \cdots$, where $m=0$ expresses an axisymmetric field configuration (e.g., ring), $m=1$ expresses the BSS, and $m=2$ a quadrupole, etc. The BSS steady-state theory by Sawa and Fujimoto (1986) and the theory by Ruzmaikin (1987) led to similar solutions, but the origin of the seed field is different in the two theories. Ruzmaikin (1987) proposed supernovae as sources of the seed field, whereas the former BSS theory assumed a primordial intergalactic field.

Although M31 possesses a predominant ring field, the question arises whether higher-order configurations are superposed on the ring. To answer this question we reanalyze the polarization data at 2.7 GHz (λ 11 cm) of M31 taken by Beck (1982).

2. Analysis

The Q and U maps at 2.7 GHz of M31 are used to calculate the polarization angle distribution over the galaxy plane. If the magnetic field is axisymmetric, its

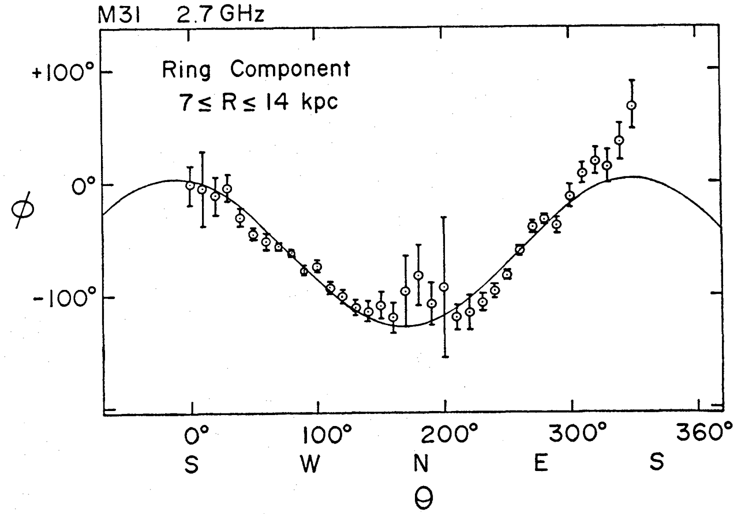

Fig. 1. Observed polarization angles at 2.7 GHz measured from the projected radial vector on the disk plane of M31 for the radius interval R=7–14 kpc plotted against the azimuthal angle θ from the southern major axis. The sinusoidal variation, as the least-squares-fit curve shows, indicates that the ring (axisymmetric) magnetic field is predominant.

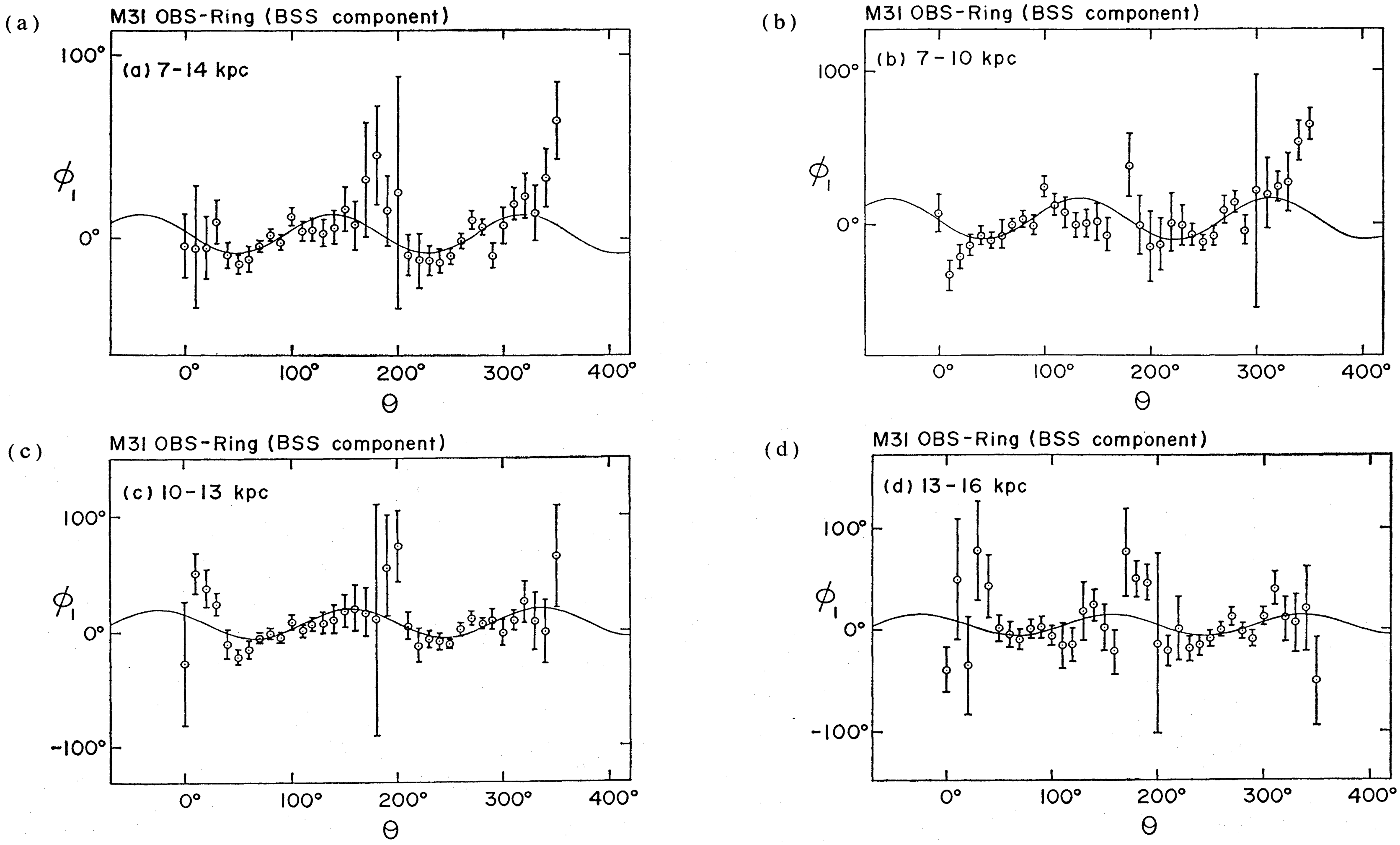

Fig. 2. (a) Residual polarization angles after subtraction of a ring-field component, namely the difference between those in figure 1 and the best-fit sinusoidal curve. The double periodicity in the residual suggests the coexistence of a bisymmetric spiral (BSS) magnetic field. (b)–(d) The same as (a) but for the radius intervals R=7–10, 10–13, and 13–16 kpc, respectively. Note the significant change in the phase of the curves for the inner (R=7–10 kpc) to outer (10–13 kpc and 13–16 kpc) radius intervals.

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Table 1. Best-fit values of A_0, A_1, θ, and ν in equations (1) and (2).*

R (kpc)	A_0	A_1	θ_1	ν
7–10	2°.8±1°.6	13°.5±2°.1	−45°±5°	7°, 187°
10–13	6.8±2.2	12.6±2.9	−24 ±5	49 , 229
13–16	4.3±3.2	10.3±4.2	−23 ±9	51 , 231
7–14	2.4±1.8	10.5±2.3	−41 ±6	15 , 195

* A pitch angle $p=-7°$ of the spiral field was assumed.

Faraday rotation causes a single-peaked sinusoidal variation of the polarization angle ϕ as measured from the radial direction along the azimuthal angle in the plane of the galaxy (Tosa and Fujimoto 1978; Sofue et al. 1986). This was clearly shown to be the case for M31 (Sofue and Takano 1981; Beck 1982). However, a careful inspection of the plots of ϕ against the azimuthal angle θ suggests some systematic deviation from a single sine curve, possibly indicating a higher-order variation.

We have subtracted the best-fit single periodical sinusoid from the observed ϕ–θ plots. Figure 1 shows the original plot of ϕ by Beck (1982) and figure 2a shows thus obtained "residual" polarization angle ϕ_1 plotted against θ averaged over the galactocentric distance range of $R=7$ and 14 kpc. Figures 2b–d show the same, but separately for three radius intervals, $R=7$–10 kpc, 10–13 kpc, and 13–16 kpc.

We can recognize a two-peaked variation in the figures. The variation may be represented in the form of a double-periodic sinusoidal curve,

$$\phi_1=A_0+A_1\cos[2(\theta-\theta_1)] . \tag{1}$$

The quantities A_0, A_1, and θ_1 can be determined by a least-squares fit to the data. Table 1 lists the obtained values of the coefficients. The amplitude A_1 slightly decreases with the radius R, although the errors in the radius interval $R=13$–16 kpc are large. The phase θ_1 also varies from $R=7$–10 to $R=10$–13 kpc. Higher-order variations with $m\geq2$ might be superposed on the data, but the data are too crude to consider them.

3. Discussion

The variation of the polarization angle with the azimuthal angle in figure 2 can be produced in principle by the following effects: (a) a variation of the intrinsic orientation of the magnetic field component $B_\perp$ in the plane of the sky; (b) a variation of the rotation measure within M31 due to a variation of the density of thermal electrons N_e and/or of the magnetic field component $B_\parallel$ along the line of sight.

A prominent two-armed spiral structure could produce a doubly-periodic variation in $B_\perp$, $B_\parallel$ or N_e (or all of them). M31, however, shows a mostly irregular spiral structure with many spiral segments and connections between arms. No systematic variation of N_e is expected in this case, while the magnetic field may well have a BSS configuration. Due to the high inclination of M31, the pitch angle of the magnetic spiral only weakly influences the orientation of $B_\perp$, but is mainly visible in $B_\parallel$, i.e., in the rotation measure.

The double periodicity of the polarization angle found in M31 well suits the Faraday rotation by a BSS magnetic field. Then equation (1) can be rewritten using the pitch angle p of the spiral field and the azimuthal position (at $\theta=\nu$) of a neutral sheet as

$$\phi_1=a_0+a_1 \sin(\theta-\nu) \sin(\theta-p-90^\circ)\ , \tag{2}$$

where a_0 and a_1 are constants. The angles ν and p are related to θ_1 via

$$\nu=2\theta_1-p-90^\circ\ . \tag{3}$$

In the case where the pitch angle of the spiral field is equal to that of the spiral arms, we have $p\sim-7^\circ$ (Arp 1964; Sawa and Sofue 1981), and ν is given in table 1.

Although the neutral sheet position ν varies significantly from the inner radius interval (R=7–10 kpc) to outer circle (R=10–13 kpc), it is still not easy to derive a consistent magnetic field structure. We need definitely more data on the detailed variation of ν with R. The existing data suffer from low resolution and insufficient signal-to-noise ratio so that the disk cannot be separated into narrower radius intervals.

However, the present data are sufficient to postulate the existence of a BSS field superposed on the ring field. In fact Ruzmaikin (1987) has shown that several dynamo modes of a large-scale disk field (mode $m=0, 1, 2, \cdots$) possibly coexist. The higher modes may become dominant in the outer regions of a galaxy. The higher modes are expected to have longer growth times and smaller field strengths so that the ground mode $m=0$ dominates in agreement with the results obtained for M31. As the dynamo theory is linear at present, interactions among the modes have not yet been discussed. External influences such as density waves and tidal interactions with companion galaxies have not yet been included. The existence of dominating BSS field configurations in many galaxies is not in conflict with the dynamo theory. Alternatively to the case of M31, where the BSS mode is superposed on the predominant ring field, it is expected that a ring (or other higher) mode is superposed in many of these galaxies with the dominating BSS field. Reanalysis of the existing data and more accurate and higher-resolution observations of these galaxies may answer this question. The results from the observations of polarized emission of spiral galaxies are a challenge to the theory of magnetic field generation.

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