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The Vertical Large-Scale Magnetic Fields in Spiral Galaxies

Yoshiaki Sofue

Department of Astronomy, Faculty of Science, The University of Tokyo,
Bunkyo-ku, Tokyo 113
and
Nobeyama Radio Observatory, Minamimaki-mura, Minamisaku-gun, Nagano 348–13*

and

Mitsuaki Fujimoto

Department of Physics, Faculty of Science, Furo-cho, Chikusa-ku,
Nagoya University, Nagoya 464

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Abstract

A primordial-origin hypothesis is presented to explain a large-scale magnetic field vertically penetrating the galactic nuclear disk. Based on this hypothesis it is shown that a vertical component of a fossil of an intergalactic magnetic field trapped to a protogalaxy is condensed toward the galactic center through a secular accretion of the disk gas. The strong vertical field thus condensed in the nuclear disk may account for the vertical straight structures observed in our galactic center.

Key words: Active galactic nuclei; Galactic center; Galaxy formation; Magnetic fields.

1. Introduction

Evidence for a magnetic field running perpendicular to the disk plane has been found in the central ~ 100 pc of the Galaxy by recent radio observations (Yusef-Zadeh et al. 1984, 1986; Inoue et al. 1984; Seiradakis et al. 1985; Tsuboi et al. 1986; Sofue et al. 1987b). The field lines are along the radio arc with straight filaments perpendicular to the galactic plane. The field extends both toward positive and negative high latitudes over ~ 100 pc. A smaller-scale poloidal field has also been suggested for a ~ 5 pc region of Sgr A (Yusef-Zadeh et al. 1986). The highly ordered magnetic structure of ~ 100-pc scale running across the galactic plane seems difficult to be accounted for by the current idea like an ejection scenario which attributes vertical structures in galaxies to an energetic blowout due to active processes within the nuclear disk. There has been no model to account for the origin and formation mechanism of such

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* Nobeyama Radio Observatory, a branch of the Tokyo Astronomical Observatory, University of Tokyo, is a facility open for general use by researchers in the field of astronomy, astrophysics, and astrochemistry.

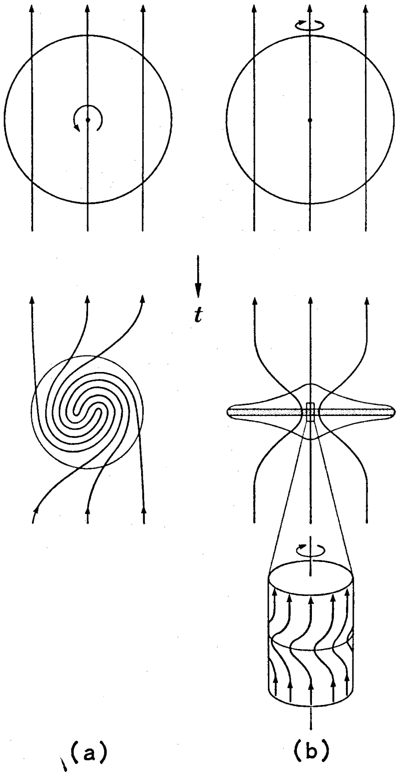

Fig. 1. Schematic illustrations of (a) evolution of a primordial magnetic field parallel to the disk plane of a spiral galaxy and (b) evolution of a vertical magnetic field.

vertical structures observed in the central region.

Piddington (1964, 1981) has long been stressing the importance of a primordial magnetic field as the origin of the galactic magnetic field; a large-scale intergalactic field was trapped to a protogalaxy and wound up to produce a spiral magnetic field. This idea and the field configuration expected therefrom are found to be consistent with the recently discovered bisymmetric spiral (BSS) magnetic field in spiral galaxies [Tosa and Fujimoto (1978); see also Sofue et al. (1986) and the literature cited therein]. Such a global spiral configuration can be sustained without being twisted by differential rotation, if the turbulent diffusion and dynamo regeneration are operative (Sawa and Fujimoto 1986; Fujimoto and Sawa 1987; Fujimoto 1987; Ruzmaikin 1987).

In these works of magnetic fields in spiral galaxies, however, the authors have always been concerned only with the disk field which is mirror-symmetric with respect to the galactic plane. Very little attention has been paid to a large-scale perpendicular component of the magnetic field penetrating the galactic disk, which we call here the vertical field. Such a vertical field would exist, if a more or less uniform intergalactic field was trapped to a protogalaxy in a tilted way with some angle against the rotation plane. This process is considered to be occurring easily from a probabilistic view point, since the trapped field is passive against the collapsing motion of a protogalaxy. In this paper we propose a self-consistent model that the vertical field in the central ~ 100 pc of our Galaxy is a fossil of the primordial field amplified by an accretion of gas to the center. It is to be noted that we are not to reject other models such as a dipole magnetic field generated by the dynamo action in the central gaseous aggregate in rigid rotation and a bisymmetric spiral field of Sawa and Fujimoto (1986) in an odd mode against the disk plane.

2. Primordial Origin of the Galactic Magnetic Field

(i) *Disk Field*

The predominant configuration of magnetic fields in spiral galaxies is shown to be bisymmetric open spiral (BSS) (see Sofue et al. 1986). One of the simple explanations of the BSS configuration is that the field has its origin in a primordial intergalactic field trapped to the protogalaxy and wound up by the galactic rotation (figure 1a). A tightly wound-up field dissipates away into the halo from the galactic disk through the turbulent diffusion and a new loosely twisted field is regenerated by the cyclonic dynamo action and a steady spiral configuration is maintained (Sawa and Fujimoto 1986; Fujimoto and Sawa 1987; Fujimoto 1987). The analysis that these authors conducted is a boundary value problem and therefore the BSS fields are not directly related to the origin. However, their seed field could be due to a primordial uniform field trapped to the protogalaxy. [See also Ruzmaikin (1987) for the supernova-origin hypothesis of the global magnetic field.]

The dissipation time scale of the wound-up field in the disk plane is approximately $\tau \sim \mathrm{Min}\,(h, \lambda)^2/lv$, where h and λ are the half thickness of the disk and the wavelength of the spiral pattern, l and v are the mean free path and the mean square velocity of turbulent eddies, and $\mathrm{Min}\,(h, \lambda) = h$ or λ for $h \lessgtr \lambda$, respectively. In the solar vicinity, τ is of the order of 10^7 yr for $h \sim 100$ pc ($\ll \lambda$), $l \sim 100$ pc, and $v \sim 10$ km s^{-1}. This time scale is much smaller than the rotation period of the Galaxy. This means that the regulation of the spiral field configuration in the galactic disk is made in a shorter time compared to the time scale of the galactic structure variation and the field is no longer frozen into the disk gas. Thus a stationary, open spiral configuration is realized and maintained for the life time of the galaxy (Sawa and Fujimoto 1986; Fujimoto and Sawa 1987).

(ii) *Vertical Field*

Since the diffusion of a vertical, large-scale field component perpendicularly penetrating the galactic disk is made only across the disk edge, the diffusion time is far longer than the above estimate. For the scale length we may take the radius of the galaxy, $\lambda \sim r \sim 10$ kpc. For $v \sim 10$ km s^{-1} and $l \sim 100$ pc, we obtain a diffusion time $\tau \sim r^2/lv \sim 10^{11}$ yr. This means that a large-scale vertical field does not diffuse away but is practically frozen into the disk, and is likely to be conveyed to the central region with the inward-drifting gas (figure 1b).

In the inner region of the Galaxy at $r < 5$ kpc, the galactic shock waves encounter the gas more frequently than in the outer region. Accordingly the time scale of the global contraction of the gas toward the center becomes much smaller than the diffusion time of the magnetic field. As a consequence the large-scale vertical field condenses in the central region, forming a stronger field than in the outer disk. The contraction of the disk gas forms a high-density nuclear disk predominantly occupied by the molecular hydrogen. The nuclear disk has a radius of about 500 pc in our Galaxy

(Sanders et al. 1984). In the nuclear disk, however, the rotation curve shows that of a rigid rotation superimposed on a high dispersion of a turbulent motion of the gas (e.g., Brown and Liszt 1984). The rigid rotation implies that a dynamo action such as in a differentially rotating disk does not work in the central region.

3. Evolution of the Galactic Magnetic Field

We try to describe in more detail a possible evolution of the magnetic field originally trapped from the intergalactic space to a protogalaxy.

(i) Stage A: Protogalactic Sphere

In a very early stage of the protogalaxy formation, when an intergalactic magnetic field was trapped into the protogalactic gas sphere, the field may have been frozen into the gas. Then the field strength in the sphere is given simply by $B_s = B_0 R_0^2 / R^2$. Here R_0 is the radius of the protogalaxy just when it started to contract and is related to the intergalactic gas density ρ_0 through $M = 4\pi\rho_0 R_0^3/3$. For $M = 10^{11}\,M_\odot$ and $\rho_0 = 10^{-5} m_{\rm H}\,{\rm cm}^{-3}$, we have $R_0 = 470$ kpc. For the radius R of the protogalaxy when the initial spherical contraction halted, we may take $R = 20$ kpc. If the intergalactic field strength is of the order of $B_0 = 10^{-9}$ G (e.g., Fujimoto et al. 1971; Sofue et al. 1979), we obtain the initial mean magnetic field in the sphere to be about $B_s \sim 6\times10^{-7}$ G.

(ii) Stage B: Disk Formation

Disk component: As the spherical protogalactic gas cloud collapses, it begins to balance the rotation and soon the flattening proceeds. This results in the amplification of the field component parallel to the disk plane by a factor of R/h with h being the disk thickness. This leads to $B_d \sim B_s(R/h) \sim 3\times10^{-5}$ G for $h \sim 300$ pc and $R \sim 20$ kpc, where B_d represents the disk component of the field. The majority of the disk gas is then transformed to stars leaving a small fraction, 5–10%, in the interstellar space. The magnetic field would escape from the stars via ambipolar diffusion and remains in the interstellar gas. Turbulent diffusion must be operative for the parallel component of the magnetic field at this stage and a substantial portion of the parallel magnetic flux diffuses away back into the intergalactic space, leaving a small portion in the interstellar gas. The remaining interstellar field would become a seed for the disk field in the BSS configuration presently observed within the gas disk. The disk field then follows the induction process discussed by Fujimoto and Sawa (1987).

Vertical component: On the other hand, the component of the primordial field perpendicular to the disk plane is not affected by the flattening of the protogalaxy. The field strength of this component, B_p, is determined only by its flux conservation across the radius. The gravitational mass in the Galaxy is distributed so as to generate a flat rotation curve at $r > 1$ kpc, or $M(r) = rV^2/G$, where $M(r)$ is the mass within the radius r, G is the gravitational constant, and V the constant rotation velocity. The surface density of the disk component is, therefore, given by $dM(r)/d(\pi r^2) = V^2/2\pi Gr$. If the vertical field is frozen into the disk gas whose surface density is expressed in the above equations, we have the radial variation of B_p to be $B_p = 2\times10^{-5} r^{-1}$ (kpc) G. Here the rotation velocity was taken as $V = 200$ km s^{-1}. Then we have $B_p = 2\times10^{-6}$ G at $r=10$ kpc and $B_p=2\times10^{-5}$ G at $r=1$ kpc.

(iii) Stage C: Accretion of the Vertical Field to the Galactic Center

As the spiral arms grow in the stellar disk, galactic shock waves occur in the gas disk. Owing to the shock compression and to the interaction with the wound-up spiral field in the disk, the gas disk secularly contracts toward the galactic center. The frozen-in vertical magnetic flux is then condensed and the field strength is given through $B_p=B_{pi}R_i^2/R_f^2$ with R_i and R_f being the initial and final values of the effective disk radius, respectively.

The distribution of the interstellar gas in the disk in our Galaxy is characterized by a ring of dense molecular and hydrogen gas at $r=5$–10 kpc with a hole in the gas in the central few kiloparsecs and by a sharp concentration near the center as the nuclear molecular hydrogen disk. We suppose that the nuclear disk was formed by a rapid contraction of the gas in the central few kiloparsecs in the past. The nuclear molecular disk has a radius of about 500 pc (Sanders et al. 1984). For an estimate of the vertical field strength in the nuclear disk, we may take $R_i=3$ kpc and $R_i=500$ pc with $B_{pi}\sim10^{-5}$ G. Then we have $B_p=4\times10^{-4}$ G.

4. Discussion

It has been shown that the vertical component of a primordial magnetic field trapped to a protogalaxy is possibly accumulated to the central region of the Galaxy. For a nominal set of parameters we obtain a vertical field strength near the galactic center as large as $B_p\sim$ a few 10^{-4} G. Recent observations of the magnetic field in the central region of our Galaxy have shown that there exists a magnetic field of $\sim10^{-4}$ G running perpendicularly to the galactic plane in the central 100 pc (Tsuboi et al. 1986; Sofue et al. 1987b). The well-ordered, large-scale magnetic structure penetrating the disk plane, with the field direction pointing from negative toward positive latitude, is naturally accounted for by the present scenario of condensation of a primordial vertical field.

The field vertically penetrating the disk is anchored to the halo gas in the space high above the galactic plane, whereas the field is pulled by the dense disk gas that rotates more rapidly than the halo. This velocity difference between the halo and disk twists the magnetic lines of force, resulting in a helical field whose pitch is symmetric with respect to the central plane but the field direction is antisymmetric. Namely an azimuthal component is produced by the differential rotation between the halo and disk (figure 1b). Sofue et al. (1987b) have shown that such a helical field really exists in our galactic center. A twisted vertical magnetic field tightly condensed to the central region is likely to be related to the ejection phenomenon like cosmic jets (Uchida et al. 1985).

There are several edge-on galaxies that have a radio emission structure emerging perpendicular to their nuclei (Hummel et al. 1983; Duric et al. 1983). Our Galaxy possesses also a similar vertical structure out of the plane (Sofue and Handa 1984; Sofue 1985). These structures may be due to ejections from the central regions perpendicular to the nuclear gas disks. Many spiral galaxies possess a highly condensed molecular gas disk in the center (e.g., Sofue et al. 1987a). These galaxies show more or less an activity in the nucleus as indicated by a strong radio source at the center which could be related to their magnetic fields. Linear polarization measurements to determine the magnetic field structure in these central regions may clarify this problem.

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