VERTICAL MAGNETIC FIELDS IN SPIRAL GALAXIES

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ABSTRACT. Evolution of a vertical magnetic field which may have existed in the primeval galaxy is discussed based on a primordial-origin hypothesis for the bisymmetric spiral configuration of magnetic fields in spiral galaxies. The vertical field is accumulated toward the nucleus and forms a strong poloidal field, which may trigger activities like jets. Quasar jets are suggested to be the result of such strong vertical fields in the cores of primeval galaxies.

1. BSS Magnetic Fields and the Primordial-Origin Hypothesis

The magnetic field configuration of spiral galaxies is shown to be predominantly bisymmetrc spiral (BSS), while a few ring and axisymmetric cases are reported (Sofue et al 1986). As to the origin of the BSS configuration we may envision two possibilities: (a) a primordial field trapped into a primeval galaxy and wound up by the disk rotation, where a steady spiral configuration is maintained by the dynamo action; and (b) a dynamo-generated large-scale spiral field which was created from infenitesimally weak random fields (Ruzmaikin et al 1985; Sawa and Fujimoto 1986). In this paper we discuss the field configuration in spiral galaxies on the basis of the primordial origin hypothesis (a). We discuss the possible evolution of the field, particularly a field perpendicular to the disk plane. We suggest that the frozen-in and amplified vertical field near the galactic centers of primordial galaxies may have been related to the strong ejection phenomena of jets in quasars.

2. Evidence for Vertical Fields in spiral Galaxies

(i) *Vertical Structures out of the Galactic plane*: The radio-continuum maps of the Milky Way show vertical structures emerging from the galactic plane (Sofue 1988). Their appearence parallel to each other suggests their coherent origin, likely driven by magnetic lines of force emerging normal to the disk plane.

(ii) *Vertical Structures in External Galaxies*: External edge-on galaxies often show vertical dust lanes. Long, coherent and thin filaments running normal to the disk of some dust-rich spirals suggest the exitence of a large-scale vertical field running across the disk plane (Sofue 1987). These vertical structures are found at radii of a few kpc and run for more than a kiloparsec in the halo.

(iii) *Vertical Magnetic Fields in the Galactic Center*: In more inner regions of the Galaxy direct evidence for a vertical field has been found with high-resolution

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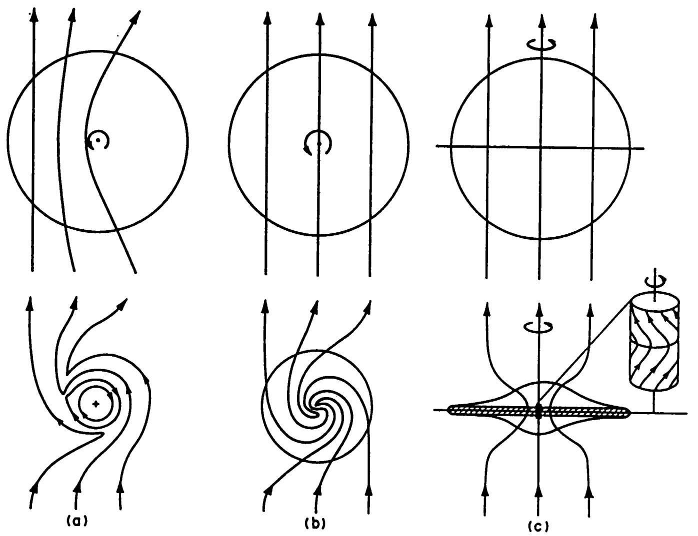

Fig.1. Primordial magnetic field trapped into a protogalaxy and its evolution: (a) and (b) disk field component; (c) vertical field component.

and/or polarization observations of the synchrotron radio emission: A large number of straight filaments extending for a hundred pc scale run almost perpendicular to the disk plane near the Arc and are well understood as the trace of a magnetic field running vertical to the disk (Yusef-Zadeh et al 1984). Some parts of these structures show strong polarization and Farday roatation directly showing the poloidal magnetic field (Tsuboi et al 1986; Sofue et al 1987; Reich 1989).

(iv) *Vertical Magnetic Fields in Nuclei of External Galaxies*: Polarization observations of the nuclear radio source in M31 shows the magnetic field orientation perpendicular to the major axis (Berkhuijsen et al 1987). Since the galaxy is nearly edge-on, this may be attributed to a poloidal magnetic field in the nucleus. Besides M31, however, no obvious magnetic structures are known for nuclei in external galaxies.

(v) *Vertical Ejections from Nuclei of Galaxies:* Nuclei of spiral galaxies often reveal jet-like features emerging perpendicular to the disk plane and/or central radio sources elongated perpendicular to the major axis (e.g. Hummel et al 1983). These ejection features may be the manifestation of a vertical field running across the nucleus.

3. Evolution of Magnetic Fields in Spiral Galaxies

(i) *Primordial-Origin Hypothesis for the Galactic Magnetic Fields*: On this hypothesis the BSS field configuration is interpreted as the fossil of an intergalactic field wound up by the primordial galaxy disk (Fig.1). The field is then maintained in a steady state by the induction-dynamo mechanism (Fujimoto and Sawa 1987; Sawa and Fujimoto 1986). Even a ring field can be produced from the primordial one, if we allow for an initial asymmetry with respect to the center (Fig.1).

(ii) *Vertical Component of the Primordial Magnetic Fields in Galaxies*: It is natural that a large-scale field component parallel to the rotation axis existed, when

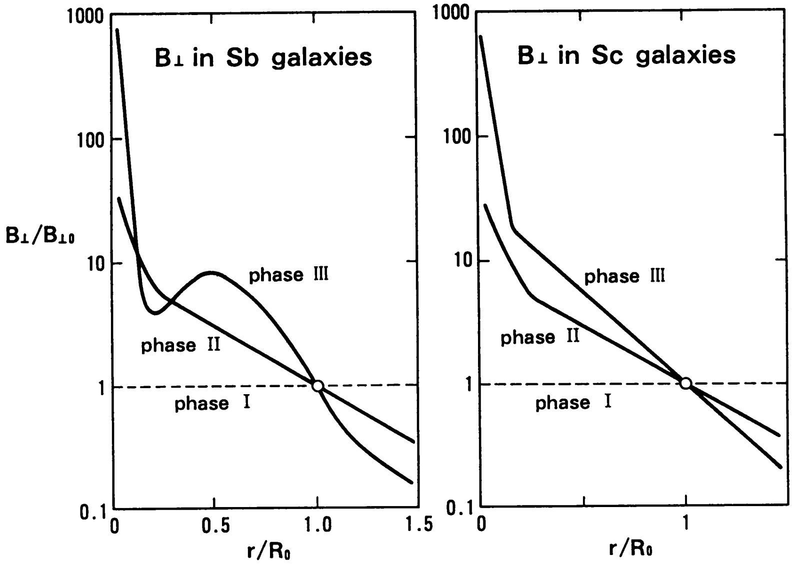

Fig.2. Evolution of vertical magnetic field strength as a function of radius normalized to the strength at a radius R_0.

a galaxy formed. This field component is also trapped to the primeval gas sphere [phase I]. Since the disk radius is large enough and the diffusion time is longer than the galaxy evolution time, the vertical field is almost frozen into the disk gas. The vertical field then follows an evolution as described below (Sofue and Fujimoto 1987).

(iii) *Evolution of Vertical Fields in Primeval Galaxies*: Starting from a uniform gas sphere (disk) and initial star formation in a proto galaxy, an exponential disk is realised by the viscosity-driven angular momentum transfer and on-going star formation (Yoshii and Sommer-Larsen 1989). Since the field is frozen into the gas, the magnetic flux conservation results in a radial distribution of the field strength obeying the exponential law, provided the initial field was uniform [phase II] (Fig.2). In the central region the gas density attains an excess by an order of magnitude over the value given by a simple exponential disk (Yoshii and Sommer-Larsen 1989), and the field strength is correspondingly high. The initial star formation then finishes when the gas is fed into stars and the density decreases to a certain threshold value, after which the magnetic field is no more frozen into the stellar disk.

(iv) *Strong Vertical Fields near the Galactic Nuclei*: The vertical magnetic field is then frozen into the gas left behind the initial star formation. At this stage the gas may have a constant threshold density below which the initial star formation did not take place, and shares a few percent of the total mass. The "interstellar" gas then follows its own evolution governed by the density wave shock, cloud-cloud collisions, and star formation. Through the shock- and viscosity-driven inflow the gas accretes toward the center. In the central region a bar-induced shock will enhance the accretion. Since the diffusion time of the vertical field is shorter than the dynamical time scale, this results in a formation of a strong vertical field in the center [pahse III] (Fig.2). In the early universe when galaxy formation took place, galaxy-galaxy collision will have been frequent and the tidal encounter may have enhanced the bar-induced inflow of gas (Noguchi 1988), and therefore strong vertical field near the center.

If the present intergalactic or intracluster magnetic field is of the order of $10^{-9\sim-10}$ G (Sofue et al 1979), the vertical field strength in the central 1 kpc of normal spiral galaxies is expected to be of the order of mG, which dominates in the central region. On the other hand spiral fields within the disk is weaker in the central few kpc (Sawa and Fujimoto 1986), while it dominates in the outer disk.

(v) *Loss of Angular Momentum by the Vertical Fields:* The interstellar gas in turn suffers magnetic torque from the vertical field which is twisted by the galactic rotation. The time scale with which the rotating gas element loses angular momentum is given by $\tau = Vr/(B^2/4\pi\rho)$, where V, r, B, and ρ are the rotation velocity, radius, magnetic field strength, and gas density, respectively. The time is then calcularted to be $\tau \sim 10^{11}, 10^8$, and 10^5 years, respectively at $r = 5$, 1 and 0.1 kpc. This shows that the magnetic torque is not negligible in the inner region of the galaxy, and the accumulation of vertical field is accelerated by the magnetic-torque/angular-momentum-loss mechanism.

4. Nuclear Activities and the Vertical Fields

(i) *Jets from the Nuclei*: The twisted vertical magnetic field near the nucleus accelerates a screwing outflow of gas, and results in a vertical jet from the nucleus (Shibata and Uchida 1988). This mechanism will explain many of the observed vertical radio features near the nuclei of spiral galaxies.

(ii) *Quasars and Jets*: It is suggested that quasars are nuclei of distant galaxies. According to our scenario about vertical field component in protogalaxies, nuclei of these galaxies may have a strong vertical field and intense accretion of gas at its initial stage. This particularly applies in such a stage when the central density enhancement of the primeval exponential disk is present. Long, energetic jets from quasars could be the manifestation of such an intensive accretion of vertical magnetic fields in the nuclei of protogalaxies.

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SHUKUROV: If the vertical magnetic field is frozen-in and advected toward the Galactic center, the azimuthal field must have the same fate: It is impossible that one component is maintained by the dynamo while the other component is frozen-in. Thus, dominance of the azimuthal field, typical for the outer parts of galaxies, should be preserved in galactic centers if your picture is correct. Does this agree with observations?

SOFUE: A detailed magnetic field in the center of a galaxy is available only in our Milky Way center at the moment, where we see a clear poloidal field of scale 100–300 pc, while no dominance of a toroidal field. For the dynamo to be operative, the magnetic field must be passive against gaseous motions. However, in the Galactic center the vertical field seems to dominate over the turbulent motion of gas. The azimuthal fossil may possibly exist even in the center. However, the azimuthal component has been tightly wound and may have reconnected away near the center, while the vertical fossil had no chance to reconnect. On the other hand, outer-disk fields, where the disk component (azimuthal) far exceeds the vertical, are likely to be maintained in a steady state by the dynamo.

RUZMAIKIN: A crucial observation which can select the relict or dynamo approach is the B_z component above and below of the Galactic disk (not near the Galactic center). The relict hypothesis predicts different signs; dynamo predicts the same signs (the even poloidal field).

SOFUE: The relict $B_\perp$ can be observed only in the central ~1 kpc region. In fact our Galactic center shows a strong, large-scale vertical field consistent with the relict model. In the outer disk the relict $B_\perp$ will be small and the one produced by the dynamo may dominate. Therefore it seems not possible to discriminate the models by observing outer disks. However, in my opinion, it seems not necessary to deny any of the possible mechanisms to explain the observations, although I simply pointed out that the vertical field observed in our Galactic center may not be easily explained by the dynamo. Note also that I am not opposing the dynamo, which should certainly play an essential role in maintaining the large-scale spiral pattern of the galactic field. I also mention that the very coherent BSS configuration over an entire galaxy disk must be explained: the dynamo is a local theory, and has no way to physically connect the field configuration at one edge of a disk to the one at the opposite edge more than ~20 kpc apart. For such a large-scale coherency the primordial-origin hypothesis seems to give the answer: the BSS (or ring) nature is the relict of a primordial field and has been maintained via the dynamo to date.

M. KRAUSE: Our observations of the rotation measures in IC 342 indicate that the azimuthal magnetic field component has the same handedness above and below the galactic plane as expected in an *even* ASS field configuration. This field configuration implies an *even* poloidal field going upwards above the plane and downwards below the plane.

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MOUSCHOVIAS: In your estimate for loss of angular momentum by the core of your galaxy, what values of gas density have you used for the galactic core and for the external medium?

SOFUE: The angular momentum loss and accretion of gas towards the center are due mainly to the dynamical effects of the gas and nonaxisymmetric potential of the galaxy. However, the magnetic torque will play some role in the central few kpc region. If the field is anchored to the halo or to intergalactic medium, the time scale of angular momentum loss is simply estimated by the magnetic torque [in this respect refer to the paper by Fujimoto and Sofue (this volume)]. If we use the formula $\tau \sim (\rho_{disk}/\rho_{ambi})^{1/2}\, R/V_{A,ambi} \sim R/V_{A,disk}$ with $\rho_{disk} \sim 10$ and $\rho_{ambi} \sim 10^{-3}$ (halo) to 10^{-5} (IGM) H cm^{-3}, we obtain a time scale of $\tau \sim 10^{7-8}$ yr for $B \sim 0.1-1$ mG and $R \sim 1$ kpc. Indeed the wave propagation under milli-Gauss circumstances is very fast. [Note that your estimation by $\tau \sim (\rho_{disk}/\rho_{ambi})\, R/V_{A,ambi}$ included a mistake (omission of the square root in the density term).]

MOUSCHOVIAS: I disagree. The external density matters a lot; the characteristic time for magnetic braking of an aligned rotator is the time required for the torsional Alfvén waves to affect a moment of inertia of the external medium equal to the moment of inertia of the galactic core (see Mouschovias and Paleologou, 1980, Astrophys. J. **237**, 877). If, for example, you use $n_{ext} \sim 10^{-5}$ cm^{-3}, the waves would have to travel a distance $n_{core}/n_{IGM} \sim 10^6$ times the size of the core before magnetic braking is noticed.

MORRIS: The objection raised by Mouschovias to your hypothesis that primordial poloidal magnetic fields are concentrated in galactic nuclei is based on the assumption that the angular momentum of the galactic gas to which the magnetic field is tied is lost by magnetic braking. This is an unnecessary assumption, as many other, non-magnetic processes lead to a net transfer of angular momentum outwards: turbulent viscosity, spiral density wave shocks or shocks associated with bars, etc.

SOFUE: Yes. The primordial (fossil) field gets concentrated in the galactic center mainly by the mass (gas) concentration during the galaxy contraction and disk formation, because the large-scale vertical field is frozen into the gas. Thereafter, further accretion of interstellar gas proceeds which also carries the fossil toward the center via the mechanisms as Dr. Morris correctly points out. In addition, I said that the amplified poloidal field, when it becomes strong enough and is not completely passive against the gas motion, will act in turn as the carrier of angular momentum from the disk to the halo. This promotes a more rapid accretion of gas and field. The time scale of this angular momentum loss is fairly short.