GALACTIC RADIO ASTRONOMY

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Contents

Chapter 6

NONTHERMAL EMISSION AND MAGNETIC FIELDS

Radio observations of the synchrotron radiation from the galactic disk and its polarization give us information about the magnetic field structure. Analyses of polarization vectors and of Faraday rotation measures along the line of sight give us information about three-dimensional orientation of magnetic fields in galaxies.

6.1 Synchrotron Emission and Polarization

6.1.1 Synchrotron intensity and magnetic field strength

The intensity of synchrotron (non-thermal) emission is related to the electron density N, electron energy E and the magnetic field strength B as

$$I_\nu \propto B^2 E_E^2 N. \tag{6.1}$$

On the assumption that the magnetic and cosmic-ray energy densities are in equilibrium,

$$\frac{B^2}{8\pi} \sim N_E E (= \int_{E_1}^{E_2} E\ N(E) dE) \tag{6.2}$$

and

$$\nu \propto B E^2, \tag{6.3}$$

we have an approximate formula which relates B and intensity I of the emission:

$$B \sim 3.3 \times 10^2 \nu_{1\ \mathrm{GHz}}^{-1/7} \varepsilon^{2/7}\ \ (\mathrm{G}), \tag{6.4}$$

where

$$\varepsilon = \frac{\int I_\nu d\nu}{L} \sim \frac{\nu I_\nu}{L}\ (\mathrm{erg\ s^{-1}\ cm^{-3}}) \tag{6.5}$$

is the emissivity with L being the line-of-sight depth of the emitting region.Thus, the field strength can be estimated from the synchrotron emissivity (intensity) of the source.

The brightness temperature of the sky at the galactic poles of the Galaxy at $\nu = 1$ GHz ($\sim$ face-on brightness of the Galaxy at the sun) is $T_{\mathrm{B}} \sim 10$ K. So, if we take a thickness of the radio disk to be 500 pc, the emissivity is

$$\varepsilon \sim \nu I_\nu / L \sim 2kT_{\mathrm{B}}\nu/\lambda^2 L \sim 2 \times 10^{-30}\ \mathrm{erg\ s^{-1}cm^{-3}}. \tag{6.6}$$

From the above expressions we obtain $B \sim 1\ \mu$G for an averaged value in the thick disk. If the disk is as thin as $L \sim 200$ pc, then $B \sim 1.4\ \mu$G. From a more precise estimation the local magnetic field strength has been obtained to be about 3 μG.

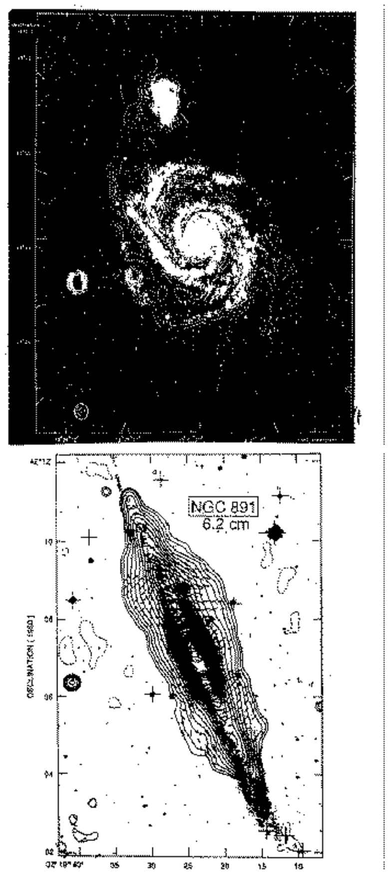

Figure 6.1: Radio continuum emission in galaxies. (a) M51: a face-on view, and (b) NGC 891: an edge-on view.

6.1.2 Linearly Polarized Emission

A single electron emits a polarized radio wave, whose electric vector is parallel to the direction of acceleration, and so the wave is polarized perpendicular to the lines of force of magnetic field. For an ensemble of electrons with an energy spectrum of the form $N(E)dE \propto E^{-\beta}dE$, the total synchrotron intensity has the maximum polarization degree of

$$p_{\max} = \frac{\beta+1}{\beta+7/3} = \frac{-\alpha+1}{-\alpha+5/3}, \tag{6.7}$$

where $\beta \sim 2.4$ for the solar vicinity value and $\alpha = -(\beta-1)/2 \sim -0.7$ is the spectral index of the emission ($I_\nu \propto \nu^\alpha$). Therefore, the maximum polarization degree from a source with an ideally aligned magnetic field is 70%. However, interstellar magnetic fields are usually not so well aligned, but are more tangled and random. Also the galactic radio emission is the mixture with thermal radiation. So, the galactic emission is usually polarized by about $p \sim$ a few %.

In such a region as the galactic center where the radio spectrum is flat, the maximum polarization degree is smaller. For example, the Radio Arc has a spectral index of $\alpha \sim 0.2$, which yields the maximum polarization degree of $p_{\mathrm{maz}} \sim 54\%$. Polarization observations at 30 - 50 GHz using the 45-m telescope at Nobeyama and with the Bonn 100-m telescope have shown that the Arc is polarized by about 50%. This high degree of polarization indicates that the Arc consists of almost perfectly aligned magnetic lines of force. Such field lines of force have been indeed observed with the VLA.

The direction of intrinsic polarization vectors is perpendicular to the magnetic field direction. Hence, if we can correct for the Faraday rotation as described below, we can obtain the direction of the magnetic field as projected on the sky.

6.1.3 Faraday Rotation

A linearly polarized radio wave can be expressed by a superposition of two circularly polarized waves whose electric vectors rotates in the clock-wise and counter-clock wise directions, respectively, which are called the right-hand (R) and left-hand (L) polarizations, or waves of ordinary and extra-ordinary modes. If an ISM involves both ionized gas (including partially ionized one) and magnetic field, the ISM is not isotropic for the wave propagation, because the magnetic field defines a certain fixed direction in the medium. Since thermal electrons of the gas rotate in the same direction around the field lines of force by Lorenz force, interaction by the R mode electric wave vector is different from that by L mode waves. This situation causes a Faraday effect on the prpgating wave, so that the refractive indices n of the R and L waves are different:

$$1 - n^2 = \frac{1.24 \times 10^4 n_{\rm e}\ ({\rm cm}^{-3})}{\nu^2 (1 \pm \nu_{\rm H} \cos\theta)}, \tag{6.8}$$

where *theta* is the angle between the line of sight and field direction, and $\nu_{\rm H}$ is the Larmor frequency of the field B. Because of a phase shift of the two modes, the resultant linear polarization vector rotates as the wave propagates. This is called the Faraday rotation of linearly polarized radio waves, and the variation of the position angle ϕ of the wave is given by

$$\phi = \phi_0 + RM\lambda^2, \tag{6.9}$$

where $\phi_0 = \phi_{\rm mag} + 90^\circ$ is the intrinsic polarization angle with $\phi_{\rm mag}$ being the position angle of the field lines projected on the sky. RM is called the rotation measure, and is given by

$$RM = 0.81 \int_0^x n_{\rm e} B_{\rm p} dx\ ({\rm rad\ m}^{-2}). \tag{6.10}$$

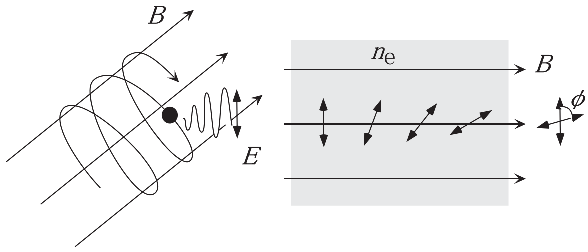

Figure 6.2: Linear polarization and Faraday rotation.

Here, n_e (in cm^{-3}) is the thermal electron density, x (in pc) is the distance along the line of sight, $B_p = B \cos\theta$ (in μG) is the line-of-sight component of the field.

RM is defined to be positive when the field line runs away from the observer, and RM is negative if the field line is toward the observer. If we observe position angles ϕ of linearly-polarized radio waves at different wavelengths and plot it as a function of λ^2, we can determine $RM \sim 0.81 n_e B_p L$. If we assume a certain value for the thermal electron density n_e and the depth L, we can approximately determine the line-of-sight component of the field.

6.1.4 Determination of Magnetic Field Oeientation

In galaxies and ISM, radio emitting sources are mixture of synchrotron source and thermal gas. In such circumstances, the three-dimensional orientation of the magnetic field can be determined as follows:
(a) Observed intensity I_ν of synchrotron radiation gives the field strength $B = (B_t^2 + B_p^2)^{1/2}$.
(b) Intrinsic polarization angle $\phi_0 - 90°$ gives the transverse direction of the field line on the sky B_t.
(c) Faraday rotation measure RM, which is determined from multi-wavelength measurement of polarization angle, gives the line-of-sight

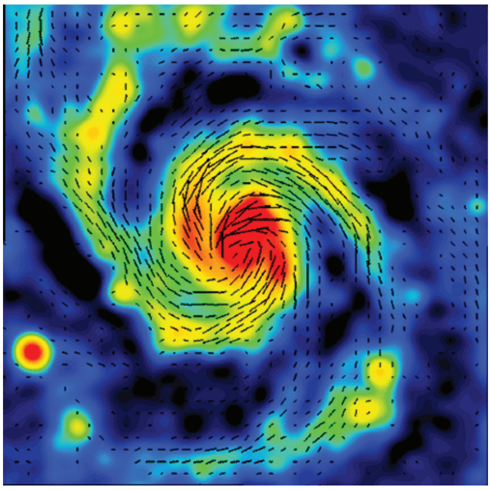

Figure 6.3: Transverse component of magnetic fields in a spiral galaxy, indicating a spiral field configuration (R. Beck: MPIfR home page).

field component B_{p}.

6.2 Magnetic Fields in Disk Galaxies

6.2.1 RM in Disk Magnetic Field

The magnetic field configuration in disk galaxies can be determined by the Faraday rotation observations, which give us information about the transverse and line-of-sight components of the field as described above. A widely adopted method to determine magnetic field configuration is called the RM vs Θ (azimuthal angle) method. In this method we plot the value of RM (or equivalently $\Delta\phi = \phi-$ arbitrary const.) as a function of Θ, where Θ is the azimuthal angle along a circle on the disk plane of the galaxy at a fixed radius.

If the magnetic field of the galaxy disk is either a ring or axisymmetric (as if the field apparently have non-zero divergence), RM shows a single sinusoidal variation with Θ. If the field is a bisymmetric spiral (BSS) configuration, in which the field line flows in from one edge of the galaxy and flow out from the opposite edge, the RM variation is double peaked sinusoidal.

There have been a number of galaxies for which the field configurations have been determined in this way. The Galaxy, M51, M81, NGC 4258, etc have a BSS field; M31 has a ring field, and NGC 6946 appears to show a spiral field with an apparent non-zero divergence.

6.2.2 BSS Magnetic Fields and the Primordial Origin Hypothesis

The magnetic field configuration of spiral galaxies is shown to be predominantly bisymmetric spiral (BSS), while a few ring and axisymmetric cases are reported. 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 infinitesimally weak random fields.

The BSS configuration in spiral galaxies can be more naturally understood on the basis of the primordial origin hypothesis. The primordial hypothesis can also explain the ring configuration as the result of a reconnection of field lines wound up in the inner region of the galaxy.

6.2.3 Vertical Fields in spiral Galaxies

In addition to the disk fields, numerous evidences for vertical magnetic fields have been observed, which may be more or less related to the activities of the disk and the nucleus.

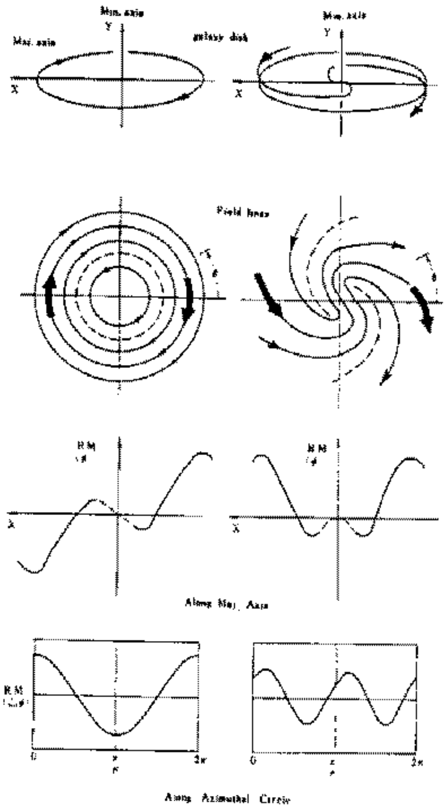

Figure 6.4: Variation of RM with Θ according to the field configuration (ring and axisymmetric, or BSS)

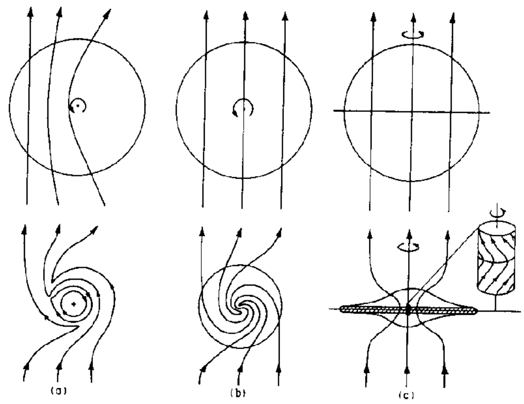

Figure 6.5: Primordial origin of the BSS and ring fields in galaxies. Primordial magnetic field trapped into a protogalaxy: (a), (b) Field in the disk; (c) Vertical field.

Vertical Structures out of the Galactic Disks

The radio-continuum maps of the Milky Way show vertical structures emerging from the galactic plane. Their appearance parallel to each other suggests their coherent origin, likely driven by magnetic lines of force emerging normal to the disk plane.

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 existence of a large-scale vertical field running across the disk plane. These vertical structures are found at radii of a few kpc and run for more than a kiloparsec in the halo.

Vertical Magnetic Fields in the Galactic Nuclei

In the central region of the Galaxy direct evidence for a vertical field has been found with high-resolution 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. Some parts of these structures show strong polarization and Faraday rotation directly showing the poloidal magnetic field .

Polarization observations of the nuclear radio source in M31 shows the magnetic field orientation perpendicular to the major axis. 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.

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. These ejection features may be the manifestation of a vertical field running across the nucleus.

6.2.4 Magnetic Fields in the Galactic Halo

Observational data for halo fields are still crude. A few edge-on galaxies like NGC 4631 show extended nonthermal radio halo. The field strength from the radio emissivity is estimated to be a few μG. There are many galaxies for which no evidence for radio halo is seen.

Magnetic fields in the halo of the Galaxy can be derived from RM analysis for external radio sources and pulsars. If we plot $\mid RM \mid$ (rotation measure) against $\mid \cot b \mid$ for radio galaxies and quasars, the upper envelope of the plot can be fitted by a relation,

$$\mid RM \mid_{\mathrm{RG,Quasar}} \simeq 30 \mid \cot b \mid \ \ (\mathrm{rad\ m}^{-2}). \tag{6.11}$$

On the other hand if we plot the same for pulsars, we obtain

$$\mid RM \mid_{\mathrm{Pulsar}} \simeq 10 \mid \cot b \mid \ \ (\mathrm{rad\ m}^{-2}). \tag{6.12}$$

The difference between the coefficients for the two plots is considered to be due to Faraday rotation in the space above a disk of thickness of about 500 pc in which most of pulsars are distributed, namely it may be due to a halo beyond a few hundred pc from the galactic plane:

$$\mid RM \mid_{\mathrm{Halo}} \sim 20 \mid \cot b \mid . \tag{6.13}$$

If we take an electron density and a thickness of the halo to be approximately 10^{-3} cm^{-3} and a few kpc, respectively, the field strength in the halo is estimated to be a few μG, about the same as in the disk.

6.3 Evolution of Magnetic Fields in Spiral Galaxies

6.3.1 Primordial Origin of Galactic Magnetic Fields

On the primordial hypothesis, the BSS field is interpreted as the fossil of an intergalactic field wound up by the primordial galaxy disk. The

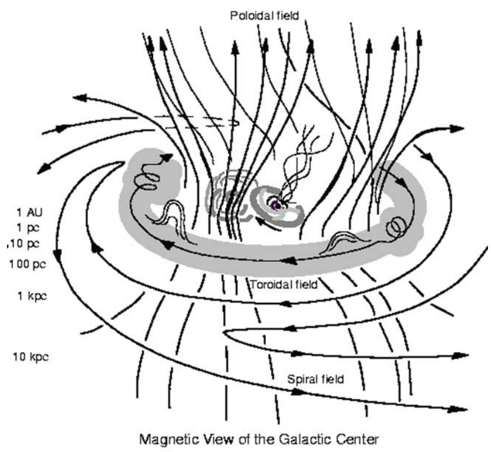

Figure 6.6: Schematic maagnetic view of the Galaxy. The scale is pseudo-logarithmic, so that the central to outer features are shown in simultaneously.

field is then maintained in a steady state by the induction-dynamo mechanism. Even a ring field can be produced from the primordial one, if we allow for an initial asymmetry with respect to the center.

ertical Component of the Primordial Magnetic Fields

It is natural that a large-scale field component parallel to the rotation axis existed, when 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.e

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 realized by the viscosity-driven angular momentum transfer and on-going star formation. 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. In the central region the gas density attains an excess by an order of magnitude over the value given by a simple exponential disk, 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.

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. 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, and therefore strong vertical field near the center.

If the present intergalactic or intra-cluster magnetic field is of the order of $10^{-9\sim-10}$ G, 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, while it dominates in the outer disk.

6.3.2 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 calculated 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 to and the accumulation of vertical field is accelerated by the magnetic-torque/angular-momentum-loss mechanism.

6.4 Nuclear Activities and the Vertical Fields

6.4.1 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. This mechanism will explain many of the observed vertical radio features near the nuclei of spiral galaxies. 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.