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Large-scale Magnetic Fields in Spiral Galaxies*

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Abstract

The magnetic field in several spiral galaxies is observed to be organised on spatial scales as large as the entire galaxy. Although irregularities in field strength and direction presumably exist on scales at least as small as $\sim$1 pc, approximately one-half of the magnetic energy appears to reside in components with simple (axisymmetric or bisymmetric) structure on the scale of the whole galaxy. Explanations of such enormous magnets include the systematic patterning of primordial fields by differential rotation and the generation of large-scale components from non-mirror-symmetric turbulence (the so-called α-effect). We discuss the observations and theory of global magnetic fields in spiral galaxies, and review a new model for the phenomenon based on the regenerative properties of axially and radially sheared galactic winds.

1. Introduction

The interstellar medium (ISM) in spiral galaxies is permeated by a magnetic field that plays an important role in several phenomena, including the acceleration and confinement of cosmic rays, the evolution and morphology of the different thermal phases found in the ISM, and the formation of stars. The magnetic field exhibits structure on a range of spatial scales, and in several galaxies is known to display systematic organisation on the scale of the entire galaxy. This large-scale magnetic structure has been the subject of a great deal of observational and theoretical research in recent years.

This paper provides an overview of observations of large-scale magnetic fields. It also describes the elements of theories that have been developed to account for these observations, including a new mechanism that connects the amplification of large-scale components to global winds in galaxies. It concludes with a brief look ahead at some intriguing questions that are likely to occupy astrophysicists over the next few years.

2. Observations

Measurement of the magnetic fields permeating the intersellar medium of the Galaxy (and of other spiral galaxies) is a demanding task. Most methods rely on the fact that the production and propagation of electromagnetic radiation

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in a magnetised plasma imprints signatures on the polarisation that contain information on the strength and direction of the field. However, the signatures are weak, and the electromagnetic radiation arriving at Earth propagates across long lines of sight through inhomogeneous fields and plasmas. Consequently, while some robust observational results are available we are far from having a complete picture of interstellar magnetic fields.

(a) Methods

Measurements of the linear polarisation of broad-band optical starlight reveal large-scale patterns in the alignment of the polarisation vector. It is believed that the polarisation is due to an interaction between the starlight and aspheric dust grains that are aligned by magnetic forces in the interstellar medium. The large-scale patterns in the polarisation are then interpreted as large-scale alignments in the magnetic vector field. Provided that the magnetic component perpendicular to the line of sight to a star is relatively uniform along the entire line of sight, the direction of polarisation is likely to give a fair indication of the direction of the transverse component of the field. By observing stars lying in different directions it is possible to trace out the direction of the transverse component across the sky, within the sphere centred at the Earth and bounded by the selected stars. It is also possible in principle to determine the direction of distant magnetic fields by studying the polarisation of stars that are apparently close to one another on the sky, but which lie at different, known distances.

While the interpretation of polarisation alignments in terms of field directions may be reasonably secure, inference of additional properties of either the dust or the magnetic field rests on complex and uncertain physical processes (e.g. Purcell and Spitzer 1971). For example, a theory of the alignment mechanism might allow the magnetic intensity to be estimated. However, the alignment mechanism proposed originally by Davis and Greenstein (1951) operates only in fields of 1 nT or more, whereas the field intensity is believed to be much lower than this. There are other alignment mechanisms that appear to work (Purcell and Spitzer 1971), but it would be optimistic to assume that the field strengths demanded by these mechanisms are accurately understood.

Radiofrequency continuum measurements provide the bulk of data on interstellar magnetic fields. Synchrotron radiation exhibits linear polarisation, with the observed direction of polarisation lying perpendicular to the transverse component of the magnetic field. For a homogeneous source, the degree of polarisation depends on the angle between the field and the line of sight. Thus for a homogenous source, the degree of polarisation could be used to determine the inclination of the three-dimensional field vector to the line of sight, while the direction of polarisation could indicate the direction of the transverse component. However, in an inhomogenous field and with intermixed synchrotron and thermal emission and absorption, it is impossible to interpret an observed polarisation amplitude as the direct result of the inclination of the field vector to the line of sight.

The emissivity of a homogeneous synchrotron source depends on both the strength of the field and the spectral energy distribution of the radiating electrons. Since astronomers rarely have independent information on one or other of the separate factors, observed emissivities are often used to derive the magnetic intensity via the assumption of equipartition between the magnetic and cosmic ray energy densities. This procedure would be more acceptable if its validity could be widely demonstrated by independent measurements. Ginzburg and Syrovatskii (1969) have reviewed the theory of synchrotron radiation.

As polarised radio continuum radiation travels through a magnetised thermal plasma, the plane of polarisation is rotated by the Faraday effect. The rotation is characterised by the rotation measure, RM, given by $RM \propto \int n_e \mathbf{B}_{\parallel} dl$. Here the integral is taken along the line of sight, n_e is the electron density, and $\mathbf{B}_{\parallel}$ is the longitudinal component of the magnetic field. The rotation measure is a function of wavelength, so that observations of the wavelength dependence of the plane of polarisation can yield the rotation measure even when the intrinsic polarisation of the source is unknown (Spitzer 1978). When non-thermal (synchrotron) electrons and thermal electrons are mixed in the source and along the path to Earth, the interpretation of the rotation measure is quite difficult (Burn 1966). Observations of some pulsars provide both the rotation measure and the dispersion measure ($\propto \int n_e dl$), allowing an estimate of the mean longitudinal component of the magnetic field.

Radiofrequency polarimetry in the 1·4 GHz hyperfine transition of atomic hydrogen presents an opportunity to measure the longitudinal magnetic field by means of the Zeeman effect. The measurement is very demanding, since the Zeeman splitting is normally a small fraction of the line width. Observations of the Zeeman effect in other radiofrequency transitions of interstellar molecules have also been made: all such measurements refer to field conditions in the 'clouds' responsible for the observed emission. As noted by Heiles (1987), Zeeman splitting and Faraday rotation reveal opposite senses of polarisation towards the Crab nebula and pulsar, presumably because the two phenomena sample different regions along the line of sight. This result should lead to caution in the acceptance of apparently simple and reliable polarimetry as a straightforward diagnostic of interstellar magnetic fields.

The morphology of some interstellar structures might also trace out the local magnetic field. For example, the shape of an aging supernova remnant (SNR) can be controlled by the ambient magnetic field. The interpretation of morphology is, however, not reliable because factors other than the magnetic field can influence the shape of the emission volume. It might also be noted that the existence of cosmic rays points to the presence of a widespread interstellar magnetic field, but the theory of cosmic ray acceleration and confinement is too uncertain at present to provide particularly useful constraints on the field strength or geometry.

(b) Results

The most extensive data refer to the magnetic field of the Galaxy, in a volume of several kpc radius centred about the Earth. As reviewed by Ruzmaikin *et al.* (1988), these data reveal a magnetic field whose largest scales are dominated by the azimuthal component. The ratio of radial to azimuthal component is consistent with alignment along the local spiral arms, and the field intensity is of order 0·2–0·3 nT. The axial component of the large-scale field is obscured by irregularities. The field is quite chaotic, and the large-scale ordered component is weaker than the rms strength of the disordered component. The scale length of the observed parts of the disordered component is of the order of 50–150 pc.

Observations of the Zeeman effect reveal intensifications of magnetic field above the ambient 0·2–0·3 nT in several classes of structure, including what are believed to be shocked regions and some interstellar clouds. There is, however, not a strong relationship between density and field strength in regions with densities spanning the range 10^6–10^8 m^{-3} (Heiles 1987). This result may be pertinent to theories of the role that magnetic fields play in the condensation/coagulation of interstellar clouds.

Observations of other galaxies have revealed global organisation of magnetic fields in several spirals and in the Magellanic Clouds. The large-scale field in spirals is generally dominated by the azimuthal component, which may exist either as an axisymmetric or bisymmetric structure. Some edge-on galaxies reveal significant axial components extending from the plane of the disk. There is, as yet, little information on the strength of the magnetic field in external galaxies other than that provided by the assumption of equipartition. The estimated strengths of the large-scale components range over 0·1–0·5 nT, and the ratio of the small- to large-scale components ranges over 0·5–2·5 (Ruzmaikin *et al.* 1988).

3. Origin of the Large-scale Field

A simple model to explain the appearance of an azimuthally dominant field in a spiral galaxy can be developed by supposing that an initial (primordial) rectilinear field is frozen into the interstellar plasma, and wound up by differential rotation in the disk. Because galaxies have spun many hundreds of times in their lifetime, this model predicts a tightly wound spiral with closely spaced field reversals, at variance with the observations. Sawa and Fuijimoto (1980) have modified this simple model by showing that diffusion into a galactic halo might prevent tight winding.

In spite of the simplicity of such primordial field theories, most theoreticians have been attracted to models based on dynamo (self-excitation, regeneration) processes to produce the field and to control its structure. In theories of this kind, an azimuthal component is produced from a radial component by differential rotation. The radial component is regenerated from the azimuthal component by cyclonic convection that possesses a net helicity as a result of Coriolis or other forces. The regeneration is frequently modelled by the so-called 'α-effect' (e.g. Krause and Rädler 1980; Ruzmaikin *et al.* 1988).

According to this theory, the large-scale field, $\overline{\mathbf{B}}$, in a turbulent dynamo is supposed to obey an induction equation that has similarities with the true magnetic induction equation arising from Maxwell's equations. The turbulent dynamo equation is

$$\frac{\partial \overline{\mathbf{B}}}{\partial t} = \nabla \times (\alpha \overline{\mathbf{B}}) + \nabla \times (\overline{\mathbf{v}} \times \overline{\mathbf{B}}) + \eta \nabla^2 \overline{\mathbf{B}},$$

where $\overline{\mathbf{B}}(t,r)$ is the large-scale field at time t and position r, $\overline{\mathbf{v}}$ is the large-scale velocity, η is the diffusion coefficient and α is a coefficient that embodies the regenerative effect of helical turbulence. Both η and α are supposed to arise from turbulence in the interstellar plasma, according to theories that are plausible but as yet not rigorously established. The turbulent induction equation incorporates two processes, differential rotation and the α-effect, that generate field and one, diffusion, that destroys it.

A linear analysis of the turbulent induction equation in a thin disk (e.g. Parker 1979; Krasheninnikova *et al.* 1989) shows that exponential field growth may occur when

$$R_\omega R_\alpha = N_D > N_D^C ,$$

where

$$R_\omega = \Delta\Omega h^2/\eta \quad \text{and} \quad R_\alpha = \alpha h/\eta .$$

Here $\Delta\Omega$ is the differential rotation across the disk, h (the disk thickness) represents the diffusion scale, N_D is the dynamo number, and N_D^C ($\approx$10) is the critical dynamo number. Several authors have solved the dispersion equation and spatial eigenvalue problem embodied in the turbulent induction equation, and hence developed linear models of galactic magnetic fields.

As an example of the application of the theory to astrophysical problems we may note the work of Starchenko and Shukurov (1989) which presents asymptotic solutions of the turbulent induction equation. The asymptotic expansion is based on the parameter $\epsilon = (h/r)N_D^{-1/3}$, where h/r is the ratio of disk thickness to radial position of the generation region. It is claimed that this work confirms the effectiveness of this dynamo in generating a bisymmetric field in M33 as a result of the particular rotation curve of this galaxy. It also appears to account for the observed field topology differences between NGC 6946 and IC 342 (which have similar rotation curves) in terms of differences in disk thickness. It is further claimed that the model depends on only three parameters, the thickness of the ionised disk, the dynamo number, and a figure-of-merit determined by the ratio of the growth rates of the $\alpha\omega$ and α^2 dynamos. The figure-of-merit depends in fact on the rotation curve, implying that the theory depends on only two fundamental galaxy properties: the rotation curve and the disk thickness.

It is difficult to critically assess the turbulent induction model because of the enormous gap between the mathematical manipulations underlying the model, and the observational knowledge we possess at present. While it seems improbable that the mathematical manipulations do indeed provide a relevant description of galactic electrodynamics, guidance towards an improved theory will be hard to obtain from observations. Progress in understanding and modelling the solar dynamo suggests that observations of the relationship between galactic magnetic structure and the associated patterns of fluid flow could be valuable, but this kind of observation is very hard to make.

There is sufficient uncertainty about the role of turbulence in galactic dynamos to warrant studies of other sources of dynamo activity. In this vein, Spencer (1990) and Spencer and Cram (1993) have constructed a new class of models for the regeneration of galactic magnetic fields based not on the α-effect, but rather on the action of shear in a galactic wind. The wind model depends on laminar flow in the wind, although turbulence is still supposed to enhance the diffusion of magnetic flux. While the observational evidence for galactic winds is hard to obtain, there are several reasons for believing that such winds exist in many galaxies.

As illustrated in Fig. 1, this model involves the generation of axial field components by radial shear of the axial flow, and the generation of radial field components by axial shear in the radial flow. Shears in the fluid flow act to

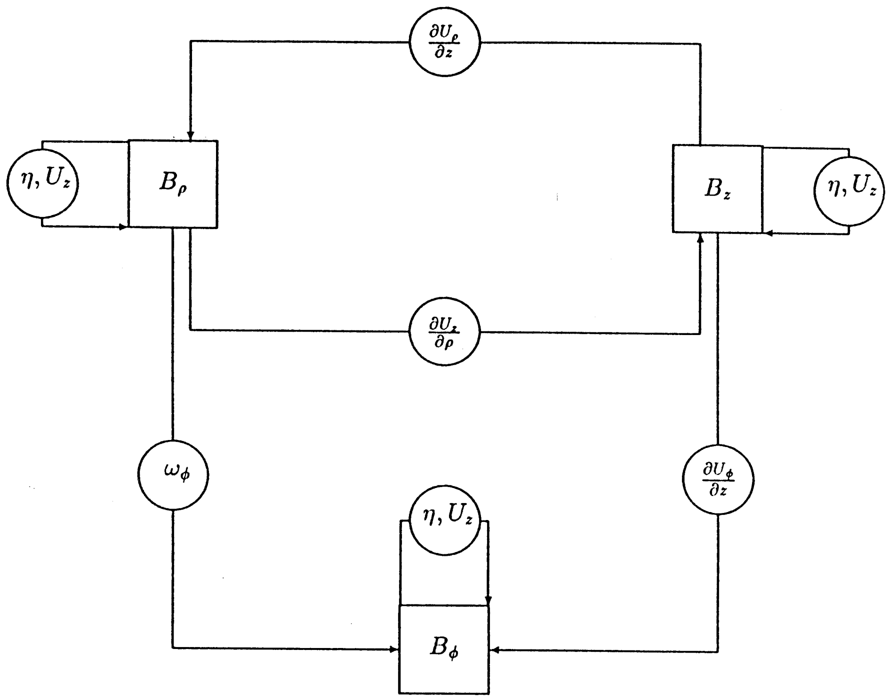

Fig. 1. Diagram showing the interconnecting processes in the laminar galactic wind model. Azimuthal field, B_ϕ, is produced from radial field, B_ρ, by differential rotation, ω_ϕ, and from the axial field, B_z, by axially sheared azimuthal flow, $\partial U_\phi/\partial z$. Axial field is produced from radial field by radially sheared axial flow, $\partial U_z/\partial \rho$, while radial field is produced from axial field by axially sheared radial flow, $\partial U_\rho/\partial z$. Each component is destroyed by turbulent diffusion, η, and may be enhanced or destroyed by axial advection, U_z.

intensify the field in certain zones of convergence. In many flow topologies, diffusion from these local field concentrations will then recreate the self-same field components that seeded the original intensification. This thus corresponds to amplification and regeneration of the field. In wind-driven models constructed to date, the azimuthal field is a byproduct of the crucial interplay between the axial and radial field components. Even so, it is quite possible to have azimuthally dominated fields in which the azimuthal field is electrodynamically passive.

The wind-driven amplification and regeneration processes have been demonstrated in a local model of a differentially rotating disk, assuming a circularly symmetric flow pattern. However, it is known that antidynamo theorems forbid the indefinite production of axisymmetric magnetic fields by laminar flows (e.g. Moffatt 1978) so that the present wind model cannot be regarded as a complete dynamo model. The model must be elaborated by removing the local approximation, and considering global nonaxisymmetric fields. A numerical model of such a system has been developed by Spencer (1993), and has proved to be a potent dynamo.

4. Prospects

Progress in understanding astrophysical systems has frequently begun with models based only on gravitational and hydrostatic pressure forces. As these models are mastered, research passes on to hydrodynamic models, and finally tackles the difficulties of electrodynamic models. This progression does not necessarily reflect increasing refinement in the theory, since electrodynamic effects may be crucially important; rather it reflects a proven astrophysical research technique for dealing step by step with complex problems. The growing interest in galactic magnetism can be seen as part of this progression towards deeper understanding of the behaviour of the interstellar medium in galaxies.

While this review has concentrated on observations of large-scale fields and theories of their origin, interstellar magnetic fields may be important in a wide range of galactic phenomena including the acceleration and confinement of cosmic rays, and the control of the accretion and condensation of clouds leading to star formation. Improvements in our understanding of the processes that generate large-scale fields will surely contribute useful insights to these other problems.

There is a pressing need for improved observations. New radio telescopes (such as the Australia Telescope) are designed to give reliable and convenient measurements of polarisation of continuum and line radiation, and we can anticipate significant improvements in the quality of basic data. An area of research that has received only limited attention concerns the interpretation of polarisation data in terms of the physical conditions in the source and along the line of sight to the source. It would be useful to have a deeper understanding of the polarimetry 'inverse problem' and an appreciation of the full range of physical models that might be consistent with a given set of observational constraints.

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