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Introduction

The importance of magnetic fields for our understanding of the Universe has been appreciated since the mid-1950s, when the advent of radio astronomy and the studies of cosmic-ray propagation and confinement revealed a Universe filled with thermal and relativistic plasmas that are controlled by magnetic fields. However, despite decades of focussed effort, our knowledge of astrophysical magnetic fields, especially those at galactic and extragalactic scales, is still incomplete and uncertain. Arguably the most important single reason for that is the intrinsic complexity of magnetic fields: physical processes involving magnetic fields, methods of their observation and theoretical modelling are notoriously complicated and often counter-intuitive.

Until recently, interstellar magnetic fields had been a rather isolated area of galactic astrophysics. The reason for that was twofold. Firstly, magnetic fields are difficult to observe and model. Secondly, they were understood too poorly to provide a useful insight into the physics of their parent objects. The widespread attitude regarding interstellar magnetic fields was succinctly described by Lodewijk Woltjer (1967):

> The argument in the past has frequently been a process of elimination: one observed certain phenomena, and one investigated what part of the phenomena could be explained; then the unexplained part was taken to show the effects of the magnetic field. It is clear in this case that, the larger one's ignorance, the stronger the magnetic field.

This mindset is also aptly reflected by Donald Cox (1990, reprinted by permission from Springer Nature), who observed that

> As usual in astrophysics, the way out of a difficulty is to invoke the poorly understood magnetic field. . . . One tends to ignore the field so long as one can get away with it.

This bias is unfortunate since magnetic fields often add greater richness, elegance and, more importantly, essential realism to the landscape of astrophysics. The situation has changed dramatically over the last 10–15 years. Theory and observations of galactic magnetic fields are now advanced enough to provide useful constraints on the kinematics and dynamics of the interstellar gas, and their importance and role are better appreciated. Magnetic fields of galaxy clusters have come to the fore and there is a rapidly growing interest in the role of magnetic fields during galaxy formation and in the Early Universe. Our aim here is to help the scientific community to make further progress in the appreciation of the significance of galactic and extragalactic magnetic fields and in revealing their origin.

We anticipate that observational activity in the field of galactic and extragalactic magnetism will be enhanced in the next decade. ‘The Origin and Evolution of Cosmic Magnetism’ is among the *Key Science Projects* of the Square Kilometre Array (SKA), a new-generation radio telescope to be built within the next decade by the international community (`http://www.skatelescope.org`). New probes of intergalactic magnetic fields have opened up, involving observations of the Cosmic Microwave Background, γ-ray and gravitational-wave astronomy. The success of these efforts will depend upon and be enhanced by theoretical knowledge and understanding of the origin and properties of magnetic fields in galaxies, galaxy clusters and intergalactic space – the subject of this book.

Galaxies are attractive objects to study (a glance at Fig. 1.1 is probably sufficient to lead one to accept this). The magnetism of their natural beauty adds to the fascinating diversity

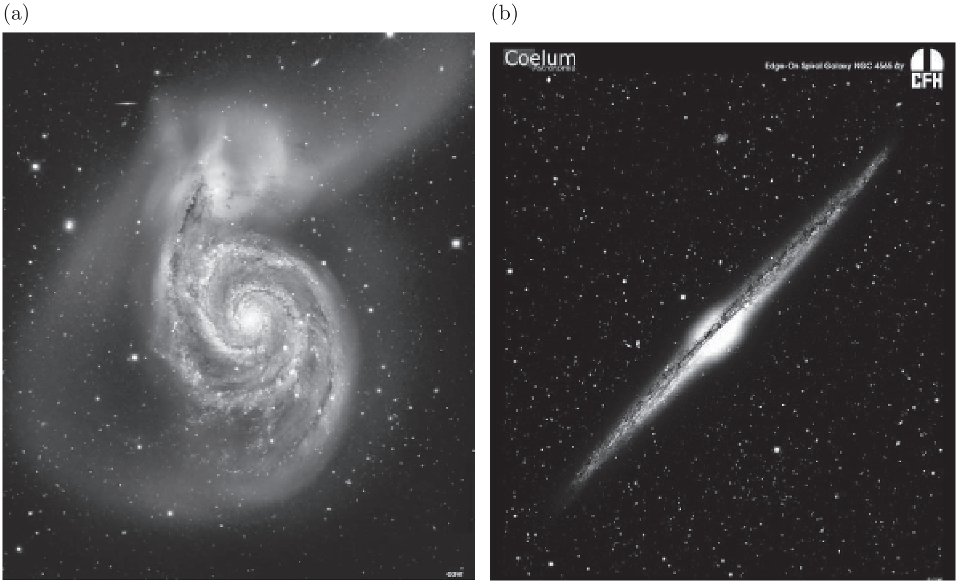

Figure 1.1 Optical images of two nearby spiral galaxies: M51 (left), with the satellite galaxy NGC 5195 at the top, and NGC 4565 (right). M51 is notable for its prominent spiral pattern. The weak, diffuse glow in the outer parts of the system is due to stars stripped out from the galaxies; these regions also contain gas and a magnetic field. M51 is the first galaxy where a well-ordered, large-scale magnetic field has been detected (Segalovitz et al., 1976) and studied since in fine detail. NGC 4565 is at about the same distance as M51, but seen nearly edge-on, so the thinness of the galactic disc is evident. The dark strip along the galactic disc is due to obscuration by interstellar dust. (Courtesy of the Canada–France–Hawaii Telescope/J.-C. Cuillandre/Coelum.)

of physical processes that occur over an enormous range of scales from the global dimension[1] of order 10 kpc down to the viscous turbulent scales of 1000 km and smaller. The visual image of a galaxy is dominated by the optical light produced by stars that contribute most of the visible galactic mass ($2 \times 10^{11} M_\odot$ for the Milky Way, where $M_\odot = 2 \times 10^{33}$ g is the mass of the Sun). A small percentage of the galactic mass is due to the interstellar gas that resides in the gravitational field produced by stars and dark matter. Spiral galaxies are flat (Fig. 1.1) because the stars and gas rapidly rotate. The gas is ionized by UV and X-ray radiation and cosmic rays; the degree of ionization of diffuse gas ranges from 30% to 100% in various phases. Interstellar gas is involved in turbulent motions that can be detected because the associated Doppler shifts broaden spectral lines emitted or absorbed by the gas beyond their width from thermal motions alone. The effective mean free path of interstellar gas particles is small enough to justify a fluid description under a broad range of conditions. Altogether, interstellar gas can be reasonably described as an electrically conducting, rotating, stratified turbulent fluid – and thus a site of various MHD processes including dynamo action.

The crucial theoretical progress in our understanding of astrophysical magnetic fields is related to the non-linear theory of magnetic fields in turbulence that is being intensely developed now. The appreciation of the role of magnetic helicity conservation in the non-linear behaviour of the mean-field turbulent dynamos is of particular importance. The rapid development of the computing power and techniques, as well as the sophistication of data analysis, provide deep new insights and inspire fundamental analytical accomplishments.

Observationally, we now have reliable and detailed data on magnetic fields in a hundred spiral galaxies and a few dozen galaxy clusters, together with a large number of radio galaxies. The observations have achieved a resolution and sensitivity sufficient to probe not only magnetic fields at scales comparable to the size of a galaxy (several kiloparsecs) but also the turbulent component of magnetic fields (at scales of 0.1 kpc and less). However, most texts on galactic magnetism focus on large-scale, regular magnetic fields, and pay relatively little attention to the evolving ideas about the physical significance and nature of random magnetic fields and their specific properties such as spatial and temporal intermittency.

A remarkable property of systems with high electric conductivity (or rather large magnetic Reynolds number R_m) is that the decay time of the magnetic field due to the microscopic (Ohmic) resistivity can be very long. Since astrophysical plasmas usually have extremely large values of R_m, the Ohmic decay time often exceeds the age of the Universe and, it is often argued, any magnetic field created in some early epoch would survive until now. Does this make dynamos unnecessary? We believe the answer to this question is no, because astrophysical plasmas are most often turbulent since their viscosity is relatively low (i.e., the Reynolds number Re is large). A fundamental property of turbulence is the energy cascade to small scales. If a magnetic field is relatively weak and $R_\mathrm{m} \gg 1$, the turbulent motions will necessarily entrain (tangle) the magnetic fields and the magnetic energy will

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[1] A length unit appropriate to galaxies is 1 pc = 3.1×10^{18} cm = 3.262 light-years. The distance of the Sun from the centre of the Milky Way is about 8.5 kpc. Apart from such units widely used in astronomy and astrophysics, we use the Gaussian cgs units throughout the text.

be transferred from the energy-range scale l_0 to small scales where the Ohmic dissipation is rapid. If the initial magnetic field has a scale much larger than l_0, it will be reduced to l_0 at the relatively short turbulent diffusion time. The time scale of magnetic field decay is then controlled by the cascade time (i.e., the eddy turnover time independent of R_m). If, on the other hand, the magnetic field is strong enough, the Lorentz force will induce motions which will become turbulent as long as $\mathrm{Re} \gg 1$. The magnetically induced turbulence will then drain the magnetic energy in a few eddy turnover times as above. Alternatively, if $\mathrm{Re} \lesssim 1$, viscosity drains the energy from the magnetically driven velocity field directly and, again, the magnetic field will decay. Altogether, any three-dimensional magnetized system must host a dynamo unless its magnetic field is maintained by external electric currents. (The three-dimensionality is required because a two-dimensional velocity field cannot be a dynamo.) Indeed, turbulent flows can drive the large- and small-scale dynamos, but magnetic fields produced by them are controlled by the dynamo mechanism rather than by the initial magnetic field. In this sense, the properties of the initial magnetic field in a turbulent system are unimportant, as long as they can provide a suitable seed for the dynamo. In other words, initial conditions are forgotten in a dynamo system (as in any other unstable system) unless the initial magnetic field is strong enough to make the dynamo nonlinear from the very beginning.

This picture emerges from a systematic exploration of astrophysical magnetic fields presented in this book, which has four major themes: Chapters 2 to 4 give a pedagogical introduction to the theory and observations of cosmic magnetic fields. Dynamo theory is the focus of Chapters 5–9, while its applications to the galactic and cluster magnetism are covered in Chapters 10–14. Chapters 15 and 16 focus on magnetic fields in the Early Universe.