1

A brief history and background

1.1 Overview of some early results and concepts

The interplay between magnetic fields and ionised gas in space was demonstrated in post-World War II studies of the Earth's aurora, and in attempts to understand the complex and energetic phenomena of the Sun's atmosphere and corona. Much of the basics of magnetoplasma processes in astrophysics have come from solar studies. Here direct measurements of the magnetic field's direction and strength have come through measurement of Zeeman splitting of transitions, and dynamical imaging in the radio, optical, and later Solar X-rays. These studies enabled a theoretical understanding of the role of magnetic fields in particle acceleration in solar flares and prominences. The process of magnetic reconnection, still incompletely understood, was gradually recognised between the late 1940s and early 1960s as an explanation for particle acceleration in solar flares – including reconnection diagrams.

Awareness of magnetic fields in *diffuse* astrophysical plasmas beyond the solar corona began with the discovery of synchrotron radiation (Schwinger 1949). It followed the earlier discovery of cosmic rays (CR) by Hess (1912) and of the polarisation of light from dust-reddened stars. Then came the realisation that supernova remnants emit synchrotron radiation (Shklovskii 1953 and the earlier references therein, Alfvén & Herlofson 1950, Kiepenheuer 1950). Synchrotron radiation requires *both* a magnetic field and relativistic electrons, of density $n_{\mathrm{e}}^{\mathrm{r}}$, through the following emissivity equation.

$$\varepsilon(\nu) \approx 10^{-23} n_{\mathrm{r0}}^{\mathrm{e}} l \xi(s) \left(6.3 \times 10^{8}\right)^{\frac{(s-1)}{2}} \times (B \sin\varphi)^{\frac{(s+1)}{2}} \upsilon^{\frac{(1-s)}{2}} \,\mathrm{ergs}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{Hz}^{-1}\,\mathrm{sterad}^{-1}. \quad (1.1)$$

The index s is the power law slope of the energy distribution of the relativistic electrons ($n_{\mathrm{e}}^{\mathrm{r}}(E) = n_{\mathrm{e0}}^{\mathrm{r}} E^{-s}$), where $\xi(s)$ is a slowly varying function of s, being unity for $s = 2.5$. l (cm) is the line-of-sight dimension of the emitting region, φ is the pitch angle of the average electron velocity with respect to the local field direction, B is the total field strength in Gauss, and ν is in Hz (*cf.* Pacholczyk 1970). The power, L, radiated over all frequencies, is

$$L = 4\pi D_{\mathrm{L}}^{2} \int_{\nu_1}^{\nu_2} f(\nu) d\nu \,\mathrm{ergs}^{-1}, \quad (1.2)$$

where D_{L} is the cosmological luminosity distance, and f is the received spectral density (erg s^{-1} cm^{-2} Hz^{-1}) of the radiation flux. L. Biermann and Schlüter (1951) estimated that interstellar turbulence would infuse the interstellar medium with magenetic fields of order 10^{-6}–10^{-5} G.

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A mechanism for the creation of a first seed magnetic field was proposed and applied to stellar magnetic fields by L. Biermann (1950). This process, commonly known as the Biermann battery, has fundamental application to any plasma. In some form it is probably the mechanism that has seeded, i.e. "created", the magnetic fields in many different astrophysical contexts.

During the late 1940s it became clear that the Milky Way contains a distributed magnetic field, and the first estimates of its value, and the notion of interstellar particle acceleration, were established. All were based on sound physical arguments, which I shall briefly review. By today's standards, the data on which sound physical arguments were based might seem impressively limited.

In 1949, Fermi proposed an alternative to Alfvén, Richtmyer, & Teller's (1949) conclusion that CR's were of solar origin and are magnetically confined to the Sun's vicinity. He argued that they could be of interstellar origin. In an insightful paper Fermi proposed that particles above a threshold energy could gain energy by reflection off turbulent motions of a magnetised interstellar medium. Evidence in support of this came from Doppler shift measurements on interstellar absorption lines by Adams (1943), which indicated about 15 kms^{-1} rms scatter in radial velocity.

Fermi's proposal that CRs can be accelerated by such "collisions" with an interstellar magnetic field (now known as Fermi acceleration) also provided a natural explanation for the power law spectrum of cosmic ray particle energies, as is observed. Using Alfvén's relation for the velocity of magnetosonic waves,

$$v_{\mathrm{A}} = \frac{B}{\sqrt{4\pi\rho}}, \tag{1.3}$$

and combining with estimates of the interstellar density of nucleons, Fermi concluded that the interstellar magnetic field strength, $B_{\mathrm{interstellar}}$, is $\approx 5 \cdot 10^{-6}$ G, in effect the consequence of an energy conversion from the kinetic energy of interstellar streaming and turbulence into magnetic energy.

Around the same time the newly discovered properties of CRs, which were at first called *Höhenstrahlung*, also led to early estimates of the interstellar magnetic field strength – using quite different arguments: By the late 1940s it was established that CR nuclei have energies up to $\approx 10^{16}$ eV. The electron component of the galactic CRs was later recognised as associated with interstellar synchrotron radiation from the Milky Way. The observational facts at *ca.* 1949 were: (i) CR energies up to 10^{16} eV, and (ii) isotropy of arrival directions. These were combined with (iii), the proton/electron charge-to-mass ratio, to deduce the strength of the interstellar magnetic field in our region of the Galaxy. Schlüter and L. Biermann (1950) argued that, *if* primary cosmic ray particles were of extragalactic origin (consistent with their isotropy) and if they pervade the Universe, then their energy density, $\varepsilon_{\mathrm{CR}}$, would be $\approx 10^{-12}$ erg cm^{-3}. This would exceed that of extragalactic light by two orders of magnitude. Fermi (1949) and Biermann & Schlüter (1951) argued that this isotropy can only be explained if CRs are *confined* by an interstellar magnetic field. For this to happen, the magnetic field energy density, ε_B, must be comparable with $\varepsilon_{\mathrm{CR}}$, otherwise the cosmic ray particles will leak out of the Galactic disk and destroy the observed isotropy. $\varepsilon_B = 10^{-12}$ erg cm^{-3} corresponds to a magnetic field strength of 5 μG. These arguments were elegant and convincing, and have stood the test of time over the intervening decades. To illustrate

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with a simple calculation we compare the gyroradius, r_B, of the (then) highest known energy primary CR nuclei ($\approx 10^{16}$ eV), with the thickness of the galactic disk.

$$r_B = \frac{m_\mathrm{p} c^2 \gamma}{eZB_\perp} \approx 10 \left(\frac{E_{16}}{Z \cdot B_{\perp -6}} \right) \ \mathrm{pc} \tag{1.4}$$

where E_{16} is the energy in units of 10^{16} eV, Z is the atomic number of the CR nucleus, m_p the proton mass and $B_{\perp -6}$ the magnetic field in microgauss. At $B_\perp = 5\ \mu$G and $E_\mathrm{CR} = 10^{16}$ eV, $r_B = 2$ pc, comfortably smaller than the scale height of the galactic disk ($z_\mathrm{G} \approx 1$ kpc).

These deductions of the Milky Way's magnetic field strength from early cosmic ray data and interstellar turbulence predated the first astronomical attempts at measuring B by about 14 years. The latter were to directly measure the Galactic magnetic field strength – by Zeeman-splitting of the 1420.4 MHz interstellar hydrogen line (Chapter 2). Such measurements were technically difficult, and only in the last few years have various Zeeman measurements of $|B|_\mathrm{interstellar}$ converged on a result that is close to the original estimates of Fermi, Schlüter, and L. Biermann. Evidence for a relatively large-scale ordered component of the interstellar magnetic field came from observations of the optical polarisation of starlight over large regions of the galactic sky (Hiltner 1951), and later from radio polarimetry of the galactic interstellar radio synchrotron radiation made during the 1950s (Wielebinski & Shakeshaft 1964).

As radio astronomy developed in the 1950s, the discrete radio sources in the newly revealed "radio sky" were thought to be aggregates of radio-emitting stars. The radio star explanation seemed, *prima facie*, a natural extension of the discovery during World War II, that the Sun dominates the radio sky as a single source at metre wavelengths. It was reinforced by the identification of one of the brightest discrete radio sources near the Galactic plane as a supernova remnant, Taurus A, the Crab Nebula. These findings appeared consistent with Grote Reber's earlier discovery that the large-scale radio sky roughly traces the Milky Way, where most stars lie.

The subsequent discovery of a few *extragalactic* radio sources, not associated with any Galactic star, inspired searches for optical identifications for the increasing numbers of discrete radio sources found throughout the 1950s. These included Cygnus A, even brighter than Taurus A, and also lying almost directly in the Galactic plane. The absence of any obvious star or supernova at the newly precise location of Cygnus A, pinpointed with a radio interferometer, now justified a deep optical search at Cygnus A's position using the 5 m Hale telescope at Mount Palomar. Baade & Minkowski (1954) found a very faint, distant galaxy system at a redshift of 0.056. This revolutionary radio-optical correspondence suggested that most of the strongest discrete sources in the radio sky are indeed *extragalactic*, and at great distances.

Their cm wave radio emission is synchrotron radiation (Equation 1.1), and although associated with a galaxy, the emission often originates in large volumes *outside* the parent galaxy. These large, supra-galactic zones – "radio lobes" – have sizes now known to range from kpc-scale to several megaparsecs in the extreme, and are discussed later in the book. The largest radio sources have dimensions that are comparable with entire galaxy clusters and with galaxy–galaxy separation distances. Pertinent to this book is the fact that they are permeated by magnetic fields. Extended radio sources are now found at redshifts $\gtrsim 6$. These systems, having significant magnetic field strengths and magnetic energy, can be found throughout the extragalactic Universe.

It is straightforward to deduce that the largest of these largest systems have been “filled” with magnetic fields over a timespan of $\approx 10^8$ years, a period that is still negligible compared with the age of the Universe. Furthermore, the energy content of these large radio-bright extragalactic clouds, 10^{60}–10^{62} ergs, is a non-negligible fraction of the *rest mass* of the parent galaxy’s central collapsed object, which appears to be their energy source. This makes them a remarkable phenomenon of the extragalactic universe. Much of the accumulated energy within these radio source lobes is in the form of magnetic flux – and generated within a relatively short period of cosmic time.

For these galaxy systems, the ultimate energy source must be gravitational, since even a nuclear energy source is insufficient. They have been a subject of considerable analysis since attention was first called to the enormous magnitude of their energies by G. R. Burbidge (1956). Later in the book we elaborate on the consequences of this central energy source, believed to be a supermassive black hole, for galactic and intergalactic magnetic fields. Its formation appears closely associated with the evolution of its host galaxy. The released energy, illustrated by Fig. 1.1, first flows outward in a highly collimated energy pipe, or “jet”. Later in the book we show how its conversion from a gravitational form is very efficient. That is, a substantial fraction is magnetic energy, and this is why such systems are important to the theme of this book.

Another possible gravitational energy reservoir for widespread magnetic fields is infall energy that is dissipated in the course of cosmological large scale structure (LSS) formation.

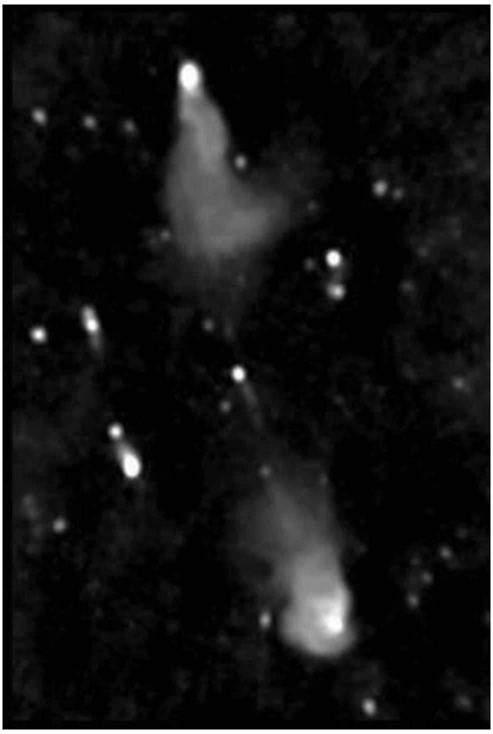

Figure 1.1 Radio image of 2147+816, as imaged by the VLA (NRAO-NVSS survey). Its projected largest dimension is $\approx$2.6 Mpc, comparable to an inter-galaxy separation distance.

As intergalactic matter falls into galaxy groups, clusters, and filaments and sheets of LSS, the accompanying shearing and turbulence create mechanisms for converting gravitational infall energy into thermal and magnetic energy.

Seed fields for galactic and intergalactic magnetic fields have been proposed to originate very early in the timeline of the Universe – before the recombination era at $z \approx 1500$, during the earlier plasma epoch, or much earlier. Some of these primordial fields might have originated close to the time of the quantum chromo dynamic (QCD) phase transition when the scale of the Universe was as small as ~1 cm and less. This latter possibility also implies interesting connections with particle physics processes in the primordial universe, which are briefly discussed later in the book. Alternatively, or in addition, later field seeding by Biermann battery processes in the first stars was possibly an important contributor. Finally, the black hole-jet processes on various scales might alone have provided much, or most of the magnetic flux of interstellar and intergalactic space. It is possible that the latter field seeding processes overwhelmed the early primordial ones due to stars.

1.2 Observational techniques and results: past, present, and future prospects

Faraday rotation measures (*RM*s) from linear polarisation measurements of extragalactic radio sources began in the 1960s. These soon covered the entire sky with sufficient angular density of sources to indicate that a large-scale, organised magnetic field permeates the disk of our Galaxy (Davies 1968), consistent with Hiltner's (1951) starlight polarisation results. Faraday rotation $\Delta\chi$ of a plane polarised wave is defined as

$$\Delta\chi = 811.9\Delta\lambda^2 \int_0^L n_e B_{||} dl \text{ radians} \tag{1.5}$$

where n_e (cm^{-3}) is the free electron density, $B_{||}$ (μgauss) in an element dl along the line of sight to a linearly polarised radiator at distance L from the observer, and λ is in metres. The Faraday *RM*, defined as $\Delta\chi/\ \Delta\lambda^2$, is thus the path integral of the electron density-weighted line-of-sight component of the magnetic field. Given some independent estimate of the associated electron density, and the dimensions of the "cloud" containing both the electrons and magnetic field, B can be estimated – as we show later with examples.

Subsequent measurements of the Faraday rotation measures for larger numbers of (polarised) extragalactic radio sources has led to a more refined modelling of the large-scale Galactic magnetic field structure (e.g. Simard-Normandin & Kronberg 1980, Sofue & Fujimoto 1983, Clegg *et al.* 1992, Kronberg & Newton-McGee 2011). The Galactic magnetic field shows an underlying organisation on a grand scale, and appears to have some large-scale field reversal(s). Recent radio studies indicate that virtually all disk galaxies are permeated by large-scale magnetic fields.

The magnetic field in "clouds" containing both synchrotron-emitting relativistic electrons, (n_r, $|B|$) and thermal electrons, n_e, (Equations 1.1, 1.3) can be diagnosed in a more detailed way by appropriately designed Faraday rotation measurements described in Chapter 2. Generally, each volume element of the cloud will generate polarised synchrotron photons, which can be Faraday rotated along the ray path to the observer. This can happen on their way to us, in any intervening magnetised zone containing n_e and $B_{||}$ – either within the cloud or in front of the cloud. A formalism was developed by Burn (1966) showing a Fourier

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transform relationship involving the observed Faraday rotation (variation of $\chi(\lambda^2)$), or *RM*. As discussed in Chapter 2, the line of sight distribution of *RM* can be applied to perform a kind of magnetic field "tomography" on a system of "clouds". Only relatively recently, some 40 years later, did it become feasible to extend magnetic field probes of distant extragalactic radio sources by applying variations of Burn's technique to newer observations of extended extragalactic sources (e.g. Brentjens & deBruyn 2005).

In the early 1970s, Faraday rotation measure data were used to probe for widespread intergalactic magnetic fields to large redshifts (Rees & Reinhardt 1972, Nelson 1973, Vallée 1975, Kronberg & Simard-Normandin 1976). The more recent discoveries that (i) the baryonic fraction of the visible universe is only a few percent, and that (ii) intergalactic space consists of cosmic voids and filaments, lead to a refined interpretation of these early $RM(z)$ results. These had produced a global, average present-epoch upper limit $B_{\mathrm{IGM}} \lesssim 10^{-9}$ G and did not distinguish what we now know as filaments, sheets, and giant voids of cosmological LSS.

Positive detections have emerged for magnetic field searches for high electron column density absorption line systems ($N_{\mathrm{e}} \gtrsim 10^{20.5}$ cm^{-2}) in front of radio-loud quasars. The interest in making such measurements is that the absorption line systems can exist at substantial redshifts – hence, significantly into the cosmic past. Thus if an intervenor galaxy at large redshift is detected in absorption, we have the opportunity to compare magnetic field strengths "then", with those "now" in related local-universe systems. Observations of this kind can test for global field strength evolution around galaxy systems over different cosmological epochs (Chapter 12).

Large radio telescopes with polarimetric capability can now image the same interstellar synchrotron emission in nearby galaxies that was detected in our own Milky Way in the early days of radio astronomy. Diffuse synchrotron radiation has recently been found within galaxy clusters, and beyond galaxy clusters in regions of significant galaxy over-density in the nearby universe. In general, searches for large-scale low-frequency (metre-λ) synchrotron radiation constitute a very direct means of detecting the presence of an intergalactic magnetic field. Such searches serve to trace "old" CR electrons and their associated magnetic field, and energy, over significant volumes of intergalactic space.

Satellite-based X-ray telescopes, through imaging and atomic spectroscopy of the intracluster intergalactic medium (ICM) within galaxy clusters, have made it possible to combine the consequently derived spatial distribution of the free electrons with Faraday rotation measures. This has led to magnetic field estimates in galaxy clusters, e.g. Kim *et al.* (1990). Energetic electrons in sufficiently large numbers also generate X-rays by inverse-Compton (IC) scattering, either of the 2.7 K CMB (Cosmic microwave background) photons, or, in more extreme cases, of their self-generated synchrotron radiation photons. Where IC-generated X-rays can be distinguished from those of hot gas bremsstrahlung, they provide additional, often important, constraints on the magnetic field.

Observations over the past thirty years have produced magnetic field detections not only in galaxy disks, but also in galaxy halos, clusters of galaxies, and in some very high redshift, i.e. cosmologically early, galaxy systems. These produce both absorption lines and Faraday rotation of the radiation from background quasars. Generally, the more we look for extragalactic magnetic fields, the more ubiquitous we find them to be.

Optical telescopes of 8 m- and higher-class can add very importantly to the power of Faraday *RM* probes, especially in distant Faraday rotating, intervening galaxies in front of background quasars and galaxies. This can be appreciated from Equation (1.5) given the dependence on n_e and B in a Faraday rotating system. High spatial and spectrographic wavelength resolution at the highest possible sensitivity can isolate column densities and temperatures of species in magnetised intervening objects that are associated with an image of Faraday rotation. The evolution of galaxy magnetic fields and gaseous conditions can thus be studied with a combination of optical and radio *RM* measurements over a large range of cosmological epoch. The addition of optical and X-ray observations augment the *RM* synthesis methods outlined in Chapter 2.

Another prospect for measuring magnetic fields is through perturbations of the cosmic microwave background (CMB) by galaxy clusters known as the Sunyaev–Zel'dovich (SZ) effect. The physical process was discovered by Sunyaev & Zel'dovich (1969) and it is largely insensitive to the cluster distance. As instrumental capabilities enable ever more precise detections of the SZ effect, it is possible to test for higher order perturbations of the SZ effect that can be sensitive to magnetic fields. The SZ effect, being largely redshift insensitive, cluster magnetic fields can be probed in this way along with other cosmological parameters, to significant redshifts. Finally, the polarisation properties of the CMB radiation itself can be analysed as an indirect diagnostic of very distant and cosmologically early magnetic fields.

The discovery of "ultra" high energy ($\gtrsim 10^{18.5}$ eV) cosmic rays (UHECR), high energy neutrinos, and extragalactic γ-ray sources provides several additional tools for probing extragalactic magnetic fields. Various interactions among hadrons, leptons, photons, and neutrinos propagating through intergalactic space can potentially be linked to intergalactic magnetic fields at different levels, often at far lower levels than what can be detected by Faraday rotation.

The succeeding chapters of this book elaborate on several topics mentioned in the preceding few pages. They will review some basic relevant theory, current and future measurement methods for diffuse astrophysical magnetic fields, results, and discuss magnetic field origins. Some astrophysical consequences and connections to other astrophysical topics are also explained and discussed.

Many of the earlier theories relating to the detection of magnetic fields (and even some results) date to the 1960s and earlier. From an experimental point of view some were well ahead of their time. More specifically, instrumental development and detections have often had to catch up with theory. In the next chapter and elsewhere in the book, we describe and elucidate methods for probing astrophysical magnetic fields in many contexts, along with discussion of some underlying physical processes.

Articles on astrophysical magnetic fields have been published over the past three decades by Priest (1985), Asseo & Sol (1987), Rees (1987), Wielebinski & Krause (1993), F. Krause (1993), Kronberg (1994), Grasso & Rubenstein (2001), Carilli & Taylor (2002) in the context of galaxy clusters, Han & Wielebinski (2002) for the Milky Way, Widrow (2002), and in a book edited by Wielebinski & Beck (2005).

References

Adams, W. S. 1943, The Structure of Interstellar H and K Lines in Fifty Stars, *Astrophys. J.*, 97, 105

Alfvén, H. & Herlofson, N. 1950, Cosmic Radiation and Radio Stars, *Phys. Rev.*, 78, 616

Alfven, H., Richtmyer, R. D., & Teller, E. 1949, On the Origin of Cosmic Rays, *Phys. Rev.*, 75, 892

Asseo, E. & Sol, H. 1987, Extragalactic Magnetic Fields, *Phys. Rep.*, 148, 307

Baade, W. & Minkowski, R. 1954, Identification of the Radio Sources in Cassiopeia, Cygnus A, and Puppis A, *Astrophys. J.*, 119, 206

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Biermann, L. 1950, Über den Ursprung der Magnetfelder auf Sternen und im interstellaren Raum (mit einem Anhang von A. Schlüter), *Zeitschrift für Naturforschung*, 5a, 65

Biermann, L. & Schlüter, A. 1951, Cosmic Radiation and Cosmic Magnetic Fields. II. Origin of Cosmic Magnetic Fields, *Phys. Rev.*, 82, 863

Brentjens, M. A. & de Bruyn, A. G. 2005, Faraday Rotation Measure Synthesis, *Astron. Astrophys.*, 441, 1217

Burbidge, G. R. 1956, On Synchrotron Radiation from Messier 87, *Astrophys. J.*, 124, 416

Burn, B. J. 1966, On the Depolarization of Discrete Radio Sources by Faraday Dispersion, *MNRAS*, 133, 67

Carilli, C. L. & Taylor, G. B. 2002, Cluster Magnetic Fields, *Ann. Rev. Astron. Astrophys.* 40, 319

Carmichael, H. 1964, A Process for Solar Flares in *The Physics of Solar Flares, Proceedings of the AAS-NASA Symposium held 28–30 October, 1963 at the Goddard Space Flight Center, Greenbelt, MD*, ed. W. N. Hess (Washington, DC: National Aeronautics and Space Administration), 451

Clegg, A. W., Cordes, J. M., Simonetti, J. H., & Kulkarni, S. R. 1992, Rotation Measures of Low-latitude Extragalactic Sources and the Magnetoionic Structure of the Galaxy, *Astrophys. J.*, 386, 143

Davies, R. D. 1968, Structure of the Galactic Magnetic Field, *Nature*, 218, 435

Fabian, A. C. & Barçons, X. 1991, Intergalactic matter, *Rep. Prog. Phys.*, 54, 1069

Fermi, E. 1949, On the Origin of the Cosmic Radiation, *Phys. Rev.*, 75, 1169

Grasso, D. & Rubenstein, H. 2001, Magnetic Fields in the Early Universe, *Phys. Rep.*, 348, 163

Han, J. L. & Wielebinski, R.W. 2002, Milestones in the Observations of Cosmic Magnetic Fields, *Chinese J. Astron. Astrophys.*, 2, 293

Hess, V. 1912 – cited in Y. Sekido & H. Elliot, eds. 1985, *Early History of Cosmic Ray Studies* (Dordrecht: D. Reidel)

Hiltner, W. A. 1951, Polarization of Stellar Radiation. III. The Polarization of 841 Stars, *Astrophys. J.*, 114, 241

Kiepenheuer, K. O. 1950, Cosmic Rays as the Source of General Galactic Radio Emission, *Phys. Rev.*, 79, 738

Kim, K. T., Kronberg, P. P., Dewdney, P.E., & Landecker, T. L. 1990, The Halo and Magnetic Field of the Coma Cluster of Galaxies, *Astrophys. J.*, 355, 29

Krause, F. 1993, The Cosmic Dynamo: A Review on History, in *IAU Symp. 157, The Cosmic Dynamo*, eds. F. Krause, K.-H. Rädler, and G. Rüdiger (Dordrecht: Springer), 487

Kronberg, P. P. 1994, Extragalactic Magnetic Fields, *Rep. Prog. Phys.*, 57, 325

Kronberg, P. P. & Simard-Normandin, M. 1976, New Evidence on the Origin of Rotation Measures in Extragalactic Radio Sources, *Nature*, 263, 653

Kronberg, P. P. & Newton-McGee, K. 2011, Remarkable Symmetries in the Milky Way Disk's Magnetic Field, *PASA*, 28, 171

Nelson, A. H. 1973, On the Interpretation of Faraday Rotation Data, *Pub. Astr. Soc. Japan*, 25, 489

Pacholczyk, A. G. 1970, *Radio Astrophysics* (San Francisco: Freeman)

Priest, E. R. 1985, The Magnetohydrodynamics of Current Sheets, *Rep. Prog. Phys.*, 48, 955

Rees, M. J. 1987, The Origin and Cosmogonic Implications of Seed Magnetic Fields, *Q. J. R. Astron. Soc.*, 28, 197

Rees, M. J. & Reinhardt, M. 1972, Some Remarks on Intergalactic Magnetic Fields, *Astron. Astrophys.*, 19, 189

Schlüter, A., & Biermann, L. 1950, Interstellarische Magetfelder Zeitschrift für Naturforschung, 5a, 237

Schwinger, J. 1949, On the Classical Radiation of Accelerated Electrons, *Phys. Rev.*, 75, 1912

Shklovskii, I. S. 1953, The Problem of Cosmic Radio Waves. *Ast. Zhur. SSSR*, 30, 577

Shklovskii, I. S. 1953, On the Nature of the Radiation of the Crab Nebula. *Dokl. Akad. Nauk. SSSR*, 90, 983.

Simard-Normandin, M. & Kronberg, P. P. 1980, Rotation Measures and the Galactic Magnetic Field, *Astrophys. J.*, 242, 74

Sofue, Y. & Fujimoto, M. 1983, A Bisymmetric Spiral Magnetic Field and the Spiral Arms in Our Galaxy, *Astrophys. J.*, 265, 722

Sunyaev, R. A. & Zel'dovich, Y. 1969, Distortions of the Background Radiation Spectrum, *Nature*, 223, 721

Sunyaev, R. A. & Zel'dovich, Y. 1969, The Interaction of Matter and Radiation in a Hot-Model Universe, *Astr. Space Sci.*, 4, 301

Vallée, J. P. 1975, Magnetic Field in the Intergalactic Region, *Nature*, 254, 23

Widrow, L. M. 2002, Origin of Galactic and Extragalactic Magnetic Fields, *Rev. Mod. Phys.*, 74, 775

Wielebinski, R. 1990, *The Interstellar Medium in Galaxies*, ed. J. M. Van der Hulst (Dordrecht: Kluwer), 349

Wielebinski, R. & Beck, R., eds. 2005, *Cosmic Magnetic Fields*, Lecture Notes in Physics (Berlin: Springer), 664

Wielebinski, R. & Krause, F. 1993, Magnetic Fields in Galaxies, *The Astronomy and Astrophysics Review*, 4, 449

Wielebinski, R. & Shakeshaft, J. R. 1964, A Survey of the Linearly Polarized Component of Galactic Radio Emission at 408 Mc/s, *MNRAS*, 128, 19

Zel'dovich, Y. & Sunyaev, R. A. 1980, The Angular Distribution of the Microwave Background, and Its Intensity in the Direction of Galaxy Clusters, *Soviet Astr. Lett.*, 6, 285