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Extragalactic magnetic fields

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Abstract

Recent advances in observational techniques reveal the widespread existence of magnetic fields in the Universe, and produce much firmer estimates of magnetic field *strengths* in interstellar and intergalactic space. Ordered, microgauss-level fields are common in spiral galaxy disks and halos, and appear to be a common property of the intra-cluster medium of clusters of galaxies, indeed well beyond the cluster core regions. Strengths of ordered magnetic fields in the intracluster medium of cooling flow clusters exceed those which are typical of the interstellar medium of the Milky Way, suggesting that galaxy formation, and even cluster dynamics are, at least in some circumstances influenced by magnetic forces, which also could possibly affect the global dynamics in areas of some galaxies, especially dwarf galaxies, which are rich in interstellar gas and cosmic rays.

Physical processes responsible for the regeneration of initial seed fields in galaxies, including mechanisms of magnetic diffusivity and dissipation which influence field amplification, are increasingly better, though far from completely, understood. We review the 'conventional', slow mean field α–ω dynamo theory for disk galaxies, and more recent modifications to the theory. Fast-acting dynamo mechanisms appear to operate in galaxies, galaxy inflow and outflow, and in cooling flow clusters. Better understanding of the magnetic properties of extragalactic radio jets, including recent 3D numerical simulations, has shown how fast dynamo processes associated with the radio jet/lobe combination can effectivity magnetize large volumes of intergalactic space. Such processes, and starbust-driven outflow during the galaxy formation epoch, could have produced the microgauss level fields now commonly seen in galaxy systems—which would obviate the need for slow acting dynamos to build up field strength slowly over cosmic time.

The observational methods for detecting and measuring extragalactic magnetic fields are discussed, along with some new indirect methods which could be used for inferring field strengths at large redshifts which are otherwise beyond the reach of direct measurement.

Seed fields can be produced in battery-like processes in a variety of systems (stars, supernovae, and supernova winds), and are expelled into intergalactic space. Various cosmological seed field generation mechanisms are reviewed, which could generate seed fields for the subsequently formed galaxies. The question of whether the original seed fields were produced in galaxies, or the pre-recombination early Universe must await a clearer picture of how the first stars and galaxies formed, up to now, largely a 'dark' era.

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Contents

1. Introduction

1.1. A little bit of history; how magnetic fields have been measured

Until recently, the role and influence of magnetic fields in the extragalactic Universe has remained an unknown, and hence often ignored aspect of astrophysics. Most of what is known of magnetoplasma processes in astrophysics has come from solar studies—where we could make direct measurements of the field direction and strength through measurement of Zeeman splitting, and gain understanding of the role of magnetic fields in particle acceleration from the dynamic analysis of solar bursts and prominences. The observations and related theory describing the role of solar magnetic fields have developed since the Second World War.

Awareness of the existence of magnetic fields in *diffuse* astrophysical plasmas, i.e. beyond the solar corona, began with the discovery of synchrotron radiation (Schwinger 1949) and important energy loss process for relativistic electrons in a magnetic field. Then came the realization in the early 1950s (Alfvén and Herlofson 1950, Kiepenheuer 1950, Shklovskii 1953) that the (then) newly discovered, non-thermal emission from the interstellar medium of the Milky Way and supernova remnants is indeed synchrotron radiation, which requires *both* a magnetic field and relativistic electrons through the emissivity equation

$$\varepsilon(\nu) \approx 10^{-23} n_{\mathrm{cr}0} l \xi(\gamma)(6.3 \times 10^{18})^{(\gamma-1)/2}$$
$$\times (\mathrm{B} \sin \varphi)^{(\gamma+1)/2} \nu^{(1-\gamma)/2} \,\mathrm{erg\,s^{-1}\,cm^{-2}\,Hz^{-1}\,Sr^{-1}}. \tag{1.1}$$

The index γ describes the power law slope of the energy distribution of the relativistic electrons ($n_{\mathrm{cr}}(E) = n_{\mathrm{cr}0} E^{-\gamma}$), $\xi(\gamma)$ is a slowly varying function of γ, being unity for $\gamma = -2.5$, l (cm) is the line-of-sight dimension of the emitting region, φ is the average electron velocity pitch angle with respect to each electron's local field direction, B is the total field strength in Gauss, and ν is in Hz (cf Pacholczyk 1970).

As radio astronomy developed in the 1950s, the discovery of extended extragalactic radio sources (EGRS) with similar, non-thermal emission spectra meant, by implication, that they too must shine by synchrotron radiation, and hence possess an associated magnetic field.

However, from verifying the existence of a magnetic field to actually measuring the field *strength* is a big, and non-trivial step since, from equation (1.1), the synchrotron emissivity, although measurable, does not give us the magnetic field strength, which scales by the local number density of relativistic electrons, $\mathrm{n_{er}}$ (and/or positrons, $\mathrm{n_{pr}}$). Obviously if we are to build magnetic fields into our understanding of galaxy formation and cosmology, we must be able to measure magnetic field strengths.

A direct way of measuring the strength of a uniform magnetic field is to measure Zeeman splitting of a radio transition in the interstellar gas.

$$\nu = \nu_{mn} \pm eB(4\pi mc)^{-1} \,\mathrm{Hz}. \tag{1.2}$$

Where ν_{mn} is a single transition, and B is in Gauss. The first successful measurements, for the interstellar H I line in absorption, were made in the late 1960s (Davies *et al* 1968, Verschuur 1968). The long time between the original suggestion that an interstellar Zeeman effect should be observable (Bolton and Wild 1957) and these first detections is a measure of the technical difficulty, at the time, of conducting such measurements. Subsequent observational studies have since made great progress, and have provided considerable information on the magnetic field strength in interstellar clouds in our galaxy (see Heiles 1990 and references therein for a recent review). Unfortunately, Zeeman splitting has not been observed in external galaxies, much less in intergalactic space, because of Doppler smearing of the radio lines due to dynamical effects, combined with the rather weak field strengths.

Zeeman splitting has also been detected in the pairing of maser transitions of the OH molecule in the λ 18 cm band. Successful measurements of magnetic field strengths using OH Zeeman splitting were made by Zuckerman *et al* (1972), and more convincingly with very long baseline interferometer observations of excited OH lines near λ 5 cm by Moran *et al* (1978). However these measurements can only be made in compact H II regions and similar systems at high densities ($n \sim 10^7\,\mathrm{cm}^{-3}$), where the magnetic fields are typically 2–10 mG and the size scales are 10^{13} to 10^{17} cm (Reid and Moran 1981). These, in any case interesting, measurements might at first sight seem irrelevant to the subject of *extragalactic* magnetic fields. However they reveal a remarkable additional fact, which may point to how galactic magnetic fields built up from primeval seed fields; namely that the *sign* of the magnetic field direction remains consistent over compact OH sources in the same region of the galaxy and, according to Reid and Silverstein (1990), appears to trace the large scale galactic field. Another similar, and unexpected phenomenon is the discovery by Appenzeller (1990) of an apparent alignment between the highly collimated circumstellar-scale flows from Herbig–Haro objects and the large scale interstellar magnetic field. This apparent coupling of sub-pc to kpc scale fields, originally suggested by Davies (1974), lends support to the idea that magnetic field compression occurs during protostellar contraction (Spitzer 1968, Mouchovias 1976, Mestel 1977), and that the field *strength*, being a few μG in the general interstellar medium (ISM) and 6×10^{-3} G at $n \sim 10^7\,\mathrm{cm}^{-3}$, goes as $|B| \propto n^{1/2}$. An isotropic contraction with a frozen-in field, by contrast, would give $|B| \propto n^{2/3}$. These results have given us some of the first quantitative indications of how magnetic fields evolve in collapsing systems. Thus they may give important clues to understanding the role of magnetic fields in collapsing galaxy systems.

Another detector of magnetic fields is Faraday rotation measure (RM) of the linearly polarized emission of radio sources, given by

$$\mathrm{RM}\ \Delta\chi/(\Delta\lambda^2) = 8.1 \times 10^5 \int n_e B_\parallel \, \mathrm{d}l \ \mathrm{rad\ m}^{-2} \qquad (1.3)$$

where χ is the rotation (degrees) of the plane of polarization measured at wavelength λ(m), n_e (cm^{-3}) is the local density of non-relativistic electrons, $B_\parallel$ the line-of-sight component of magnetic field (G), and l the path length (pc). The magnetic field strengths and baryonic matter densities in interstellar and intergalactic space are such that Faraday rotation is detectable at radio wavelengths. From (1.3) we see that, to estimate the uniform magnetic field *strength* from Faraday rotation, we require an independent measurement of the free electron density, and knowledge of its weighted distribution along the line of sight. For pulsars in our galaxy, this is available in the form of the *dispersion measure* ($\mathrm{DM} \propto \int n_e \, \mathrm{d}l$) of pulsars. DMs can be measured from the relative pulse delay versus frequency relation, so that the ratio RM/DM gives a weighted value of the line-of-sight component of field strength along the interstellar sight line to the pulsar. This type of magnetic field measurement was first performed by Lyne and Smith (1968). Unfortunately, pulsars are too faint to observe in external galaxies, so that this method cannot be applied to the measurement of extragalactic field strengths. A possible caveat to this statement might conceivably follow from the increasing evidence for *intrinsic* rapid time variability—down to intra-day scales—of some very compact quasars (cf Quirrenbach *et al* 1991). If suitable 'time markers' in the light curves of extragalactic objects can be identified over a frequency range large enough to measure their extragalactic DM, this, combined with an RM (from simultaneous multi-frequency polarization measurements) would give a measure of the extragalactic magnetic field strength, *modulo* some assumptions about the field reversal scale.

In practice, and as discussed in section 5.2.1, the finite angular resolution will cause (1.3) to be an average over different lines of sight, depending on the scale of the magnetized region being measured. Since we would like to measure *one* line of sight, this means the higher the angular resolution, the better. If we can independently measure the density of the ionized gas associated with the Faraday rotation, *and* measure the field reversal scale, the magnetic field strength can be derived. Thus, a combination of RM and n_e determinations gives us the best prospect of measuring, or estimating, magnetic field strengths in extragalactic systems.

Beginning in the 1960s, Faraday RMs from linear polarization measurements of extragalactic radio sources, led to the discovery that a large scale, organized magnetic field permeates the disk of our galaxy (Davies 1968), and subsequent measurements of the RMs of ever larger numbers of (polarized) extragalactic radio sources has led to a more refined modelling of the large scale galactic magnetic field structure (Simard-Normandin and Kronberg 1980, Sofue *et al* 1983, Vallée *et al* 1988, Clegg *et al* 1992). The galactic magnetic field appears organized on a grand scale, and also has some large scale field reversal(s). Recent studies of external galaxies (cf Wielebinski 1990) indicate that all disk galaxies are permeated by large scale magnetic fields.

Apart from Faraday rotation combined with independent electron density and field reversal scale estimates, there are few prospects for *directly* measuring magnetic field strengths in the extragalactic universe. However, even in the absence of companion data on n_e, detailed imaging of the polarized radio synchrotron emission and the RM in external galaxies, radio galaxies, and galaxy clusters has given us considerable new information on the morphology, and degree of ordering of extragalactic magnetic fields. Additionally, there are indirect and potentially powerful methods for estimating, or limiting field strengths, which we discuss in section 5.4.

Related overview articles dealing with astrophysical magnetic fields have been published by Asseo and Sol (1987), Priest (1985), Rees (1987a), and Wielebinski and Krause (1993). An interesting historical prologue to the subject has been written by F Krause (1993). Recent and informative review articles can be found on the related topics of radio emission from normal galaxies by Condon (1992), the disk-halo connection in galaxies by Dettmar (1992), and the intergalactic medium by Fabian and Barcons (1991).

1.2. The extent and implications of extragalactic magnetic fields

Observations over the last ten years have produced magnetic field detections not only in galaxy disks, but also in galaxy halos, clusters of galaxies, and in some very distant galaxy systems which 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.

It is important to understand how galaxy formation and evolution is influenced by the existence of magnetic fields, whose presence has been so far largely ignored in the modelling of these processes. In particular, we would like to know how magnetic fields have been amplified over cosmic time to the μG levels observed in present-epoch galaxy disks. Was the original weak seed field a product of the Big Bang, or were the first magnetic fields created in stars by Biermann's 'battery' process (Biermann 1950), and subsequently ejected into the early intergalactic medium? To provide some answer to this question, we need to estimate intergalactic field strengths both at the present, and earlier cosmological epochs.

Studies of the Sun's magnetic field have led to a good deal of understanding of the amplification, or *regeneration*, of magnetic fields, in particular the dynamo mechanism (Parker 1955, Steenbeck and Krause 1969). The MHD dynamo proposed for galaxy disks is driven by two fundamental components, one due to non-uniform rotation, called the ω-effect, and the second due to cyclonic motions, called the α-effect. Other important phenomena are diffusivity, caused by resistive dissipation, and/or magnetic reconnection. For the Sun, and for Sun–Earth interactions both of these latter are important. Certainly dynamo processes, and possibly reconnection appear to operate on galactic and intergalactic scales, and it is currently a major challenge to both observation and theory to elaborate and better understand how they function.

We would like to know if the intergalactic voids are permeated by a widespread magnetic field, and if there is any evidence for or against field strength evolution in galaxies since the time of galaxy formation. If there is a widespread intergalactic field, was it frozen into the baryonic IG gas? If so, the evolution of its strength over cosmic time should be derivable from the co-moving, uncondensed matter density, $\rho(z)$ over the observable redshift range. If magnetic fields were widespread since the early universe were they dynamically significant, and if so at what crucial periods of galaxy evolution? Or, restating the question: how have widespread magnetic fields affected the evolution of stars and galaxies since the early universe?

Some *a priori* statements of expectation can be made. First, intergalactic magnetic fields will constrain the heat conductivity of the gas. They also provide an additional component of pressure to the interstellar and intergalactic gas. They couple cosmic ray particles to the non-relativistic gas, and depending on density of magnetic energy relative to the bulk dynamical and thermal energy densities of the gas, magnetic fields could strongly constrain the dynamics of galaxy formation. Purely the effect of an (even weak) magnetic field on the *conductivity* of the interstellar gas will have important consequences for galactic evolution. From an observational standpoint, the magnetic field structure in disks and halos can serve as a tracer of the disk dynamics and, though less directly, of the past dynamics thanks to the high conductivity of interstellar gas and consequent long lifetime of the interstellar fields. The following sections review the state of our knowledge of these fields and some of their implications.

2. Large scale magnetic fields in cosmologically nearby galaxies

2.1. Introduction

Both the theory and observations of extragalactic magnetic field strengths and structures have made great progress in the past five years; in this section we give an overview of observational methods and results, and of the 'standard' dynamo theory of field amplification in galaxy disks, and compare theory and observation of galaxy-scale fields.

Current research into galactic magnetic fields is aimed at answering the following specific questions and puzzles.

(i) How was the observed large scale organization of galactic magnetic fields achieved?

(ii) How do the large scale patterns of magnetic fields correlate with other aspects of galaxies, such as star formation rate, overall dynamics, molecular gas distribution, strength of outflow, etc?

(iii) To what extent, and by what physical mechanisms do disk galaxies amplify their large scale magnetic fields, and what determines the limiting field strengths achieved over a galaxy's lifetime?

(iv) What were the pre-galactic seed field strengths; were they of order 10^{-11} G or fainter, or did the galaxy form in the presence of pervasive magnetic fields of order 10^{-8} to 10^{-6} G levels? If the initial field strengths were 10^{-8} G or weaker, dynamo amplification, an exponential process, is required. However, if microgauss fields already existed at protogalactic epochs, then large scale dynamos may only have influenced the geometry more than the strength of magnetic fields in *already formed* galaxies.

(v) Were galaxies the prime generators of intergalactic magnetic fields in the first place—through outflow of magnetoplasma over cosmic time—or were significant fields already generated in the pregalactic era?

(vi) Did the degree of ordering and strength of the interstellar magnetic field have a strong influence on the locations and dynamics of starforming regions?

Some important clues are beginning to emerge from recent, detailed observations of nearby galaxies, mostly in the radio. In the following, we review the various observational means available of detecting and measuring the galactic magnetic fields, and summarize what these data reveal. We then summarize the basic dynamo theory of field regeneration, and compare its predictions with current observations. We discuss their successes and shortcomings in reproducing observed galaxy-scale fields. We conclude that a slow buildup of large scale galactic fields over cosmic time from very small initial seed fields now appears less likely to explain observations of galaxy-scale magnetic fields than was first thought.

The Milky Way and other late type galaxies are permeated with (i) cosmic ray gas, (ii) magnetic fields, which generate polarized synchrotron radiation (iii) ionized (and neutral) interstellar gas which causes Faraday rotation in the radio, and (iv) interstellar grains which align with the interstellar field and induce linear polarization in the optical starlight by selective absorption or scattering. These four ingredients make it possible to observationally trace the large (and small) scale magnetic structure in galaxies. Component (i) (represented by equation (1.1)) has an intrinsic polarization of up to $\approx$75% in a completely aligned magnetic field. We note that the observed *degree* of linear polarization in a 2D projection (what is observed) does not necessarily reveal the true 3D degree of alignment of the magnetic field, nor the *sign* of the local magnetic field vector. More specifically, observations of polarized synchrotron emission do not distinguish between a zone of true unidirectional, aligned field, and one where the magnetic field lines are stretched (or compressed) in *one* dimension, but are systematically reversing their sign (e.g. for a disk seen edge-on—a point elucidated by Laing (1981)). Suitable observations of (i), (ii) and (iii) can reveal the sense of the magnetic field, and also the strength of the line-of-sight field component (equation (1.3)) if n_e is independently measureable.

Optical polarization observations relevant to (iv) have made great strides due to the recent availability of imaging CCD polarimeters (cf Scarrott 1991). Optical polarization is a tracer of the interstellar magnetic field direction, as was first shown by Davis and Greenstein (1951). In the 'Davis–Greenstein effect', non-spherical interstellar grains will align their angular momentum vector with the local magnetic field direction, thereby causing direction-dependent absorption and scattering of the incident starlight. Their detailed interpretation requires some additional knowledge, or assumptions, about the size and scattering properties of interstellar dust and electrons. Interstellar optical polarization can be caused by simple scattering, and also by dichroic extinction i.e. differential transmission for X- and Y-polarized photons due to interstellar grains which are aligned with the local galactic magnetic field (Scarrott *et al* 1986). Observation of the wavelength dependence of the optical polarization at a given point in the galaxy can distinguish 'signature' $p(\%)$-λ curves (Zerkowski curves) due to these different effects—for which the grain size-range and composition needs to be known, or modelled. A notable advantage of optical polarimetry is the higher resolution than what is possible with current radio techniques. Thus, optical polarization data can detect small-scale fluctuations in galactic fields. As with polarimetry of the synchrotron radiation, and in contrast to Faraday RM imaging, optical polarimetry does not convey information about the field *sign*.

2.2. *Observational overview of large scale magnetic fields in spiral galaxies*

2.2.1. Current instrumental capabilities. The improved sensitivity and polarimetric capability of both radio and optical telescopes has revealed a great deal about the morphology and extent of magnetic fields in galaxies over the past five to ten years. In this section we explain the observational methods (well described by Krause 1990), and illustrate how they can be used to reveal magnetic field morphology and strength in relatively nearby galaxies. The latter have typical projected sizes of a few to a few tens of arcminutes, so that typically 5 to 15 linear resolution elements can be obtained with large, single-dish radiotelescopes at $2\ \text{cm} \leqslant \lambda \leqslant 20\ \text{cm}$—the usable wavelength range for this purpose. Good, and well calibrated beam characteristics are required for polarization of these extended objects, where the telescope's beam is embedded in an extended polarized source. The 100 m Effelsberg telescope of the Max-Planck-Institut für Radioastronomie (resolution $= 4.0'(\lambda/10\ \text{cm})$) has been a prime instrument for such measurements at the shorter λs. At the longer wavelengths and for more distant galaxies, the higher resolution of *radio arrays* is necessary; notably the NRAO VLA and the Westerbork Synthesis Radio Telescopes. There is a complicating difficulty with interferometers for imaging *diffuse* polarized emission in nearby galaxies which results from their inherent tendency to filter out the largest scale components of diffuse polarized emission. It is also sometimes difficult to deconvolve the latter from polarized sidelobe structure of the individual array antennas, since the largest images—e.g. M31—are sometimes larger than the beam size of a single interferometer element.

2.2.2. Current knowledge of spiral galaxy disk magnetic fields. Figure 1 shows a recent λ 2.8 cm (10.7 GHz) Effelsberg 100 m telescope 'magnetic field' image of the 6 Mpc distant, barred spiral galaxy Messier 83 at 68″ resolution (Neininger *et al* 1991). The large scale coherence of the magnetic field is striking, and this is typical of the *ca* 20 nearby galaxies mapped thus far at *some* radio wavelength. A derivation of the true projected magnetic field orientation normally requires polarization images at two, and preferably more radio wavelengths, so that Faraday rotation (equation (1.3)) can be removed at each image point. At the relatively short radio wavelength of 2.8 cm a Faraday rotation of 2.4° (relatively insignificant) corresponds to a Faraday rotation measure (RM) of 55 rad m^{-2} which, from our general knowledge of galaxy disk RMs, is

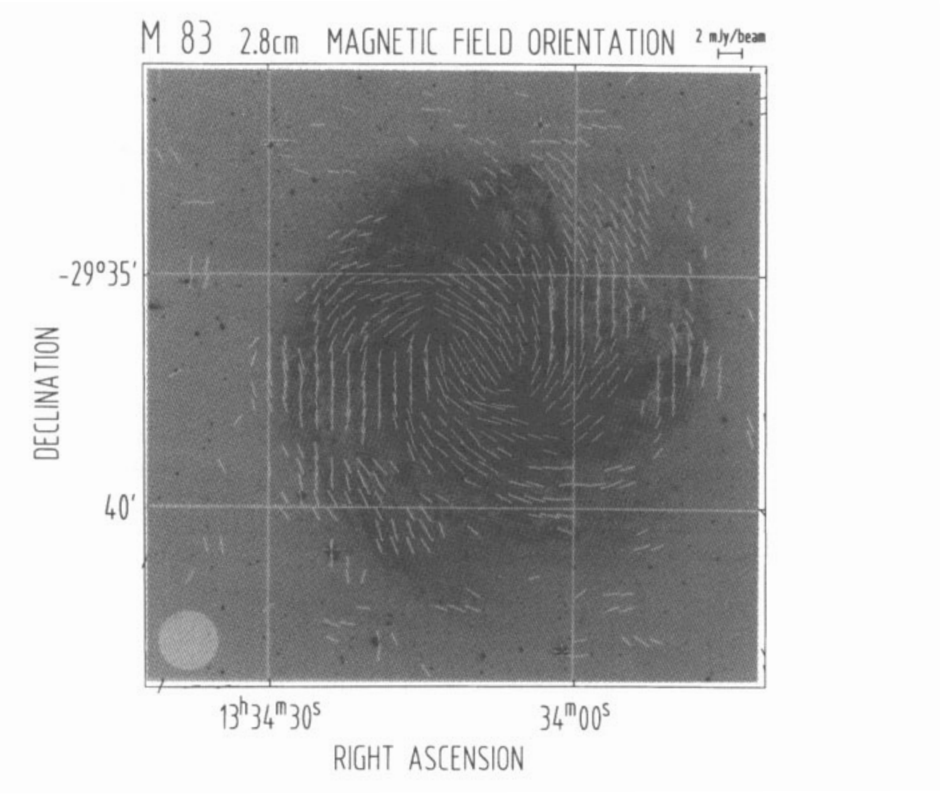


Figure 1. A radio-optical superposition of M83, in which the normals to the maximum E-vector direction at λ 2.8 cm gives a good approximation of the projected magnetic field orientation at a resolution (circle at lower left) of 1.2′ ($\approx$2 kpc). Figure from Neininger *et al* (1991).

unlikely to be exceeded at this resolution for a relatively 'top-on' view of the disk. Thus, a single short λ polarization map such as in figure 1 gives a good approximation to the intrinsic magnetic field orientation over the galaxy.

The fact that the polarized (synchrotron) component of the diffuse radio emission becomes fainter with increasing frequency ($S/\Omega \propto \nu^{\alpha}$, $\alpha \approx -0.6$) underlines the 'state-of-the-art' nature of the image in figure 1 which, at $\nu = 10.7$ GHz, is already sensitivity limited. A higher angular resolution would further reduce the flux density per beam and hence reduce the polarized signal. An advantageous consequence of the low Faraday rotation at higher radio frequencies near 10 GHz is that differential Faraday rotation is minimized, which would otherwise cause depolarization along each bundle of sight-lines within the galaxy. Thus, the galaxy is not 'Faraday opaque', which can be the case at longer λs, e.g. at $\approx$20 cm (cf Neininger *et al* 1993 for the case of M83).

A similar large scale, organized field is revealed by polarimetry of the optical surface brightness, as illustrated in the recent image in figure 2 of NGC 1068. The overall magnetic field alignment is striking, as in the radio polarization maps. Although no information about the *sign* of the *B*-direction can be inferred from optical polarization images, their resolution is limited only by the sensitivity of the detector/telescope combination, down to the optical 'seeing' limit of resolution, which is of order 1 arcsecond for a ground-based telescope. Because of the multiple causes of optical polarization, and problems of optical

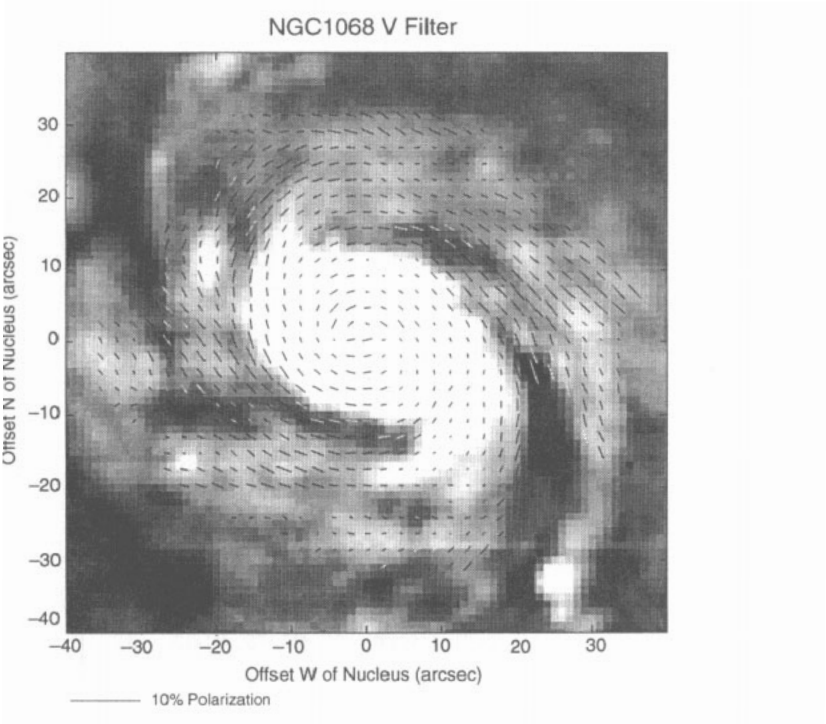


Figure 2. The prevailing magnetic field orientation in the optical V-band for the galaxy NGC 1068 (S M Scarrott, private communication). Typical degrees of optical polarization lie in the range 0% to 5%.

extinction in inclined galaxy disks, the most yielding of optical information on the magnetic field morphology are nearby, face-on galaxies like the one shown.

Not shown in figure 1 is the Faraday rotation measure (RM), which can also tell us, at each polarization pixel, whether the field has a component which is directed into or out of the plane of the sky. Whether or not there are global reversals of prevailing magnetic field *sense* is an interesting question, which bears directly on the field amplification mechanism, and possibly on how the protogalactic ω axis was coupled (if it was) to a primeval intergalactic field. RM oberservations can distinguish whether the global galaxy disk field has an *axisymmetric*, or *bisymmetric* form, as illustrated schematically in figure 3. Observational discrimination between these two possibilities can be made with multi-λ polarization images, using a straightforward technique first suggested by Tosa and Fujimoto (1978). For the bisymmetric field case in figure 3(*a*), we can model the global magnetic field as a spiral (as justified from figures 1 and 2), and plot the observed RM as a function of azimuth angle (θ) for a suitable radial zone (r_{outer}-r_{inner}) within the de-projected plane of the galaxy's disk. For an inclination angle $i > 0°$ (face-on $= 0°$), a plot of RM against θ has four zero-crossings for a bisymmetric field galaxy, as opposed to two for an axisymmetric (non-reversing) global field morphology. This is illustrated in figure 3(*c*), along with data from two galaxies. Additional geometric details of the disk field can be specified, such as the pitch angle, p, of the spiral field direction, and position angle, Φ, of the point of maximum RM on the circle, in which case the model RM-θ curve can be expressed as

$$\mathrm{RM}(\theta) = \tfrac{1}{2}\mathrm{RM}_0 \tan i[\cos(2\theta - p - \Phi) + \cos(p - \Phi)] \qquad (2.1)$$

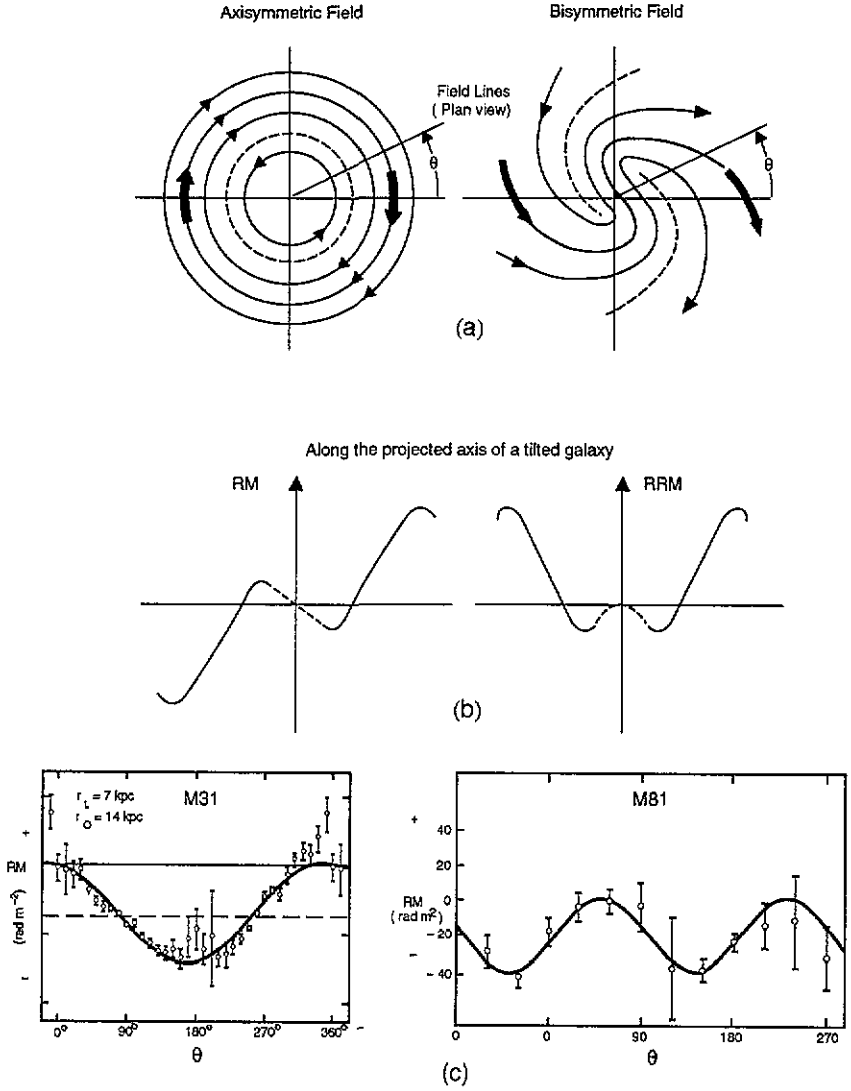


Figure 3. (*a*) Face-on view of a model axisymmetric (*left*) and bisymmetric (*right*) magnetic field distribution in a galactic disk. (*b*) RM(r) measured along the major axis of the projected galaxy for the axisymmetric (*left*), and bisymmetric (*right*) case, respectively. (*c*) The form of the RM(θ) distribution within an annulus of the deprojected galaxy for an axisymmetric and bisymmetric field, along with the actual data for two different galaxies. Adapted from Tosa and Fujimoto (1978) (*a*), Sofue *et al* (1985) (*b*), Beck (1982) (M31) and Krause *et al* (1989) (M81) (*c*).

(Tosa and Fujimoto 1978, Sofue *et al* 1986). A quicker observational discriminant between asymmetric and bisymmetric structure, proposed by Sofue *et al* (1985), is simply to plot the observed RM(r) along the projected major axis of the galaxy disk, from which the 'signatures' of an axisymmetric and bisymmetric structure can be distinguished. This is illustrated in figure 3(*b*). Better still would be a detailed 2D RM map over the entire galaxy surface. Among the very few such images at the time of writing is that of NGC 6946 by Ehle and Beck (1993), which reveals a global, galaxy-scale 'flip' of the RM *sign* between the two halves of this galaxy's disk—thus indicating an overall axisymmetric field configuration. It should be noted that the model curves in figure 3 assume purely toroidal fields in an infinitely thin disk—which is now generally realized to be unrealistically simple (cf sections 2.3, 5, 6).

From the available subset of nearby galaxies having RM(θ) measurements analysed as just described, both axisymmetric and bisymmetric configurations appear to exist. It is also increasingly apparent that some galaxies do not conform to either, including M83 in figure 1. In this connection we note that these classifications may be sensitive to the linear resolution available, and also possibly to the galaxy's inclination or disk thickness (z-height). Thus galaxy magnetic field configurations, and the classification scheme are subject to future modification. In general, global disk fields appear more aligned in the inter-arm regions, and less so in the visible arms (Beck 1991), and the degree of field uniformity is anticorrelated with the intensity of CO line emission, which comes from the denser, hence starforming regions—i.e. the visible spiral arms (Bajaja *et al* 1991). As more detail emerges, the situation becomes more complex; for example in M31 (the Andromeda galaxy), where good linear resolution obtains due to its proximity, the patterns of Faraday rotation and field ordering do not conform on *smaller* scales to either a simple AS or BS model (Krause *et al* 1989, Beck *et al* 1989). A more complex pattern has also emerged in detailed studies of M83 (Sukumar and Allen 1989, 1990, Neininger *et al* 1993). While the magnetic field structure is generally better aligned in the *outer*most regions of spiral galaxies, the simple model assumptions of equation (2.1) and figure 3 are oversimplified at smaller galactocentric radii. More specifically, the form of the curves in figure 3(c) requires that the pitch angle, p, be constant over the galaxy's disk. This may not normally be so, as is already evident in M31 and M83. We discuss further observational evidence and physical reasons below, for magnetic fields directed *out of* a galaxy's plane. Also, systematic field reversals may be occurring which may not conform to a large scale bisymmetric field, but which may rather be due to effects which are local, and possibly transient. Thus, the field models suggested in figure 3(a) may, with future data prove to be very oversimplified; in particular they do not incorporate halo or out-of-plane fields (cf sections 2.3.5, 2.3.6).

2.2.3. Observations of magnetic fields in halos of galaxies. A datum of interest is the magnetoionic strength *above* the disk of our own galaxy, and in the Galactic Halo-which we can compare with the 'out-of-disk' and halo magnetic fields of other spiral galaxies. Simard-Normandin and Kronberg (1980) used the (l, b) distribution of EGRS RMs to estimate the Milky Way's magnetoionic scale height, and determined a value of 1.4.kpc (full width), which is relatively insenstive to the field reversal scale. This is similar to the galactic scale height of the hot gas, ≈1 kpc (cf Kulkarni and Heiles 1987, Reynolds 1990). It also indicates that any Faraday RM in the halo of our galaxy is small compared with that in the disk. Information is just beginning to appear on the Faraday rotation in the higher halos of nearby spiral galaxies, however recent attempts to detect synchrotron-emitting 'halos' of galaxies seen edge-on indicate full widths (*to the* 1% *level of surface brightness*) of 2–4 kpc (Klein *et al* 1984, Hummel 1990). This result is not inconsistent with the scale height quoted above. We note, though, that a few galaxies, those with increased star formation activity, reveal pronounced and larger halos at lower radio frequencies, in which polarized emission traces the magnetic field out to large distances above their galactic planes. These are discussed separately below (section 3.1).

Improved resolution and sensitivity to radio synchrotron emission off the disks of some normal galaxies—which were observationally selected to be edge-on for the purpose of investigating the out-of-plane field geometry—has recently provided valuable new information on the z-component of disk fields, and the orientation and degree of ordering of these fields out to large z-heights. A case in point is the edge-on galaxy NGC 891 (which is largely similar to our Milky Way). NGC 891 shows polarized synchrotron radiation up to 4 kpc into the halo, in which the field ordering first increases, then decreases with z (Hummel *et al* 1991). Another edge-on galaxy, NGC 4631 shows a similar behaviour (Hummel *et al* 1988, 1991), but with a radially aligned magnetic field direction (the sense is not measured) out to ≈ 7 kpc from the disk—see figure 7 (section 3.1 below). For the same galaxy, another scale height has been measured, namely that of the ionized gas layer by imaging the diffuse optical H_α emission, giving a scale height of ≈ 1.1 kpc (Rand *et al* 1990, Dettmar 1990). The H_α data agree with a similar scale height of ≈ 0.9 kpc estimated from Faraday dispersion due to thermal ionized gas embedded within the polarized halo emission (Hummel *et al* 1991).

2.3. *The physics of magnetic field amplification and evolution in spiral galaxies*

2.3.1. The fundamental processes. The equations governing the evolution of magnetic field in non-viscous conducting plasma consist of Maxwell's equations, Ohm's law, the equation of continuity, and an equation of motion:

$$\partial \boldsymbol{B}/\partial t = -c\nabla \times \boldsymbol{E} \tag{2.1}$$

$$\nabla \cdot \boldsymbol{B} = 0 \quad \text{and} \quad \nabla \cdot \boldsymbol{E} = 4\pi\rho_c \qquad \text{Maxwell's equations} \tag{2.2}$$

$$\nabla \times \boldsymbol{B} = (4\pi/c)\boldsymbol{j} + c^{-1}\,\partial \boldsymbol{E}/\partial t \tag{2.3}$$

$$\boldsymbol{j} = \sigma(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B}/c) \qquad \text{Ohm's law} \tag{2.4}$$

$$\partial\rho/\partial t + \nabla \cdot (\rho \boldsymbol{v}) = 0 \qquad \text{the continuity equation} \tag{2.5}$$

$$\rho\{\partial \boldsymbol{v}/\partial t + (\boldsymbol{v} \cdot \nabla)\boldsymbol{v}\} = -\nabla\Phi - \nabla P + \boldsymbol{j} \times \boldsymbol{B}/c \qquad \text{the equation of motion.} \tag{2.6}$$

The electric and magnetic fields are $\boldsymbol{E}$ and $\boldsymbol{B}$, respectively, ρ is the mass density, $\boldsymbol{j}$ is the current density, σ is the conductivity, ρ_c is the net charge density, P the pressure, $\boldsymbol{v}$ the velocity, and Φ is the gravitational potential. We note in passing that P includes the interstellar thermal gas and cosmic ray pressures, *including* that of the (sometimes ignored) relativistic protons and heavier nuclei. These particles may have $\approx 10^2$ times the energy of the 'visible' synchrotron-emitting relativistic electrons. The evolution of the magnetic field is described by solutions to the induction equation (cf Parker 1979), which can be derived from equations (2.1), (2.3) and (2.4)

$$\partial \boldsymbol{B}/\partial t = \nabla \times (\boldsymbol{v} \times \boldsymbol{B}) - \nabla \times \eta(\nabla \times \boldsymbol{B}) \tag{2.7}$$

where $\eta = c^2/4\pi\sigma$ is the magnetic diffusivity. If the magnetic field is 'frozen in', then $\eta = 0$ (or $\sigma = \infty$), so that the term $\nabla \times \eta(\nabla \times \boldsymbol{B})$ vanishes. Another relevant quantity is the magnetic Reynolds number,

$$R_m = [\lambda_B][\lambda_v]/\eta \tag{2.8}$$

where $[\lambda_B]$ and $[\lambda_v]$ are the typical variation scales for $\boldsymbol{B}$ and $\boldsymbol{v}$, respectively. For most purposes in this review, the regime $R_m \gg 1$ applies. In the absence of pressure and density perturbations, MHD waves will propagate with the Alfvén velocity which is given by

$$V_A = B/\sqrt{4\pi\rho}. \tag{2.9}$$

For a more complete discussion of physical processes in magnetoplasmas the reader is referred to Parker (1979), Zel'dovich *et al* (1983), Priest (1985), Asseo and Sol (1987) and references therein. It is important to note that equation (2.7) does not contain a source term for magnetic field. This underlines the need for theories to account for the source of magnetic fields—such as the Biermann battery mechanism, or a cosmological seed field (cf section 5). Thus a pre-existing 'seed' field is presupposed. The second important point is that even after a source, or seed field is identified, a generation process is required to sustain the fields against resistive and other decay processes—represented by the second term in equation (2.7).

The gravitationally-driven dynamics of disk galaxies naturally provide a large scale, ordered motion with a large energy density. The following section describes the 'conventional' galactic dynamo mechanism, which is based on concepts developed earlier for the Sun and Earth (Parker 1955, Steenbeck *et al* 1966, Steenbeck and Krause 1969, and others). It attempts to describe how ordered galactic motions can amplify, and at the same time produce ordered magnetic fields, which 'tap into' the larger source of gravitational energy in large spiral galaxies. It assumes that the initial fields were very much weaker than at the present epoch—an assumption which we shall later call into question. It also largely ignores the role of cosmic rays, an aspect which we also discuss later.

2.3.2. The conventional galactic dynamo in 'well-behaved' disk galaxies. Spiral disk galaxies possess gravitationally driven ordered motions, namely a 'solid body' ($v_\phi \propto r$) rotation which, due to the galaxy's distributed mass, transforms into differential rotation at larger galactocentric radii. The latter may or may not be quasi-Keplerian (depending on the global distribution of mass), but in any case there is velocity shear ($\partial v/\partial r$). Superimposed on these global dynamics are streaming motions, possibly induced by density waves and/or magnetic fields (see below) and, for some galaxies, non-axisymmetric motions due to gravitational interactions with satellite or other nearby galaxies. Finally there are interstellar turbulent motions, typically a few km s^{-1}. Typical (kinetic) energy densities due to global rotation, $\varepsilon_{\rm grav}$, are of order 3.3×10^{-10} erg cm^{-3}, but these decrease significantly at large galactocentric radii. By contrast, energy densities of the synchrotron-emitting cosmic ray gas $\varepsilon_{\rm cr}$ are of order 10^{-12} erg cm^{-3} and the interstellar magnetic energy density is $\varepsilon_{\rm m} = ((B/5\,\mu{\rm G})^2 \times 10^{-12}$ erg cm^{-3}. The energy density of the smaller-scale turbulent motions, $\varepsilon_{\rm t} = \frac{1}{2}\rho v^2$, is $\approx 0.6 \times 10^{-12}$ erg cm^{-3}. Of fundamental significance for the physics of large scale MHD processes in galaxies are the facts just illustrated, that $\varepsilon_{\rm grav}$ dominates the others (except at large galactocentric radii), and that

$$\varepsilon_{\rm cr} \approx \varepsilon_{\rm m} \approx \varepsilon_{\rm t}. \tag{2.10}$$

We can further note that the ΔV of density wave-induced streaming motions are of order 5–10 km s^{-1}, so that $\Delta\varepsilon_{\rm grav} \approx 3 \times 10^{-13}$ erg cm^{-3}, is not much different from $\varepsilon_{\rm cr}$, $\varepsilon_{\rm m}$ and $\varepsilon_{\rm t}$. Another important energy component to consider is that due to supernovae (or multiple supernovae within a small galactic region) and dense clusters of young stars, both of which can, temporarily and locally, deposit significant energy densities (in the form of $\varepsilon_{\rm cr}$, $\varepsilon_{\rm m}$ and $\varepsilon_{\rm t}$) into the otherwise 'quiescent' interstellar disk. We shall call this component ε_*. These basic energetic facts are key to the evolution of magnetic fields in galaxy disks.

An elegant theory for field amplification called the α-ω dynamo was originally applied to solar magnetic fields (Steenbeck and Krause 1969), and was worked out in the 1960s for galactic magnetic fields by Stix (1975), White (1978), Parker (1966, 1971) and Vainstein and Ruzmaikin (1971). The theory makes use of what is called the *mean field approximation* (cf Krause and Rädler 1980) which is needed to accommodate the fact that we are dealing with averages over a range of correlation scales $\langle l_i \rangle$ and times $\langle t_i \rangle$ of the velocity field, and fluctuations in the magnetic field $\langle B_i \rangle$. Proof of the validity of the mean field approximation, although not trivial, has been worked out (Krause and Rädler 1980, Zel'dovich *et al* 1983; cf also van Kampen 1974, Knobloch 1978); it is, roughly speaking, an MHD analogue of statistical mechanical methods in the study of gases. However the validity of the mean-field solutions has been questioned by Kulsrud and Anderson (1992) who calculate that the build-up of fluctuation energy on small scales occurs before the mean field has a chance to be amplified (see section 2.3.5 below for a related discussion). This latter question should eventually be resolvable through ISM magnetic field measurements over the appropriate range of scales. The tentative result is that the magnetic fluctuation energy does not appear to increase at smaller scales. In fluid mechanics the energy density–wavenumber (k) distribution follows a Kolmogorov spectrum, whose logarithmic slope is $-\frac{5}{3}$ up to some maximum k, where viscosity effect take over and cause a small-scale (high k) cut-off. By contrast, in magnetohydrodynamic theory there appears to be no analagously definitive exponent which can confidently specify the variation of magnetic field strength with fluctuation scale. In a stratified, rotating and turbulent (or convective) section of the galaxy disk, the first induction action, which is due to the velocity shear, $\mathrm{d}\omega/\mathrm{d}r$, causes an azimuthal field, B_ϕ, if there is initially a radial field, B_r (Krause 1987). If we approximate the galaxy disk as a flattened, oblate spheroid of scale b along the rotation (z-) axis, and whose radial scale is a, we can, following Krause (1987), define an ω parameter

$$C_\omega = a^2/\eta\{r\,\mathrm{d}\omega/\mathrm{d}r\} \tag{2.11}$$

where r is the radial coordinate. We now consider an additional effect when turbulence is introduced into this stratified, magnetized layer: *turbulent* motion will be subject to the Coriolis force in this rotating system. Thus, for example, as a bubble of gas expands out of the plane, it will create an expanding 'loop' which, due to its B_z component (see

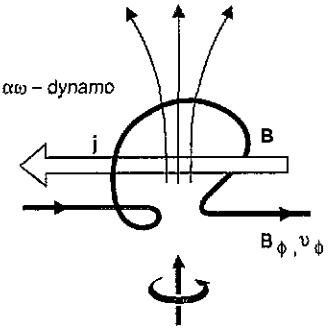


Figure 4. Illustration of the α-effect due to the Coriolis force in a rotating galaxy disk (after Krause 1987).

figure 4) will be twisted by the Coriolis force as it moves out of the plane; in the right-handed sense above the plane (if ω is directed upwards as in figure 4), and in the opposite sense below the plane, thus introducing an natural helicity to the outflowing magneto-plasma. This gives rise to the so-called α-effect. Note that the moving $\boldsymbol{B}_z$ component will induce a current which is antiparallel to B_ϕ (see also below).

Another natural consequence of the α-effect is the production of a poloidal magnetic field component. Because the energy density of the rotational motion is normally higher than ε_t in a well behaved spiral galaxy, the repeated twisting and stretching effects can amplify the field in the disk. In mean-field electrodynamics, α, related to the helicity, $\langle \boldsymbol{v}\cdot(\nabla\cdot\boldsymbol{v})\rangle$, is defined as

$$\alpha = -\tfrac{1}{3}\tau\langle \boldsymbol{v}_\mathrm{T}\cdot(\nabla\times\boldsymbol{v}_\mathrm{T})\rangle \tag{2.12}$$

where τ is the correlation time of the turbulent velocity field represented by $\boldsymbol{v}_\mathrm{T}$. The characteristic α-parameter (again following Krause 1987) is

$$C_\alpha = a\alpha/\eta. \tag{2.13}$$

We are now in a position to evaluate these parameters for the disk of a spiral galaxy, such as the Milky Way. The rotational shear, $r\,\mathrm{d}\omega/\mathrm{d}r$ (Oort's constant) near the Sun is -30 kpc km s^{-1}, v_T is ≈ 10 km s^{-1}, $a \approx 15$ kpc. The size of the turbulent elements, $\lambda \approx 100$ pc. The lifetime of the turbulent elements, τ, the only non-measurable, can be reasonably estimated from $\lambda/v \approx 3\times10^{14}$ s ($=10^7$ yr). A key point is that, specifically due to the Coriolis force, the average $\langle \boldsymbol{v}_\mathrm{T}\cdot(\nabla\times\boldsymbol{v}_\mathrm{T})\rangle$ is non-zero, so that when we incorporate α into the field regeneration equation (2.7), we see that the α-term will affect the *growth* of the magnetic field. The helicity can be expressed as

$$\langle \boldsymbol{v}_\mathrm{T}\cdot(\nabla\times\boldsymbol{v}_\mathrm{T})\rangle = \langle \boldsymbol{v}^2\rangle(\omega\tau)/L \tag{2.14}$$

(Krause 1987) where L ($\gtrsim\lambda$) is the scale height, a value for which can be taken from Simard-Normandin and Kronberg's (1980) estimate of the magneto-ionic thickness of the Milky Way's disk in the vincity of the Sun (section 2.2.3).

To illustrate how a differentially rotating galaxy disk can amplify a pre-existing magnetic field, we re-write equation (2.7) now incorporating α:

$$\partial\boldsymbol{B}/\partial t = \alpha\nabla\times\boldsymbol{B} + \eta\nabla^2\boldsymbol{B} \tag{2.15}$$

where α and η are taken as constants (up to this point). A typical galactic value for the magnetic diffusivity is $\eta \approx 0.1\lambda v$, $\approx 10^{25}$ cm^2 s^{-1}.

2.3.3. Solutions to the mean field dynamo regeneration equation in the linear regime. Solutions to (2.15) can be written in the form

$$\boldsymbol{B} = (\pm\sin kz, \cos kz, 0)\,\mathrm{e}^{\gamma t} \tag{2.16}$$

where $\gamma = -\eta k^2 \pm \alpha k$, k being the wavenumber (Zel'dovich *et al* 1983). $|\boldsymbol{B}|$ grows exponentially with time for non-zero helicity, positive or negative, and if the scales are sufficiently large ($k < |\alpha|\eta$). Another consequence of equation (2.15) is that a mean electric field, hence a mean current, will be directed along the magnetic field (Moffatt 1978, Krause and Rädler 1980) as illustrated in figure 4. The mean field generation equation should be regarded as an approximation of a complex MHD problem in 3D, and there are several simplifying assumptions implicit in our summary discussion here. Our purpose here is limited to illustrating the fundamental physical processes, and to showing how the solutions indeed provide a first-order confirmation of the observed geometry of magnetic fields in disk galaxies, and possibly their present-day strengths. Later in sections 2.3.4 and 2.3.5, we shall cast doubt on whether the standard, mean field dynamo can actually work in many galaxies.

A requirement of (2.15) and (2.16) is that characteristic field growth times be longer than τ. Other restrictive statements we have made above must be modified under different (but still reasonable!) assumptions. For example, our statement above that connects the mean helicity with the α parameter is subject to the assumption that the turbulence associated with α is *isotropic*. In reality, because of stratification, gravity, and rotational motion in galaxy disks, α is generally a tensor (cf Krause and Rädler 1980, 1986, Elstner *et al* (1992). As Zel'dovich *et al* (1983) point out, mean field generation, i.e. solutions of the form $|\boldsymbol{B}| \propto e^{\gamma t}(\mathrm{Re}\ \gamma > 0)$ are also possible if the turbulence is homogeneous and *an*isotropic. For the purpose of this review, this latter fact serves to underline the relative robustness (though not unchallenged) of the mean field solutions as they apply to disk galaxies. The reader is referred to Zel'dovich *et al* (1983) for a lucid physical treatment of kinematic turbulent dynamos, and their application to galactic magnetic fields.

To create an expected 'model' field distribution, it is instructive to parameterize the α and ω effects separately, and then establish, for typical disk galaxy conditions, which modes dominate in what part of the galaxy. The numerical values of the ω and α parameters (2.11 and 2.13), from the observationally estimated values in (2.3.2) above are: $C_\omega \approx -7000$ (the minus sign from the negative $\mathrm{d}\omega/\mathrm{d}r$), and $C_\alpha \approx 50\ \lambda/L$. It is immediately evident that $|C_\omega|/C_\alpha \gg 1$, meaning that the dominant induction action for the amplification of the azimuthal (toroidal) field in the disk is differential rotation (cf Krause 1987). Another useful parameter is $C_1 = C_\alpha C_\omega \approx -10^{-5}$ for the Milky Way. The C-parameters are convenient for exploring the solutions for model galaxy disks, which were first obtained by Stix (1975). The general result for the α–ω dynamo is illustrated in figure 5: The azimuthal field distribution is shown on the right-hand side of this composite flat-ellipse model, and the left side illustrates that a *poloidal* component, which has a quadrupole geometry in 3D, is also produced by the α–ω dynamo.

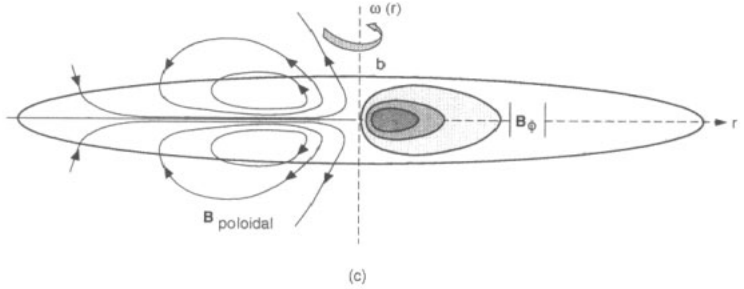


Figure 5. The 3D magnetic field configuration produced by the α–ω dynamo in the flat ellipsoid model of Stix (1975), and White (1978) (adapted from White 1978), showing the morphology of the mean-field solutions for the azimuthal (rh side) component, and a 2D slice of the quadrupolar poloidal component (lh side).

The $\boldsymbol{B}$ solution shown in figure 5 is axisymmetric with respect to the galaxy's rotation axis, and it has reflection symmetry about the equatorial plane. Other solution modes are possible, and testable against observations, especially those of the Faraday RM distribution. Other eigensolutions of the regeneration equation can also produce field geometries which are *antisymmetric* about the equator (cf Krause 1987), and other azimuthal modes. In particular, the azimuth dependence of B is modulated by $e^{im\theta}$ where $m=0$ and $m=1$ give axisymmetric and bisymmetric field distributions, respectively, as illustrated in figure 3. Two nearby galaxies (M81 and M51) appear to have an $m=1$ mode azimuthal field distribution (cf Krause *et al* 1989, Tosa and Fujimoto 1978, Horellou *et al* 1990 and figure 3(*c*)), while some other others, e.g. NGC 6946, appear consistent with an $m=0$ mode for the global field, at least at low angular resolution. This is indeed the solution mode for the mean-field α–ω dynamo with the highest growth rate, for the linear regime and with no distortions from axisymmetry (cf also Elstner *et al* 1992 for relevant numerical simulations). We note, however, that B-field maps from the radio data with the highest linear resolution (in kpc) suggest that reality may not be as simple as just indicated (section 2.2.2). A final judgement on the morphology of magnetic orientation *and sign* should await higher resolution images. So far, the highest resolution comes from the optical B-images but, as noted earlier, they are insensitive to the field sign.

Stimulated by the apparent existence of a dominant $m=1$ mode in at least some galaxies (see section 2.2.2 above), several workers have explored the appropriate model parameter space for stable bisymmetric disk field solutions to the dynamo equations. Fujimoto and Sawa (1987, 1990) and Chiba and Tosa (1990) have produced numerical simulations showing this to be favoured for thick magneto-ionic disk layers ($z_m \gtrsim 0.5$ kpc) and larger turbulent velocities which persist away from the disk. Solutions exist which give a quasi-rigid rotation, ω_{BSS}, which is close to that for spiral density wave pattern, ω_{DW}. This makes it possible, even likely, for a *resonant coupling* to be set up between the two phenomena (Fujimoto and Sawa 1990, Tosa and Chiba 1990, Chiba and Tosa 1990). We recall (section 2.3.2) that the energy associated with the density wave-driven velocity perturbations is comparable to that in the magnetic field perturbations. Such an effect has at least two interesting implications for galaxy evolution: (i) large scale bisymmetric field amplification could, in the right circumstances, be enhanced by density wave patterns and *vice versa*, and (ii) the diffusion times of density waves, $\approx 10^9$ yr (Toomre 1969), might be substantially modified, in particular, lengthened by *magnetic reinforcement* (see below).

Moss and Tuominen (1990) investigate solutions for 'thick disk' models in the *non-linear* regime (caused by an 'α-quenching' mechanism—see also Brandenburg *et al* 1989). They conclude that long term oscillations are possible between solution modes, in which bisymmetric and axisymmetric field geometries alternate over a galaxy's lifetime. They also find that the final mode, whether stationary or oscillatory, could depend on the initial conditions. The possibility of such non-linear, 'transient' phenomena has emerged largely as the result of increasing experience with non-linear galactic dynamo models. In particular Brandenburg *et al* (1992) and Poezd *et al* (1993), suggest that non-axisymmetric field patterns, including large scale field reversals in galaxy disks, are possibly *transient* phenomena, rather than stable solutions. This possibility, at least for the time being, complicates the interpretation of the early magnetic history of galaxies. Unlike with the Sun, we are not permitted the luxury of observing the time evolution of large scale galactic magnetic features!

An ingenious scenario to explain stable, non-axisymmetric fields has been proposed by Mestel and Subramanian (1991). They consider the two-arm spiral—the type most clearly observed to have a bisymmetric field pattern—which has been traditionally believed to be density wave-driven. They make the physically plausible assumption that the α parameter is azimuth-dependent, and that it follows the spiral pattern imposed by the density wave. They obtain rapidly growing bisymmetric fields which corotate with the spiral pattern, in approximate agreement with the results of Fujimoto and Sawa (1990). Further, Mestel and Subramanian (1991) invoke independent arguments (Nakano 1984, Campbell and Mestel 1987) that a stronger field will bias the stellar mass spectrum, favouring the formation of more massive stars. The associated expanding H II regions/supernova remnants and planetary nebulae will then increase the turbulence, and hence quite likely the helicity (through interaction with the galactic rotation). This, in turn would further enhance the non-axisymmetric α-distribution which is capable of reinforcing the dynamo which produced the bisymmetric field. This is a new idea, in which the field acts as a type of 'catalyst', which increases energy input into the interstellar turbulence. If true, Mestel and Subramanian's mechanism would make it much more natural for the spiral structure to be at least partially magnetically influenced with the currently estimated field strengths, in contrast to previous thinking in this subject (see e.g. Binney and Tremaine 1987).

Initial conditions resulting from mergers, or earlier tidal encounters clearly would violate the assumption of initial axisymmetry inherent in the models discussed above, and have thus far not been explored in detail (see also section 5.5.1). The general conclusion from the above is that departures from axisymmetry, which are strongly indicated in some galaxies, can be reproduced as either transient or permanent solutions to the mean field α–ω dynamo regeneration equations. Lesch (1993) has emphasized the importance of the *intrastellar gas*, in contrast to the stellar component, in the excitation of non-axisymmetric instabilities in galaxies. His numerical model calculations produce significantly shorter field amplification times when the dynamo action is driven by non-axisymmetric features (e.g. strong bars, and some tidal interaction effects), than for an axisymmetric dynamo.

A further important point emphasized by Krause and Meinel (1988) is that, as long as C_α (equation (2.13)) exceeds the critical value for field growth, the relative sizes of the linear growth rates may be unimportant in deciding what the final field configurations will be. Saturation effects, and non-linear effects due to back-reactions can erase a galaxy's memory of the relative growth rates of different field amplification modes.

2.3.4. The dynamo effect for inner galactic rotation zones (the α^2-dynamo). In the nuclear regions, the magnetic field should have a poloidal geometry according to the standard dynamo model (cf figure 5). Unfortunately it is difficult to observationally isolate the morphology of the magnetic fields in and above the $\mathrm{d}\omega/\mathrm{d}r \approx 0$ zone from the disks onto which they are normally seen projected.

In the inner galactic zones, which are interior to most of the galaxy's mass, and ω is independent of galactocentric radius ($\mathrm{d}\omega/\mathrm{d}r \approx 0$), the parameter C_ω is much smaller than in the outer galaxy disk. Hence the conditions for the amplification of disk fields no longer apply. However, the current generated by the helicity (α-effect) just outside where $\mathrm{d}\omega/\mathrm{d}r$ becomes non-zero, generates a poloidal field component. In addition, because the inner rotating and conducting gas has *some* helicity ($\alpha \neq 0$), it causes a poloidal current, which reinforces the toroidal magnetic field. In turn, this toroidal magnetic field drives a toroidal current, which reinforces the poloidal magnetic field (cf Krause 1987). This is the α^2 dynamo effect, which (*a*) stabilizes and/or amplifies the poloidal field component (B_z) in the inner ($\mathrm{d}\omega/\mathrm{d}r \approx 0$) region of the galaxy, and (*b*) provides a natural coupling to the predominantly azimuthal field in the outer, $\mathrm{d}\omega/\mathrm{d}r < 0$ disk, which is due to the α–ω dynamo described earlier. All of this assumes the absence of large scale outflow winds from the inner galactic zones.

2.3.5. The current state of comprehensive (disk + halo) dynamo-generated field morphologies in 'normal' spiral galaxies. A more complete model of a dynamo-regenerated magnetic field must include the halo, for which Sokoloff and Shukurov (1990) have proposed a mean-field dynamo model. In their model, the dynamo field growth times are of the order of, or greater than a typical galaxy's lifetime, so that some memory of the hypothesized primordial field could be discernable, given detailed observations of Faraday rotation in the halo. Unfortunately the latter are difficult to obtain, even in a 2D projection for a galaxy seen edge-on. This is partly because of the loss of the third geometrical dimension in a system where axisymmetry cannot be assumed, and indeed may contain a quadrupolar mode (cf figure 5). Additionally, as emphasized by Sukumar and Allen (1991) in their study of NGC 891 and NGC 4565, significant Faraday dispersion effects at decimetre λs—just where the polarized synchrotron radiation is most readily detectable—'erases' information about the magnetic field geometry at the rear parts of the halo, which is difficult, if not impossible to reconstruct. Theoretical modelling has been extended to combined halo + disk numerical simulation model calculations by Brandenburg *et al* (1992), in which the halo possesses strong turbulent diffusivity, and an $\alpha_{\text{halo}} \approx 10 \times \alpha_{\text{disk}}$. Initial axisymmetry is preserved throughout in their calculations, and galactic winds are assumed to be small ($\leqslant 50$ km s^{-1}), so that the field is not advected away into the IGM and thereby 'spoiling' the dynamo effect (see, however, below). The results of these, and the recent simulations of Elstner *et al* (1992) show that even with these simplifying assumptions, quite complex galactic field structures can emerge from the numerical solutions. Brandenburg *et al* (1993) have more recently extended their numerical models, concentrating on halos, and introducing galactic winds and departures from isotropy in α. They have succeeded in obtaining solutions which give broad agreement with the 2D halo field maps of NGC 891 (which has a weak wind), and NGC 4631 (figure 7) which has a stronger wind and a striking, quasi-radial halo magnetic field geometry.

Parker (1992) has pointed out that, although the observation-based estimates of the physical parameters in section 2.3.2 give mean field solutions which appear to agree with observations, one key parameter, the turbulent diffusivity η, needs careful physical justification (cf also Rosner and Deluca 1989). Standard dynamo theory, as reviewed above, *prescribes* random kinematic swirling and mixing in order to explain the turbulent eddy diffusion, $\eta_t \approx 10^{25}$ cm^2 s^{-1} (Parker 1955, 1970, 1979, Steenbeck *et al* 1966, Vainstein and Zel'dovich 1972). This model is based on both global and local kinematics, and assumes that the field is mixed and filamented down to scales of order 0.1 au. This smallest size is roughly the mixing scale which is required in order that molecular resistivity can provide the required dissipation of large scale fields in $\approx 10^8$ yr; i.e. that required to provide a large enough value of η so that the field regeneration according to equation (2.15) will actually work. As Parker (1992) has emphasized, there is no known way, with $\langle \boldsymbol{B} \rangle$ as strong as several μG and $|\Delta \boldsymbol{B}| (\approx \langle \boldsymbol{B} \rangle)$ fluctuating on a scale of ≈ 100 pc, that the tension in such a strong $\langle \boldsymbol{B} \rangle$ would permit the free swirling and mixing of magnetic flux which is needed to explain an eddy diffusion corresponding to $\eta_t \approx 10^{25}$ cm^2 s^{-1}. Such swirling and mixing are what is required to make large scale fields dissipate in 10^8 yr. Also, such turbulent mixing down to these small scales (a scenario favoured by Kulsrud and Anderson 1992) would imply the generation of much stronger small scale fields—for which there is no observational evidence. Observational indications of fluctuations with $\lambda \approx 10^{11}$ cm *have* been found by Lee and Jokipii (1976) but they are probably small amplitude, linear Alfvén waves which are unable to reduce galactic Joule dissipation rates down to the $\approx 10^8$ yr required to make the conventional galactic α–ω dynamo work (cf Parker 1992). Similar doubts about the effectiveness of the diffusivity term in the standard dynamo theory have been raised by Knobloch and Rosner (1981), and Rosner and DeLuca (1989), who emphasized, among other things, the likelihood of the galactic dynamo operating significantly out of the thin galactic disk. Numerical simulations of *thick* disk dynamos have meanwhile been undertaken by Moss and Tuominen (cf section 2.3.3 above), and others.

Does the α–ω dynamo, despite some observational support, therefore not work? Or is there something missing? What the conventional literature on the mean-field α–ω dynamo does not examine is the detailed spatial and temporal nature of the (relativistic) *cosmic ray* gas, provided by supernovae and pulsars, and the non-relativistic hot gas (10^5–10^7 K) from active sites of star formation, i.e. large H II complexes and associations of O and B stars. It also ignores the recently verified existence of organized outflow from such sites—especially in the nuclear region. Such complexes can inject an additional energy density $\varepsilon_{\rm CR}+\varepsilon_*$ (the latter due to ionizing radiation and non-relativistic hot gas from young star complexes) which is $\approx 10^{-11}$ erg cm^{-3} over ≈ 100 pc or more. This can be an order of magnitude *larger* than the other energy densities in (2.10). Furthermore, symmetric outflow would destroy the symmetry of field *sense* above and below the plane which was illustrated in figure 5. Also, over a few $\times\,10^8$ yr, several of these transient ($\tau_* \approx 10^7$ yr) 'events' will occur at random over a galaxy's disk, and their effect will be to disrupt any long term monotonic mean-field dynamo build-up of a large scale field.

A related point is that the combination of the supernovae and O and B stars can produce 'galactic fountains' (Shapiro and Field 1976, Bregman 1980, Cox 1981, Edgar and Chevalier 1986 and Kahn 1981), and more generally, *galactic winds* (cf Holzer and Axford 1971, Mathews and Baker 1971, Bardeen and Berger 1978, Habe and Ikeuchi 1980, Völk *et al* 1990, Breitschwerdt *et al* 1991). These phenomena will naturally tend to drive significant outflow from galactic disks. At this point it is relevant to mention the more extreme case of a starburst nucleus, which creates an even stronger outflow, such as recently revealed in M82 (cf section 3.1 below).

The effectiveness of the standard α–ω dynamo has been questioned from another standpoint by Kulsrud (1986), who points out that the galactic disk field is tied largely to the densest clouds, which are *ipso facto* the most neutral clouds, so that the cloud-field coupling is not strong enough to prevent the field from simply passing through the clouds with the largest kinetic energy density. Thus the competing effects just mentioned would, according to Kulsrud, prevent a tight wind-up, or significant dynamo field generation (cf also Kulsrud 1990).

These phenomena have two broad implications for extragalactic magnetic fields: (*a*) they appear to force a re-examination of how large scale fields are generated and amplified in galaxies—which is our concern in this section. (*b*) As we shall discuss in section 6, they may have profound implications for the origin and strength of extragalactic magnetic fields. If the slow-acting (over several $\times\,10^8$ yr) mean field α–ω dynamo is not effective, or is regularly disrupted by enhanced star formation activity, then μG-level fields may have existed at the protogalaxy stage. As we discuss later, there is increasing evidence to suggest that this may have been the case. Meanwhile we review some further developments of the mean-field galactic dynamo theory.

2.3.6. A modified galactic dynamo incorporating the effects of outflow. The energetic nature of the stellar events mentioned above will produce some vertical waviness in the galaxy disk field, thus permitting the *dense* gas to slide downward along the field lines, while the buoyant and energetic cosmic ray gas tends to inflate the outward-directed wave bulges (cf Mouschovias 1974, Parker 1966, 1979 pp 325–33, 1992, and Shibata *et al* 1989, 1990). This 'bulging and looping' of the disk mean field lines is associated with an interstellar gas clumping scale of ≈500 pc over $\approx 2\times 10^7$ yr—the characteristic lifetime of the star-forming complexes mentioned above. The ongoing generation of cosmic rays in the gaseous disk will produce ballooning loops of field, which are inflated outward at >30 km s^{-1} to distances of ≈1 kpc, thus forming a halo above the disk (cf Parker 1965, 1990, 1992, Kahn 1991).

In Parker's (1992) proposed modified α–ω dynamo, the resulting close-packed, and outwardly inflating loops provide a natural opportunity for rapid magnetic reconnection between opposing, vertically oriented magnetic field lines (see figure 6). This, plus the rapid outward diffusion of the close-packed magnetic lobes provide the diffusivity (η_t) which is otherwise difficult to physically justify on the 'standard' dynamo model (section 2.3.5). Another 'natural' feature of Parker's model is that the outwardly inflated magnetic loops can sever themselves, by reconnection, from the disk field. They then behave as 'freely rotating' loops due to the Coriolis force. Further reconnection fuses the large number of loops into a large scale poloidal field. This scenario appears capable of explaining, at least qualitatively, the observed halo field geometry in Sukumar and Allen's (1991) observations of NGC 891, as do also the numerical models of Brandenburg *et al* (1992) and Elstner *et al* (1992). A key, and attractive aspect of Parker's modified α–ω dynamo is that it is a *fast dynamo*, whose 'speed' increases with disk activity (i.e. outflow force). Whereas the conventional mean-field dynamo amplifies the azimuthal disk field slowly over $\approx 10^9$ yr or more, and is susceptible to inevitable disruption by outflow due to disk star formation activity, Parker's fast acting dynamo *thrives* on the outflow; indeed it is the *source* of the turbulent diffusivity. The more vigorous the outflow, the faster, and more effective is the dynamo action.

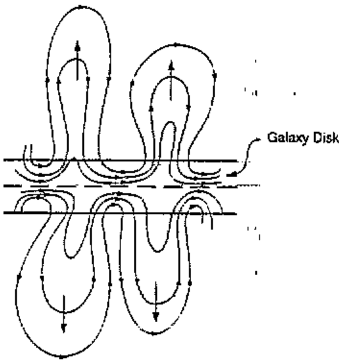


Figure 6. Illustration of the formation of vertical magnetic loops, inflated by cosmic rays and hot gas, which can detach by reconnection from the disk field (Parker 1994).

2.4. *How well does the galactic dynamo theory conform to the observations?*

The answer to this question is mixed; the large scale magnetic field geometry of 'well-behaved' spiral galaxies agrees with some, though not all, of the straightforward predictions and model simulations of linear dynamo theory. The affirmative side of the answer is that the predominant field modes do seem to be the simplest ones, as illustrated by recent data shown for M83 and NGC 1068 in figures 1 and 2. This is probably the most significant result, in that it shows that, *if* the observed large scale fields were amplified by the α–ω dynamo in the disks, the prominent modes are the *low order* ones, an outcome which is not *a priori* obvious. However, the angular resolution for many of the galaxies is probably not good enough to confirm definitive agreement with the standard α–ω dynamo theory. Apart from 'geometrical' tests, observation-based estimates of magnetic field strength indicate that, if the observed fields were entirely the effect of a galactic dynamo, the (non-linear) amplification must saturate at 2–8 μG, which is when the magnetic energy density ε_{m} $(=10^{-12}(|B|/5\ \mu\mathrm{G})^2\ \mathrm{erg\ cm^{-3}})$ becomes comparable with $\varepsilon_{\mathrm{cr}}$ and ε_{t}.

Recent images of improved sensitivity and resolution are beginning to elucidate some further details of the magnetic structure near the plane of spiral galaxies. The highest degree of magnetic field ordering generally occurs in the outermost regions of galaxy disks, and the interarm regions. Conversely, field orientation is generally more randomized in the star-forming complexes within spiral arms, and also possibly at smaller galactocentric radii. Specifically, field disordering tends to correlate with locally enhanced Hα (seen optically) and CO 1–0 (λ 2.7 mm) emission (Bajaja *et al* 1990), and sometimes enhanced H I (λ 21 cm) surface brightness. Where the field ordering is high, the field orientation usually conforms to the galaxy's spiral pattern (figures 1, 2). Most or all of these properties and correlations have been described in the analysis of recent surface polarimetry observations of NGC 6946 (Ehle and Beck 1993), M83 (Sukumar and Allen 1990, Neininger *et al* 1991), and M51 (Beck *et al* 1987, Scarrott *et al* 1987 (optical polarization), and Neininger 1992).

The unprecedented detail of these recent observations has provided some of the first clear evidence for local deviations or 'disruptions' of the otherwise ordered azimuthal disk component (Sukumar and Allen 1990, Horellou *et al* 1992). In M31, the suggested detection of arc-like looping of field lines between tie-down points $\approx$2 kpc apart, where the field lines bulge out of the disk, is possibly due to a Parker–Jeans instability (Beck *et al* 1989). Such phenomena may be the nascent beginnings of magnetic field expulsion. On a simple energetic calculation, where more intense than normal star formation occurs, a 'breakout' of field into the local halo and IGM will result. This type of evidence reinforces the notion that such instabilities will 'snuff out' the slow field strength build-up by the conventional α–ω dynamo process in an assumed ever-quiescent galaxy disk. This, potentially, puts the conventional α–ω dynamo theory in great difficulty if the dynamo is *required* to explain the amplification of very weak seed fields in the early universe up to present-day μG levels. Parker's modified α–ω dynamo (section 2.3.6), although not yet incorporated in a detailed numerical model, might overcome this shortcoming, by allowing for a fast dynamo amplification of weaker seed fields, if indeed the protogalactic fields were much weaker.

Another test of dynamo models which require a slow field build-up over cosmic time is to estimate the magnetic field strengths in low-mass and dwarf irregular galaxies, whose lower mass and rotation might be expected to cause field regeneration to a different, lower value than large spiral galaxies. Observations of two such galaxies, the Large and Small Magellanic Clouds (LMC and SMC), indicate (using the assumption of equipartition) interstellar field strengths at the few microgauss level (Loiseau *et al* 1987 (SMC), Klein *et al* 1989, 1993 (LMC)). Allowing for uncertainties in the estimates, these field strengths are essentially the same as measured in the Milky Way using pulsars, and in other large spiral galaxies. The similarity of the magnetic field strengths in these low mass, *slowly rotating* galaxies thus casts doubt on the requirement of a slow-acting α–ω dynamo to regenerate an initially weak primordial field to a few microgauss over several billion years.

2.5. Where, and to what extent could magnetic forces compete with gravity in galaxy systems?

Nelson (1987) and Battaner *et al* (1991) have called attention to the consequences, not yet widely considered, of the fact that interstellar magnetic field *strengths* in nearby spiral galaxy disks appear to decline much more slowly with galactocentric radius than the average disk matter density. Estimates of the magnetic field strength are made from a combination of measurements of the synchrotron emissivity (equation (1.1)) over the galaxy disk, the assumption of equipartition between the cosmic ray particle and magnetic field energy densities, Faraday rotation, and estimates of the ionized interstellar gas density. Whereas the rotational energy density $\varepsilon_{\rm rot}$ near the co-rotation radius is ≈400 times the magnetic energy density, $\varepsilon_{\rm m}$, the ratio $\varepsilon_{\rm rot}/\varepsilon_{\rm m}$ decreases in the outer disk to the point where magnetic stresses become comparable with gravity, and possibly even dominate. In other words, in the RHS of equation (2.6), the third term becomes comparable to, or greater than the first term.

Significant magnetic stresses could pose a challenge to conventional theories of outer galaxy dynamics. The relative prominence of magnetic stresses at large galactocentric radii can also more naturally account for the observed 'flaring' of galactic disks at those radii (cf Binney 1992), a phenomenon which has been difficult to understand on pure gravitational dynamics. To the extent that magnetic stresses of the (largely azimuthal) disk fields extend to large radii, the result will be to *increase* the rotational velocity (V_r) at the larger r, relative to the quasi-Keplerian velocity which would be expected in the absence of, e.g., a dark matter halo (Nelson 1987). It is precisely the flat, i.e. non-Keplerian, (V_r) against r relation which has been taken as one of the key pieces of evidence for dark matter around galaxies. Thus it appears conceivable that magnetic forces can 'compete' with gravitational forces, and might help provide the explanation for the flatness of galaxy rotation curves at the larger galactocentric radii. The relative importance of $\varepsilon_{\rm m}$ in outer galaxy disk regions is supported (though not proven) by the recent finding that the magnetic field strengths appear to correlate with neutral hydrogen column densities in galaxy disks and in a molecular clouds (Han and Qiao 1993); we could infer that, since the vertical H I column density in galaxy disks is relatively insensitive to galactocentric radius beyond a few kpc, and since H I extends to large radii in spiral galaxies, a significantly strong (and probably ordered) magnetic field also exists at these large radii.

This possibility puts a premium on definitive observational tests for differences between (V_r) against r curves for matter whose motion is purely gravitational (e.g. *old* stars), as distinct from that which could be influenced by both the gravitational and large scale magnetic forces in equation (2.6) (namely the interstellar gas, and the newly formed, bright stars which will move with it). Unfortunately, virtually all of the V against r data on galaxies come from transitions in the interstellar gas (the 21 cm line of H I and recombination lines of H II), or from spectra of young stars. Since the age of these (conveniently bright) stars is typically $\ll 10^8$ years, they have moved only a fraction of a galactic rotation ($\approx 3\times 10^8$ yr at $r = 12$ kpc) since they formed out of the interstellar gas, and may therefore not be purely ballistic probes of the galactic gravitational potential. Better probes of galactic gravitational potentials at large galactocentric radii would be the oldest disk stars—e.g. main sequence dwarfs—which are unfortunately very faint. They would be best detected by observation of their *collective* absorption spectra, and only with the largest optical telescopes. If such objects have a different V against r curve from the interstellar gas, a magnetic influence on galactic rotation would be inferred. Unfortunately very few such measurements on old ($>10^9$ yr) stars have been undertaken to date.

Another case in point is the magnetic energy in the intracluster medium of clusters of galaxies: As we discuss in section 4 below, widespread, μG-level fields are also found to exist in the intracluster medium (ICM) of some galaxy clusters. In some cooling flow clusters, ICM field values approach 10–40 μG locally (section 4.1.3). The corresponding magnetic energy density of the latter is greater than for galaxy disk fields (which exhibit ordering on comparable scales). This revelation of widespread, and sometimes strong localized (relative to a galaxy cluster size) *cluster* ICM fields suggests that galaxy fields merge with those of the intracluster medium. If so, our conventional ideas of magnetic field amplification in galaxies, and the role of magnetic as well as gravitational forces in galaxy formation are just beginning to be explored.

Small galaxies like the Magellanic Clouds and other dwarf galaxies have less mass, but are gas and dust-rich, and have cosmic ray electrons and organized magnetic fields of comparable magnitude to large spirals (cf section 2.4 above). Thus, they too may be 'connected' with the surrounding IGM as mentioned above, and subjected to magnetic drag which could cause angular momentum exchange with the surrounding IGM. The consequence could be a non-negligible magnetic force contribution to their global dynamics. The rotational velocity in the outer regions of these low-mass galaxies is likely to be even more susceptible to magnetic tension than large spirals, due to their lower mass.

Dwarf galaxies are particularly interesting in this context, especially if normal large galaxies formed originally from the merging of smaller sub-galaxies. Galactic 'building blocks' of this type would almost certainly have been rich in at least partly ionized gas, which would therefore have been well coupled to organized, galaxy-scale, magnetic fields. *If* they already had microgauss-level fields at this stage, magnetic drag effects (to say nothing of thermal conductivity effects) would likely have provided a significant force component in the merging process.

On the contrary, the motions of satellite galaxies whose orbital motions are purely gravitational (e.g. Kulessa and Lynden-Bell 1992) supports the existence of an unseen matter component associated with the Milky Way. It seems unlikely that magnetism in general could be used to completely eliminate hypothesized dark matter distributions around galaxies. The point of the foregoing discussion is to emphasize that large scale magnetic forces must be accounted for, or ruled out before galaxy mass distributions can be confidently calculated. This applies especially to small, gas-rich galaxies.

Although magnetic forces are probably not the only factor connected to the ultimate amount and distribution of dark matter, the bets would seem open at this point on *whether there are links between magnetic forces and the amount of dark mátter.* This in turn is linked to the question of the overall matter density in the universe and whether we live in an open, and older universe $q_0 \ll \frac{1}{2}$ (or $\Omega \ll 1$), or a closed 'flat' $\Omega = 1$ universe, *for which large amounts of dark matter seem essential in 'conventional' Friedmann* cosmological models having $\Lambda = 0$. An interesting question is therefore whether magnetic fields could help 'alleviate' the currently problematic 'cosmic time crunch' in Friedmann Universe models with $\Omega = 1$—which require the heavier elements to be produced, and galaxies to form, in an uncomfortably short proper time.

3. Magnetic field outflow into the IGM from galaxy-generated activity

3.1. Evidence for the magnetic 'seeding' of the intergalactic medium due to 'normal' activity of nearby galaxies

A subset of spiral galaxies possess a synchrotron-emitting halo—best seen if the galaxy happens to be edge on. Two recently studied examples are NGC 4631, an edge-on spiral

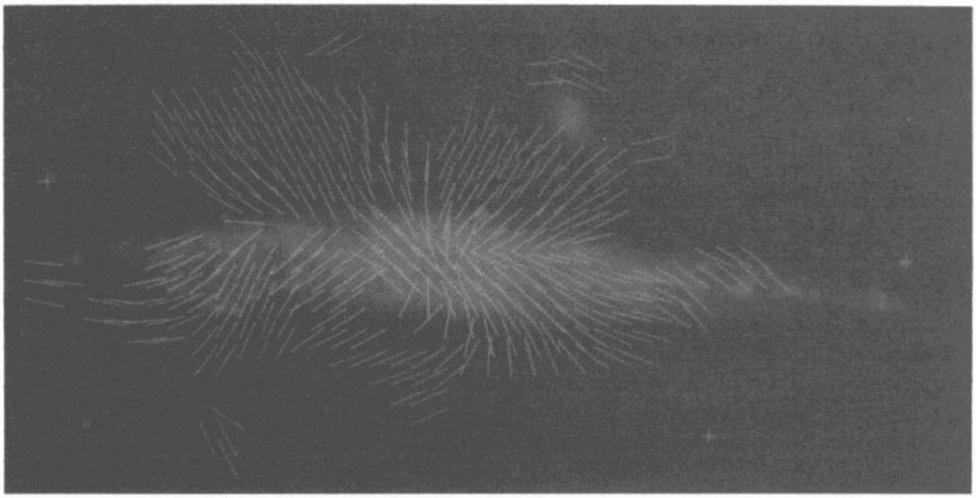


Figure 7. A radio-optical overlay of the galaxy NGC 4631, shows the optical image, and lines which indicate the projected magnetic field orientation in the galaxy's halo (source: Golla and Hummel 1994).

galaxy (figure 7), which has widespread enhanced star formation activity, and M82, the nearest, hence 'prototypical' starbust galaxy which has pronounced outflow (figure 8). M82 has recently been found to possess a large scale poloidal-like magnetic field. These systems, especially M82, may provide important clues to the strength and origin of *extragalactic* magnetic fields. This is because halo magnetic fields are associated with

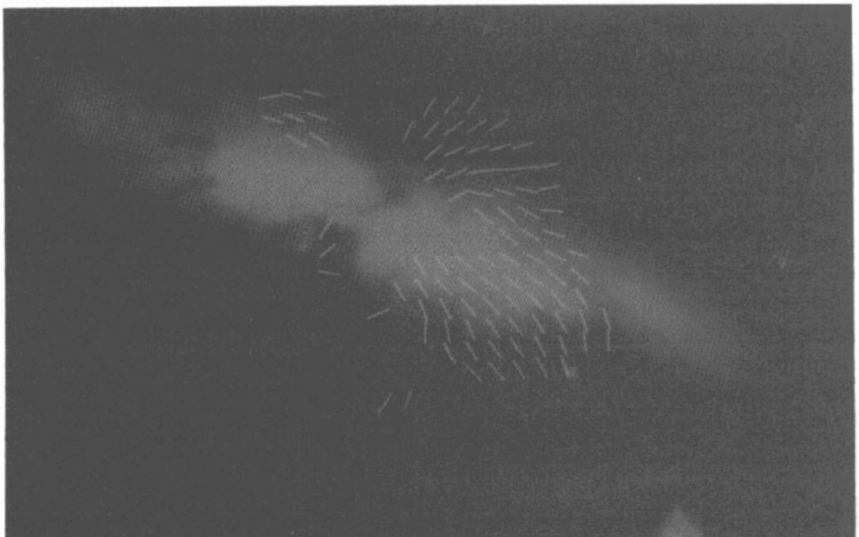


Figure 8. The projected magnetic field lines within the outflow region of M82, from de-Faraday-rotated polarization images whose sensitivity was $\approx 200\,\mu$Jy/beam and angular resolution 15″ (reproduced from Reuter *et al* 1994).

outflowing winds, which are the consequence of supernovae and related stellar activity in galaxy disks, and thus can be anticipated on *a priori* energetic grounds, as Heiles (1987) has argued.

The observations illustrated in figures 7 and 8 show a number of interesting facts which need to be accounted for in a theoretical field regeneration model. They show that, in distinction to large scale field ordering parallel to galaxy disks, the out-of-plane magnetic field lines, at least in some zones, are directed *out of* the plane. Using assumptions of equipartition, Hummel *et al* (1991) estimate $\approx 8\ \mu$G for the magnetic field *strength* in the disk of NGC 4631 and $\approx 5\ \mu$G in its halo. The same authors estimate $\approx 8\ \mu$G in the (smaller) halo of another galaxy, NGC 891, compared with 13 μG in the disk due to its higher synchrotron luminosity. Recent analysis of M31 (the Andromeda galaxy), which is seen partly face-on, reveals zones where the field appears to turn up out of the galaxy's plane (Beck *et al* 1989). It is apparent that these halo fields originate in the galaxy disks, and propagate somehow into the halo.

A more dramatic example of halo magnetic field structure is in the 'starburst galaxy', M82. A small zone within 400 pc of M82's nucleus is undergoing intense star formation and is generating about $4 \times 10^{10}\ L_{\odot}$ (Kronberg *et al* 1985). The resulting luminosity density makes it inevitable that outflow will occur in such a system. This active region emits H_{α}, [O II]), CO, etc line emission, as well as x-rays, IR continuum radiation due to heated dust, and synchrotron radiation. Figure 8 shows one of the first magnetic field patterns seen in the outflow zone around a starburst galaxy, obtained from recent VLA observations of high sensitivity, and at a resolution of only 15″. An extensive magnetized halo has also been detected around the active spiral galaxy NGC 253 (Carilli *et al* 1992).

The vigorous stellar activity within the inner 1 kpc of M82 (Kronberg *et al* 1985), and its associated outflow of cosmic rays (Seaquist and Odegard 1991, Reuter *et al* 1992), x-ray emission (Kronberg *et al* 1985, Schaaf *et al* 1989) and associated *strong* magnetic field (Reuter *et al* 1993) have made M82 a key testbed for explaining the magnetic field generation process in this and other galaxies with starburst-like nuclear activity. The α^2-dynamo (section 2.3.4) proposed for the inner corotating zones of 'quiescent' galaxies, clearly does not apply here. Observations now make it clear that magnetic fields are expelled along with plasma at greater than M82's escape velocity, and that if Parker's reconnecting, detached magnetic loops from a spiral disk are correct, we may be seeing (figure 8) a more powerful version of a similar physical process.

M82 appears thus to be a nearby-universe testbed for the generation *and outward transport* of magnetic fields. The starburst produces a high velocity outflow, which is *at most* 10^8 years old. By contrast, the dynamo amplification time of the out-of-plane fields illustrated in figure 5 would need to be of order 10^{10} years in the slow-acting mean-field dynamo model. Thus, the magnetic fields around M82 are unambiguously produced by the outflow phenomenon, which happens on a much shorter timescale than the dynamical age of the galaxy. This interesting discovery puts constraints on processes of magnetic field regeneration. It demonstrates that mechanisms other than the slow galactic scale dynamo *are* able to amplify and, as discussed below, perhaps create magnetic fields.

Lesch *et al* (1989a) have proposed an ingenious model for the *generation* as well as the *amplification* of large scale magnetic fields in the nucleus of M82 and similar systems. In their model, M82 can create a kpc-scale magnetic field by a *galactic scale* version of Biermann's battery, caused by the interaction of the galactic plane component of the nuclear starburst wind with the rotating, dense molecular gas torus which surrounds M82's nucleus. The latter has been revealed in both λ 21 cm H I observations (Weliachew *et al* 1984), and in λ 2.7 mm CO (1-0) observations (Lo *et al* 1985, Nakai *et al* 1987, Loiseau *et al* 1988). A hot, subsonic outflowing plasma from within the molecular ring excites sound waves propagating at $c_s=(5/3)^{1/2}(kT_e/m_p)^{1/2}$, ($k$ is Boltzmann's constant, T_e the electron temperature, and m_p the proton mass). In the model of Lesch *et al* (1989*a*), these become compressional waves which, on arrival at the rotating torus, push the radially streaming plasma into the azimuthally rotating molecular gas. Because the electrons couple more easily to the gas than the protons, the *differential* stopping time ($t_{sp}=(m_p/m_e)t_{sc}$) causes a current to build up in the ring, which generates a poloidal magnetic field. This initial magnetic field is amplified by a combination of $\boldsymbol{v}\times\boldsymbol{B}$ compression and turbulence, a process described in detail by Alfvén and Fälthammar (1963), Parker (1979), and others. Lesch *et al* (1989a) point out that, in M82, the wavelength, λ_s, of the sound waves is comparable with the dimensions of the system. The waves will reach the radius of the torus, $R_T\approx 225$ pc before being damped, they are then reflected back from the inner edge of the torus on a time scale $t_R\approx 2R_T/c_s$ which is $\approx 10^7$ yr. This is the time scale over which the battery current breaks down, so that as long as $t_R>$ the diffusion time t_D $(=L^2/4\eta_T$ s), a current is maintained. (L is the characteristic scale). A consequence is that the ring current will prevail over the tendency of the plasma to cancel it. Lesch *et al* (1989a) estimate $t_D\approx 10^6$ yr in M82's inner molecular ring, in which case the current, and hence a poloidal field (which is observed—see figure 8) will be built up.

Given the creation of the nuclear poloidal field by a galactic battery, the molecular ring, which marks the end of the co-rotation zone can probably 'feed' field outward into the differentially rotating disk so that, over longer times, an α-ω dynamo might be able to propagate and amplify the galaxy's disk field, as discussed in the preceding sections. A significant implication of the scenario proposed by Lesch *et al* (1989a), if correct, is that a galaxy can generate, and propagate its own, self-created field. The additional fact, just demonstrated, that starburst galaxies and their cousins are able to eject magnetized plasma into the ambient intergalactic medium presents, in principle, the possibility that seed fields in the early universe could originate in galaxies (cf section 5.4.1 for a related discussion).

3.2. Injection of magnetic fields into the intergalactic medium by extragalactic radio source jets and lobes

The supra-galaxy scale morphology of double radio sources, their associated large energies (Burbidge 1956), and the high collimation of their radiating jets make them a remarkable phemonenon of the extragalactic universe. Large scale jets and associated radio source structure (reviewed recently by Bridle 1991) also have their analogues on stellar scales, e.g. in binary star systems and protostellar objects, where a magnetized accretion disk produces a highly collimated outflow (cf Mestel 1972, Lovelace *et al* 1991, Stone and Norman 1992a, b, Norman and Heyvaerts 1990 for a review). Recent observations (e.g. Yusef-Zadeh *et al* 1990) reveal associated synchrotron emission in stellar jet systems, thereby providing direct evidence of magnetic fields associated with these stellar jets. These reinforce the idea that the physical mechanisms operating in these stellar systems are generically similar to those in extragalactic jets. Figure 9 shows, from VLA observations, the highly collimated nature of an extragalactic radio source

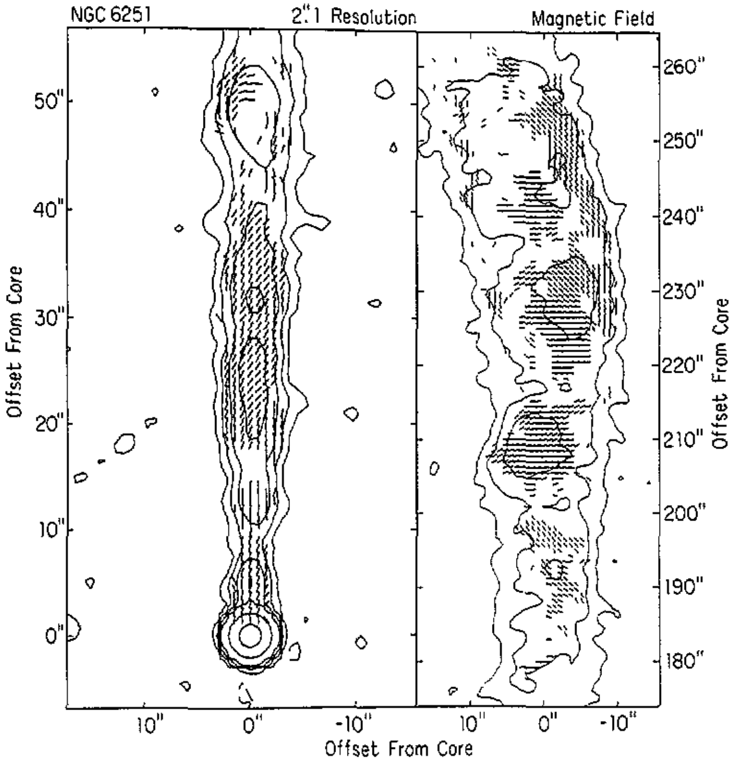
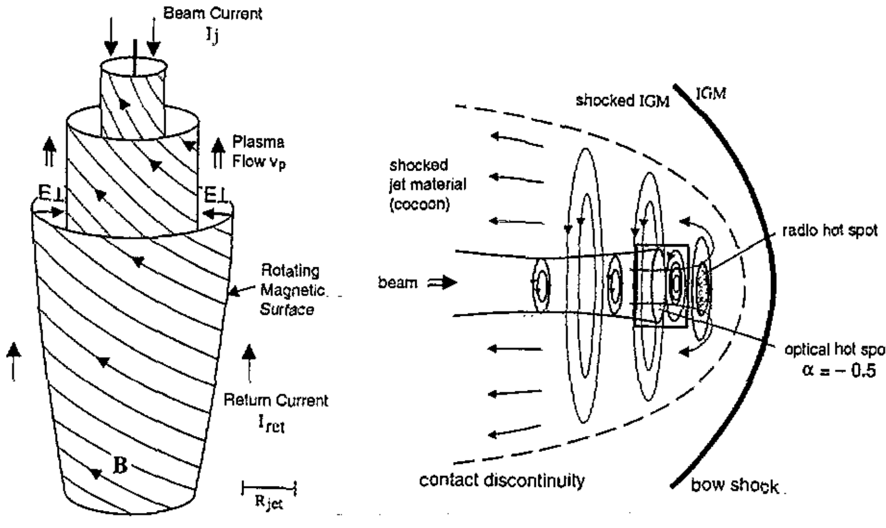


Figure 9. Radio image of the radio galaxy NGC 6251, showing the strong, and ordered variations of magnetic field direction. The lines show the projected magnetic field orientation (from Perley *et al* 1984b).

jet, and its coherent magnetic field structure as illustrated by its linearly polarized synchrotron emission.

3.2.1. Magnetic fields in galaxy-scale jets. Significant impetus to our understanding of extragalactic radio jets was given by a model proposed by Blandford and Rees (1974), which could reproduce the collimation and large energy transport into the outer lobes of extragalactic radio sources ($>10^{60}$ erg in $\approx 10^{8}$ yr) by means of a jet containing a light, relativistic gas. In Blandford and Rees' model, the highly shocked termination point of the jet forms a 'working surface' from which energy is dissipated into the inflated radio lobes surrounding the jet. The jet may well have *bulk* relativistic motion, although the Lorenz factor of the bulk motion is a topic of current investigation (cf Begelman 1992 for a recent discussion of this point). However the large magnetic energy associated with the radio lobes, and the details of the polarization and filamentary structure revealed over the last dozen years (see e.g. Carilli *et al* 1988) cannot be explained in detail without incorporating magnetic fields and magnetic field regeneration into the models. To achieve a physical understanding of these non-linear systems, detailed computational MHD modelling of all stages of the phenomenon is required, from the sub-pc scale accretion disk to the 100 kpc-scale radio lobes (cf Balbus and Hawley 1991, Begelman *et al* 1984, Begelman 1993, Lovelace 1976, Priest 1985, Pudritz and Norman 1986, Asseo and Sol 1987, Benford 1987, Camenzind 1987, Hawley and



THE JET
(a)

THE HOT SPOT
(b)

Figure 10. (*a*) Idealized structure of relativistic MHD jet, showing the magnetic sheaths and current flow. (*b*) The termination and outer shock zone where a relativistic, magnetized jet terminates against an outer shock zone in the ambient IGM (adapted from Lesch *et al* 1989b).

Balbus 1991, Königl 1989, Fraix-Burnet and Peltier 1991, Matthews and Scheuer 1990, Uchida 1990, Norman *et al* 1991, Clarke *et al* 1992, Romanova and Lovelace 1992).

A current, idealized MHD model of a jet works roughly as follows (see figure 10(*a*)). A beam current, which generates a toroidal magnetic field, flows close to the jet axis. Magnetic field zones occur within nested 'surfaces', and it is along these surfaces that the plasma actually flows. A return current, which balances the 'beam current', flows along the outer magnetic sheath (figure 10(*a*)). The rotation of the field lines gives rise to electric fields which are perpendicular to the magnetic surfaces (Lesch *et al* 1989b). The beam terminates in a hot spot, or 'working surface' (figure 10(*b*)), beyond which is the contact discontinuity separating the jet material from the ambient IGM. The outermost discontinuity is the bow shock due to the supersonic motion relative to the IGM.

The evidence is now persuasive that magnetic fields are integral to the functioning of extragalactic jets. Their function is twofold; (i) The interaction between magnetic and gas dynamical forces, described by solutions to the MHD equations (equations (2.1)-(2.6)), can be shown to make the jet function as a highly collimated *energy flow conduit* over distances approaching intergalactic dimensions. The magnetic field distribution is largely toroidal relative to the jet axis, as illustrated in figure 10(*a*). (ii) Magnetized jets may also serve as *accelerators of cosmic rays* which, by synchrotron radiation, illuminate both the jets and the large, inflated radio lobes which are fed by the jet. The radio spectra in jets give direct evidence that relativistic electrons must be *either accelerated in the jet, or else be transported in a very low B-field environment* from the galaxy nucleus, since their synchrotron radiation lifetimes are often much shorter than the transport time from the base of the jet (i.e. the galaxy nucleus, accretion disk, etc).

Various possibilities exist for relativistic particle acceleration in jets: acceleration can occur by magnetic reconnection (a collisionless process) in the electric field of the neutral layer close to the jet axis (see figure 10(*a*)), as a result of non-axisymmetric flows, and turbulence—cf Romanova and Lovelace (1992) for a recent discussion of reconnection acceleration. A magnetic reconnection mechanism for accretion disks has also been recently proposed by Lesch (1991). Particle acceleration has also been proposed to be due to a combination of magnetic forces and Kelvin–Helmholz type velocity shear instabilites (Romanova and Lovelace 1992, see also Königl and Choudhuri 1985, Eilek and Hughes 1990). In addition, Fermi acceleration due to particle-Alfvén wave scattering in shocks and regions of plasma turbulence might be operative (cf Axford 1977, Blandford and Ostriker 1978), provided that the particles' average gyroradius $r_g \ll r_s$, the scale of the shock discontinuity, or $r_g \ll \lambda_A$ the minimum Alfvén wave wavelength. Fermi-type mechanisms might be efficient for cosmic ray acceleration in strong shocks in radio hotspots (Meisenheimer *et al* 1989). However their relative effectiveness for electrons in extragalactic jets is unclear.

3.2.2. Convergence of observation and theory of radio jets and lobes. Extended radio jet sources have been broadly classified into two groups by Fanaroff and Riley (1974). 'FR I' sources have lower radio power ($<10^{25}$ W Hz^{-1} at 1.4 GHz), are centre- rather than edge-brightened, and have two-sided, more diffuse jets in which the line-of-sight averaged magnetic field is predominantly *transverse* to the jet axis. These merge into diffuse, edge-fading outer lobes. The higher power FR II sources have strongly emitting outer lobes which are much more abrubtly bounded than the FR I radio sources, and have higher surface brightness radio knots (cf Bridle 1986). When they have luminous jets between the quasar nucleus and (usually just one) outer lobe, the magnetic field orientation is along the local jet direction. Within the past 5 years or so, MHD simulations have been able to at least qualitatively explain these characteristics, thanks to leading edge computing power (see e.g. Clarke *et al* 1989). Figure 11 shows the result of a recent 3-D jet-radio lobe MHD simulation (Clarke 1993). Simulations of this sort are able for the first time to reproduce the magnetic field morphology in reasonable detail within jets and lobes, including the filamentary structure (cf also Rees 1987). These have recently emerged in high dynamic range and high resolution VLA images (e.g. Perley *et al* 1984a for the Cygnus A radio galaxy, and Dreher and Feigelson 1984 for the radio galaxy 3C353).

3.2.3. Radio jets and lobes as sources of intergalactic magnetic fields? The answer to this important question probably lies in the results of MHD simulations such as in figure 11, which can successfully reproduce the observed emission filaments and polarization structure of the radio lobes of some sources. The simulations confirm that significant magnetic field amplification occurs when Kelvin–Helmholtz instabilities in a shear layer are amplified by the kinematic (fast) dynamo. This is a direct consequence of the induction equation (equation (2.7)). As the field is amplified—by a few to 100 times in the simulation in figure 11—the shear layer is transformed into filaments, as required by the solution to the magnetic induction equation. In a flat shear layer where shear is in the x-direction, and y is the direction normal to the shear, equation (2.7) (with $\eta = 0$) reduces to

$$\partial B_x/\partial t = B_y \partial v_x/\partial y \qquad \text{from which } B_x/B_y \sim (2v_x \partial t)/l \qquad (3.1)$$

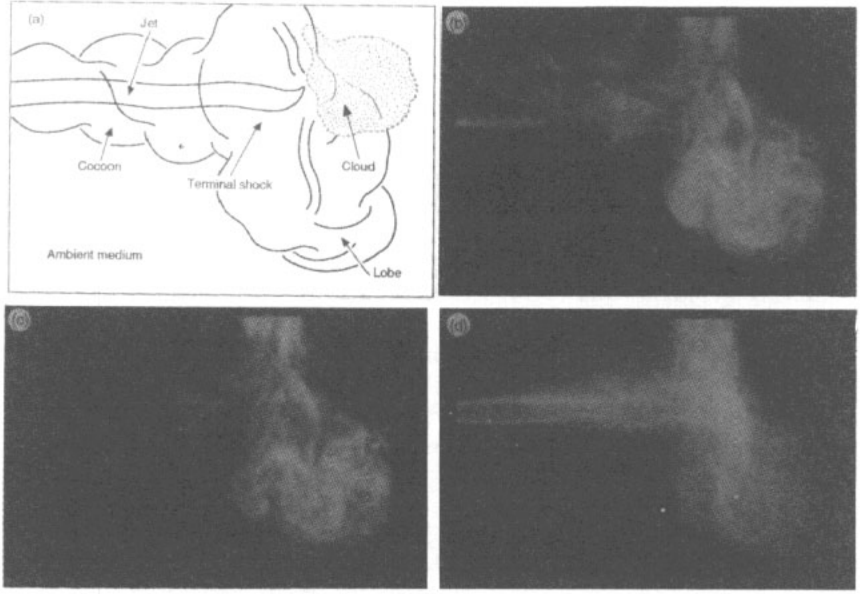


Figure 11. Simulation of a jet-cloud combination (from D A Clarke 1993). (*a*) shows a sketch of the salient features, (*b*) shows the total emissivity (Stokes parameter I). (*c*) shows a grey scale of the magnetic pressure ($\propto |B^2|$), and (*d*) shows the velocity shear modulus integrated along the line of sight.

where l is the length of the filamentary ('roller') 3 eddy, and ∂t is its lifetime. Transsonic flow in the lobe is assumed, i.e. $v_x \sim c_s$, the speed sound. Then, since $\partial t \sim \lambda / c_s$, (3.1) can be rewritten as

$$B_x / B_y \sim 2\lambda / l \qquad (3.2)$$

(Clarke 1993). This illustrates how the kinematic dynamo amplification of the magnetic field can be directly inferred from the observed width-to-length ratio (λ/l) of the filaments (figure 11). These ratios range typically up to a few tens. This fairly unambiguous, and remarkable result confirms that extended radio lobes amplify magnetic fields (also predicted by De Young 1980 and Ruzmaikin *et al* 1989), thus explaining their strong synchrotron radiation over large volumes of intergalactic space. Given the large size of extended lobes of radio galaxies and quasars, which range from a few kpc to ~1 Mpc, it is demonstrated how the combination of strong radio source jets and lobes can magnetize the intergalactic medium, as Rees (1987), Ruzmaikin *et al* (1989) and Jafelice and Opher (1990, 1992) have suggested.

The substantial contrast in $|B|$ mentioned above in the radio lobe filaments has two further implications; it suggests that, since such filaments are dynamic, some particle acceleration likely occurs throughout the lobes (i.e. not *just* in the jets and hotspots). Also, the relativistic electron lifetimes ($\propto B_\perp^{-2} E^{-1}$) will vary significantly within the lobes, which also makes it likely that the cosmic ray diffusion rates will be different within and outside of the filaments, but within the lobes.

Due to our limited knowledge of the cosmic occurrence rate of extended radio sources at earlier cosmological epochs, it is difficult to calculate the global effect of radio sources on the general IGM field. Daly and Loeb (1990) have produced calculations which yield $B_{\mathrm{IGM}} \approx 10^{-11}$ G. If the seed fields of galaxies came from previous generations of extended EGRS, then 'EGRS-seeding' of the IGM must have been efficient at least by redshifts of ≈ 3. Very extended (required for efficient seeding) radio sources are generally not found beyond $z \approx 2$. It is not yet clear whether they are a phenomenon of only the 'mature' universe, or whether they *did* exist in the past, but their synchrotron-emitting electrons were 'snuffed out' by inverse-Compton scattering off the much denser photon field in the earlier universe. In that case, their fields would remain, and would only be illuminated by synchrotron emission at very low frequencies, which would be redshifted to still lower frequencies at our epoch of observation. Another potential *galaxy-generated* source of an IGM field, namely starburst galaxies and their analogues, is discussed in section 3. The existence and generation of magnetic fields in the IGM in galaxy clusters (ICM) is discussed in section 4.

4. Magnetic fields associated with clusters of galaxies

4.1. Faraday rotation and x-ray probes of galaxy cluster magnetic fields

Intergalactic gas in galaxy clusters has a typical electron density of 10^{-4}–10^{-2} cm^{-3}, temperature in the range 10^7–10^8 K, and an extent of ~ 1 Mpc. At this temperature range, which makes clusters significant x-ray sources ($L_x \approx 10^{43}$–10^{45} erg s^{-1}), the ion sound speed is comparable to the galaxies' velocity dispersion in the cluster, which is ~ 400–1200 km s^{-1}. A minority of clusters contain cosmic ray electrons which, over dimensions comparable to that of the hot gas, emit a diffuse 'halo' of synchrotron radiation, thus revealing an intracluster magnetic field. Our discussion here focuses specifically on cluster magnetic fields and their measurement: the extensive subject of intergalactic gas has been covered in a recent review in this journal by Fabian and Barcons (1991).

4.1.1. Radio and x-ray methods for probing cluster magnetic fields. Intracluster magnetic fields can be most easily detected via synchrotron radiation (equation (1.1)) from co-extensive cosmic rays (cf also section 4.3 below). Thus, the first evidence for magnetic fields came via detection of a synchrotron halo: in the Coma cluster of galaxies (Willson 1970, Jaffe *et al* 1976, Hanisch *et al* 1979, Kim *et al* 1990), in Abell 754 (Waldthausen 1980), Abell 2256 (Bridle *et al* 1979, Kim 1993), Abell 2319 (Harris and Miley 1978), and subsequently several others—see Hanisch (1987) for a more extensive bibliography.

Unfortunately the synchrotron emissivity does not give the field *strength* (equation (1.1)) unless we have independent knowledge of the true number density of relativistic electrons. Apart from detecting the synchrotron-emitting halo, ICM magnetic fields can be probed in three further ways: (i) multi-frequency polarization mapping of the synchrotron halo emission which, due to the co-extensive thermal gas, will undergo differential Faraday rotation and depolarization as a function of radio wavelength. Because the Faraday rotation law (equation (1.3)) also contains the (non-relativistic) electron density and an unknown number of field reversals, independent estimates of these latter two quantities lead to an estimate of $|\boldsymbol{B}|$. (ii) Comparing the Faraday rotation of *background* radio sources shining through the cluster (cf Lawler and Dennison 1982, Kim *et al* 1990) with comparable sources whose ray path to us avoids the cluster, to test for excess Faraday rotation due to the cluster's ICM. (iii) Using Faraday rotation mapping of extended radio sources embedded within the cluster as a polarized 'surface', against which foreground intra-cluster variations of $\Delta\chi = 8.1 \times 10^5 \lambda^2 \int n_e B_\parallel \, dl$ can be measured. This assumes that the Faraday rotation internal to the radio lobes of cluster sources is smaller than that being probed in the ICM. Each of these methods requires, ideally, a companion x-ray image, with x-ray spectral information so that estimates of both T_e and n_e within the cluster can be made. Then a weighted $\langle |\boldsymbol{B}| \rangle$ can be estimated. In the following we review recent attempts to make cluster magnetic field estimates using the above three types of observations.

4.1.2. Recent magnetic field measurements in the ICM of 'normal' galaxy clusters and groups. Method (i) is difficult, because of the extreme faintness of the steep-spectrum halo emission at a useful resolution at $\lambda < 10$ cm. Although the synchrotron emissivity becomes rapidly stronger at longer λs, only few radio telescopes have the required (<1′) angular resolution. Furthermore, the 'Faraday depth' (cf Burn 1966, Tribble 1991) at $\lambda > 20$ cm is so high that the linear polarization can become completely self-depolarized by its own differential Faraday rotation. One of the few such observations attempted, by Kim *et al* (1990) for the Coma cluster, indeed found the Coma cluster's halo to be largely depolarized at 21 cm, and too weak at shorter radio λs. Method (ii) is promising for nearby clusters, and was successfully used by Kim *et al* (1990) to make the first, relatively firm estimate of magnetic field *strength* in the intracluster medium. Their result, for the Coma cluster core region, is 1.7 ± 0.9 μG, and was obtained using 18 background source RMs near in position to the Coma cluster (see figure 12). This field strength estimate used x-ray data from Abramopoulos and Ku (1983) to estimate n_e (cf equation (1.3)), and an estimate of the field reversal scale was obtained from the RM variation scale in an extended head-tail galaxy within the cluster. By interstellar medium standards, the field is surprisingly strong, being comparable with the disk interstellar field in our galaxy (~3–4 μG). It is likely that the field strength near the Coma cluster core (not well sampled with the RM data in figure 12) is even higher. A field strength estimate for another relatively nearby cluster, Abell 2319, was made by Vallée *et al* (1986). The density of suitable background RM probes on the sky is insufficient to apply this method to most other clusters, so attempts have been made to compare RMs for large numbers of background sources at differing impact parameter distances for a sample of many clusters. Using this technique, Lawler and Dennison (1982) obtained the first tentative positive statistical signal of cluster ICM rotation measures.

More recently, Kim *et al* (1991) used a sample of 53 Abell galaxy clusters, 19 of which had x-ray core size measurements, and obtained the surprising and interesting result that magnetic field strengths near ~1 μG extend typically to ~0.5 Mpc from the cluster centres. Since clusters with strong radio halos are rare, their result further suggests that μG-level fields are widespread in the ICM whether or not a cluster has a strong radio halo. The fact that magnetic fields near μG level are widespread in galaxy clusters is, independently, consistent with a lower limit of 0.3–0.5 μG which is implied by the observed general absence of inverse-Compton-generated x-rays in clusters (cf Gursky and Schwartz 1977, Harris and Grindlay 1979, Henriksen and Mushotzky 1986, Rephaeli and Gruber 1988).

Evidence of a different kind, and a version of method (iii) above, has been produced by Garrington *et al* (1988), and Garrington and Conway (1991), who discovered a systematic side-to-side asymmetry of the *depolarization ratio* between two frequencies in a large sample of FR II radio sources covering a substantial redshift range. They interpret this near (jet) side/far side difference relative to the radio galaxy nucleus to

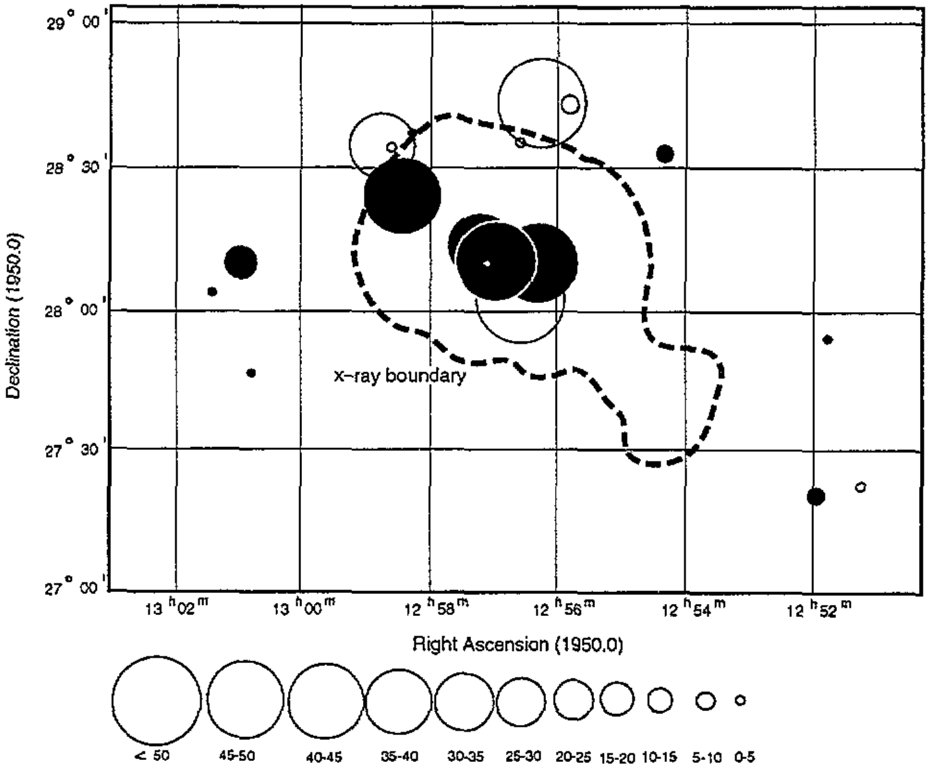


Figure 12. RM distribution of 18 background radio sources relative to the x-ray boundary of the Coma cluster of galaxies, which shows a clear excess RMs added by the intracluster medium (source Kim *et al* 1990). Filled and open circles show positive, and negative RM's respectively. The dashed line shows the ROSAT x-ray boundary at approx. 0.12 counts/ 400 arcsec^2 for the ROSAT PSPC detector, in the range 0.5–2.4 keV (from Briel *et al* 1992).

be due to a 30–100 kpc radius ionized gas halo having a magnetic field strength of at least 1 μG in the low redshift sources, and tangled on a scale of <5 kpc. They ascribe this environment to that which is typical around cD galaxies in galaxy groups or poor clusters of galaxies. Although these more 'typical' radio sources are not usually in rich clusters, the result is important, in that it supports the findings described above, by suggesting that μG level magnetic fields are widespread, at least wherever there is significant hot gas in galaxy systems. Although the energy density in 1–2 μG fields is usually much less than that in the hot gas, their influence on conductivity is sufficient to indirectly influence the dynamics of the ICM, and the long term evolutionary scenario of galaxies in clusters. What remains to be understood is how, and when, these fields were generated and amplified to these levels.

4.1.3. Dectection of strong magnetic-fields in cooling flow clusters. High resolution, multi-frequency VLA radio images of extended radio galaxies associated with cD galaxies in the centres of dense, 'cooling flow' clusters have, using method (iii), revealed extremely large Faraday rotations from kpc-scale, ordered magnetic fields: Examples are Cygnus A (Dreher *et al* 1987), M87 (Owen *et al* 1990), Hydra A (Taylor *et al* 1990, Taylor and Perley 1993), 3C295 (Perley and Taylor 1991) and Abell 1795 (Ge and Owen 1993).

The Cygnus A radio source contains systematic RM gradients of 100 to 600 rad m^{-2} kpc^{-1}, and regions of large scale magnetic field coherence. In other regions, RM jumps of up to 3000 rad m^{-2} occur over scales <400 pc in the cluster (Perley 1990). Hydra A, also associated with a cD galaxy and x-ray emission (David *et al* 1990), has RM fluctuations of close to 12 000 rad m^{-2}, with organized magnetic field changes on scales of up to 100 kpc (Taylor and Perley 1993). The large extent of the RM probe offered by Hydra A shows that magnetic field strengths of up to $\approx 30\ \mu G$ exist in its host cluster. Furthermore, the magnetic pressure closer to the cluster core is roughly two orders of magnitude greater than the dynamic gas inflow pressure as inferred from the model of White and Sarazin (1987)—cf Taylor *et al* (1990). Cluster field values of $\sim 30\ \mu G$, have also been found around the radio galaxy 3C295 at a redshift of 0.461 (Perley and Taylor 1991). As for Cygnus A and Hydra A, evidence for the lack of depolarization within the magnetized zones generating the high RM gradients favours their location *outside*, rather than within, the boundary of the radio lobes (Perley 1990).

These results suggest *prima facie* that, at least in cooling flow clusters, individual galaxies may form out of a strongly magnetized environment having prior magnetic field strengths at least as large as in the ISM of 'evolved' galaxy disks.

4.2. Regeneration and amplification of magnetic fields in the intercluster medium

Early ideas on the amplification of magnetic fields in galaxy clusters came from attempts to explain what is probably a closely coupled phenomenon—namely the re-acceleration of ICM relativistic electrons. This is required by observations which confirm their spatial distribution well away from active galaxies and radio sources near the cluster centre—for example in the Coma cluster. Jaffe (1980) proposed that turbulent wakes behind galaxies moving through the ICM would re-accelerate relativistic electrons, and maintain the magnetic field at μG levels. Similar ideas were discussed by Roland *et al* (1981), and Ruzmaikin *et al* (1989) who suggested a turbulent dynamo mechanism. More recently Goldman and Rephaeli (1991), De Young (1992) and Tribble (1993), proposed that cluster mergers provide the conditions required to explain the radio synchrotron halos in a small minority of clusters (like Coma). They argue, in contrast, that turbulence due to galactic wakes are not effective enough to amplify ICM fields to μG levels, as is observed.

An important element is to understand the physics of cooling flows (cf Edge *et al* 1992), since there is strong circumstantial evidence (section 4.1.3) that the generation of very strong magnetic fields is connected with the cooling flow process. Recent results described above indicate that $B^2/8\pi$ is, at least locally, energetically comparable to the turbulent and thermal energy densities, and possibly more energetic than the dynamical energy density of the cooling flow itself. However, $>1\ \mu G$ fields also exist in some clusters which are not of the 'cooling flow' type, and for both these classes of cluster, substantial magnetic fields are also found well beyond the cluster core. Soker and Sarazin (1990) propose how a large scale, radially oriented field structure would be produced by a cooling flow. It is not clear, however, that the recently discovered strong RM features are consistent with this model. The reduced conductivity in cooling flow clusters naturally creates conditions for multiphase cooling flows, as recently suggested, and modelled by Tribble (1992). On the contrary, Rosner and Tucker (1989) argue that tangled intracluster magnetic fields do not significantly reduce the thermal conduction in clusters, which leads them to suggest that cooling flow rates in giant cluster-dominating elliptical galaxies are typically $\leqslant 0.1\ M_{\odot}/yr$, which is up to an order of magnitude smaller than has generally been thought.

It has been suggested (e.g. Ruzmaikin *et al* 1989, Eilek 1993) that, at least for cooling flow clusters, large scale dynamo amplification is operating to produce such strong fields. Our understanding of the details will improve with further radio and especially high resolution multi-band x-ray images in future. Given the complex mix of gravitational and (now evidently) magnetic forces at play, the problem to solve has a highly non-linear character, and will probably require numerical solutions by analogy with the MHD equations which have recently provided insight into the physics of radio source jets and lobes. Fast dynamo amplification of magnetic fields in radio lobes (figure 11 and section 3.2.3) may indicate an analagous process for magnetic field amplification in cooling flows.

With recent evidence for μG-level fields in *most* clusters, some form of dynamo is probably also responsible, although at what stage in the cluster's history is not yet clear. The answer to this question will illuminate the role of magnetic forces in galaxy evolution in general. If massive inflow on a cluster scale can amplify magnetic fields, the process may also work effectively for infalling gas onto a single galaxy, as Pudritz and Silk (1989) and Pudritz (1990) have suggested to explain galactic magnetic field strengths.

The foregoing results and ideas reveal an emerging picture of extragalactic magnetic fields which was not available to us a few years ago: magnetic field strengths in galaxy clusters (excepting dense cooling flow filaments, and the lobes of extragalactic radio sources) appear to be of order 1 to a few microgauss. This is comparable with that found in the interstellar medium of our own galaxy, where the co-spatial gas density is much higher. Both the statistical evidence for Abell clusters (Kim *et al* 1991), and the *supracluster* emission found around the Coma cluster (see next section) suggest that microgauss-level fields extend beyond the core regions of clusters, where the gas density is lower still. Intergalactic magnetic field strengths appear to care little about the density of their associated thermal gas; what this seems to be telling us is that there is a near-universal interstellar/intergalactic field strength in the local universe, whose energy density is close to that of the microwave background radiation, $\varepsilon_{\mathrm{bg}}$. The background-equivalent magnetic field strength $\boldsymbol{B}_{\mathrm{bge}} \approx 3 \times 10^{-6}$ G. If there is a physical cause-effect connection to $\varepsilon_{\mathrm{bg}}$, e.g. via the cosmic ray background energy density (cf section 5.4.4), which is also similar, this would provide at least empirical support for the idea that interstellar and intergalactic magnetic fields have always 'saturated' to $\boldsymbol{B}_{\mathrm{bge}}$, barring other localized processes which may drive the field higher. Examples of the latter would be dense cooling flows in clusters, radio jets and lobes, and very dense, star-forming molecular clouds. It seems reasonable, and not inconsistent with observation, to postulate that galaxy systems have evolved in a magnetic environment *where* $|\boldsymbol{B}| \gtrsim 1\mu G$ *over most of the cosmic look-back time.*

4.3. Low frequency radio emission as a tracer of extragalactic magnetic fields

Cosmic rays serve as particularly effective 'illuminators' of intergalactic magnetic fields at low radio frequencies. This is because of the relatively high spectral density of synchrotron radiation at low frequencies, reflecting the high value of γ (typically 2.4–3), which defines the power law distribution of cosmic ray electron energies: $N(E) \sim E^{-\gamma}$ (cf equation (1.1)). The critical frequency (near which most of the synchrotron radiation is emitted) is related to E by $\nu_C = (3eB \sin \varphi / 4\pi m^3 c^5) E^2$ (Pacholczyk 1970). An advantage of observing at the lowest possible radio frequencies is that we preferentially detect the lowest energy CR electrons, which survive the longest to 'keep illuminating' the associated magnetic field.

To calculate the longest possible loss time for a CR electron, we define a 'cosmic background-equivalent' magnetic field, $\boldsymbol{B}_{\rm bge}$, for which a CR electron's energy loss rate by synchrotron radiation ($\partial E/\partial t \propto |\boldsymbol{B}|^2 E^2$) equals that due to inverse Compton scattering off the microwave background radiation ($(\partial E/\partial t) \propto \varepsilon_{\rm bg} E^2$ where $\varepsilon_{\rm bg} = 4.8 \times 10^{-13}(1+z)^4$ erg cm^{-3}. Thus, for $\boldsymbol{B} \approx \boldsymbol{B}_{\rm bge}$ the energy density of the magnetic field ($\boldsymbol{B}^2/8\pi$) equals that in the cosmic background radiation ($\varepsilon_{\rm bg}$). For $z \ll 1$, to which we restrict the present discussion, $\boldsymbol{B}_{\rm bge} \approx 3 \times 10^{-6}$ G. Larger magnetic field strengths will cause shorter, synchrotron radiation-dominated lifetimes, whereas for $\boldsymbol{B} < \boldsymbol{B}_{\rm bge}$ a CR electron's loss rate, being dominated by inverse Compton scattering, will depend only on its energy and $\varepsilon_{\rm bg}$ (cf Rees 1967, Pachoczyk 1970 for a discussion of the basic radiation processes).

We can write an expression for the inverse Compton-dominated lifetime, $\tau_{\rm max}$, for synchrotron-radiating CR electrons which are observed at a frequency ν, expressing the electron energy in terms of ν and B, as

$$\tau_{\rm max} \approx 3 \times 10^8 \, (\nu/327 \, {\rm MHz})^{-1/2} (|\boldsymbol{B}|/|\boldsymbol{B}_{\rm bge}|)^{1/2} \, {\rm yr} \tag{4.1}$$

where $(|\boldsymbol{B}|/|\boldsymbol{B}_{\rm bge}| \lesssim 1)$. The factor $(|\boldsymbol{B}|/|\boldsymbol{B}_{\rm bge}|)^{1/2}$, is probably not far below unity as suggested by recently measured ICM field values. Thus we see that the maximum 'fossil lifetime' of relativistic electrons scales to first order by $\approx \nu^{-1/2}$. Observing frequencies of interest are approximately between 20 MHz and 400 MHz: below 20 MHz, refraction and absorption by the ionized component of the interstellar medium and/or the ionosphere become important. Above ~400 MHz, the emissivity becomes too low for the most sensitive detection of diffuse intergalactic synchrotron emission. In addition, the higher energy electrons, which radiate on average at higher frequencies, are less likely to have propagated to large distances from their acceleration sites because of their shorter loss times. Observing frequencies below ≈20 MHz are conceivable from space, if one is restricted to high galactic latitudes.

Until recently both the low resolution, and difficulties with earthbound and solar interference and ionospheric phase fluctuations, have prevented accurate imaging at frequencies below ~300 MHz. To distinguish true diffuse intergalactic synchrotron emission from a blend of discrete extragalactic radio sources, an angular resolution of ≈1′ or better is required. This, at $\nu = 75$ MHz for example, requires a well-filled antenna array (to achieve the required image quality), which extends to ≈30 km or more. Furthermore, interference suppression and phase irregularities in the ionosphere need to be eliminated, which require compute-intensive data processing techniques. These requirements are being fulfilled for the first time (by the NRAO VLA recently outfitted to low frequencies, the Giant Metre Wave Telescope (GMRT) at Pune, India, and the Westerbork Synthesis Radio Telescope (WSRT) in the Netherlands), a development which opens new possibilities for the detection of large scale IG magnetic fields. Relation (4.1) shows that radio images at $\nu \approx 30$ MHz could show diffuse, magnetized intergalactic gas in the local universe which was produced $\approx 10^9$ years ago, on the assumption that $|\boldsymbol{B}|$ is not much different from $|\boldsymbol{B}_{\rm bge}|$. Such observations could give clues from the *local* Universe to the evolution of magnetic field strength over a significant period of cosmic time in such systems, e.g. in old, extended radio source lobes. An important complement will be sensitive imaging of diffuse x-ray emission which is produced by the inverse Compton mechanism (see also section 5.4.2).

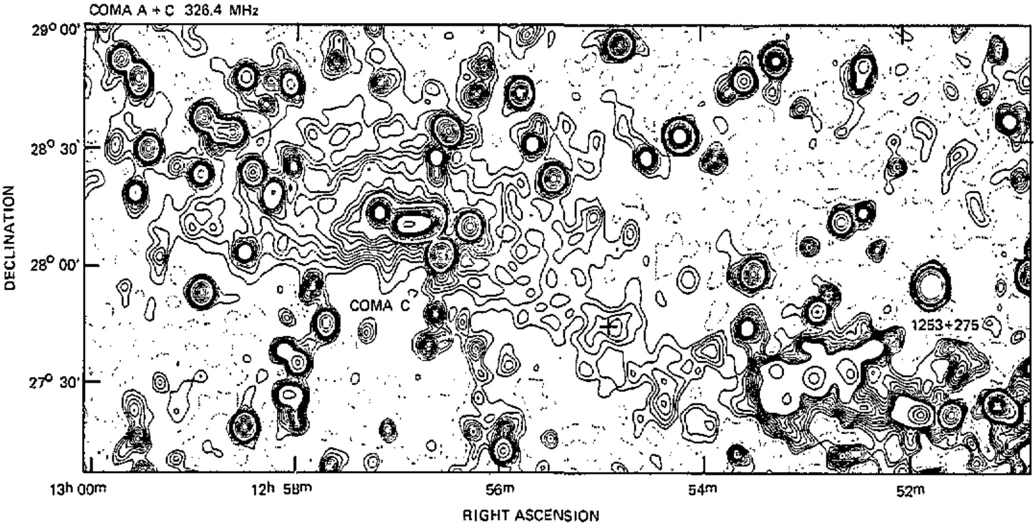


Figure 13. Radio image showing 326 MHz emission along in intergalactic 'bridge', which appears to connect the Coma cluster of galaxies (Coma C) with the Coma A complex of radio emission (source: Kim *et al* 1989).

Figure 13 shows a WSRT image at 326 MHz published by Kim *et al* (1989) of the 326 MHz intergalactic synchrotron emission surrounding the Coma cluster of galaxies, which may be prototypical of the type of radiation which could be imaged in future at much lower frequencies. They found emission extending beyond the Coma-cluster, indicating an extended, magnetized region on a supercluster scale. Measurements of this type do not yield the field strength directly (equation (1.1)), but the assumption of equipartition between particle and magnetic density gives field strengths of ca $2 \times 10^{-7}(1+k)^{2/7}$ G in the region in Kim *et al*'s observations which is well outside of the cluster core. (k is the ratio of CR proton to electron energies, usually estimated at between 10 and 100.)

These first low frequency images with high dynamic range suggest that future *lower* frequency images of high sensitivity and resolution will yield a great deal of new information of the distribution of intergalactic magnetic fields on large scales. Low frequency radio astronomy may play an important role in the detection of intergalactic magnetic fields. Precision low frequency images at high resolution of the extragalactic sky may prove in future to be as important for studies of galaxy evolution and cosmology as the recent microwave background surveys.

5. The detection of galactic and extragalactic magnetic fields at earlier cosmological epochs

The Galaxy-corrected Faraday rotation measure of a distant quasar can be broken into three unrelated components in equation (1.3): (i) the RM which is intrinsic to the source (IRM), (ii) a component added by some *intervening* galaxy system (e.g. galaxy disk or halo, galaxy group, or cluster of galaxies), and (iii) hypothetically, that due to an all-pervading, cosmologically scaled magneto-ionic medium. Using measured or estimated values of n_e, and the field reversal scale, an RM associated with any of these three components could give an estimate, or limit to the associated magnetic field (cf Kronberg and Perry 1982). The *observed* value of a rotation measure generated at redshift, z, will have its detectability reduced by $(1+z)^{-2}$. On the other hand due to cosmological expansion, $n_e \sim (1+z)^3$, and $|\boldsymbol{B}_{\rm igm}| \sim (1+z)^2$, assuming flux conservation i.e. $\boldsymbol{B}$ in component (iii) is frozen in to the IGM plasma. This illustrates how $n_e B$ could, for large z, overwhelm the $(1+z)^{-2}$ watering down effect on the observed RMS and thereby produce a detectable RM signal, *if* the magneto-ionic strength follows the cosmological scale factor in some reasonable way. We briefly review the results of observational attempts to probe components (ii)–(iii) at significant cosmological lookback times.

5.1. *Searches for a magnetic field in the widespread intergalactic medium up to the redshifts of quasars*

The availability of larger samples of extragalactic source rotation measures in the 1970s led to the first tests for a Faraday rotation from a widespread, and cosmologically scaled intergalactic magneto-ionic medium (Rees and Reinhardt 1972, Nelson 1973, Kronberg and Simard-Normandin 1976). The density, $n_{\rm ig}(z)$, of a widespread intergalactic ionized gas can be parameterized as a fraction, Φ of the total matter density, which increases with cosmological epoch as $(1+z)^3$. For a characteristic reversal scale of widespread IG magnetic field, a measured RM (z) out to some maximum $(z_{\rm m})$ can be related to the widespread magnetic field using equation (1.3) modified as follows:

$$\mathrm{RM}(z_{\rm m}) = 8.1 \times 10^5 \int n_e(z) B_{\parallel}(z)(1+z)^{-2}\, \mathrm{d}l(z)\ \mathrm{rad\ m^{-2}} \tag{5.1}$$

where

$$\mathrm{d}l(z) = (10^{-6} c/H_0)(1+z)(1+\Omega z)^{-1/2}\, \mathrm{d}z\ \mathrm{Mpc} \tag{5.2}$$

for a $\Lambda = 0$ Friedmann universe. n_e is in cm^{-3}, c in km s^{-1}, H_0 in km s^{-1} Mpc^{-1}, and B in G.

If such a field were ordered on the scale of the universe, then an observed systematic increase of RM(z) would occur for a preferred direction in the sky which could, in principle also be determined (Woltjer 1965, Zel'dovich 1965, Brecher and Blumenthal 1970). Early claims to the detection of such an aligned field (e.g. Sofue *et al* 1968) were not substantiated in subsequent, better quasar RM data. These same data limit any systematic growth of RM(z) to ≈ 5 rad m^{-2} or less at $z = 2.5$ (Kronberg and Simard-Normandin 1976, Kronberg 1976). This, for a Friedmann universe with $\Omega = 1$ and $H_0 =$ 75 km s^{-1} Mpc^{-1}, places a limit on any *cosmologically aligned* $|\boldsymbol{B}_{\rm igm}|$ of $\approx 10^{-11}$ G at the present epoch.

A field which is aligned on cosmological scales is unlikely. Given the large scale homogeneity and isotropy of the universe back to the last scattering surface at $z \approx 10^3$, one assumes that any widespread field in the universe has a characteristic l_0 at the present epoch. Recent evidence from galaxy cluster RMs suggests that the largest reversal scale, l_0, is crudely of order 1 Mpc. Scaling this by $(1+z)^{-1}$, and applying the observational limit to RM$(z_{\rm m})$ out to $z_{\rm m} = 2.5$ gives $|\boldsymbol{B}_{\rm igm}| \lesssim 10^{-9}$ G at the current epoch for any widespread, all-pervading field. With future, more extensive and accurate RM data out to larger $z_{\rm m}$, it should be possible to improve the sensitivity of this measurement. 10^{-9} G lies at the upper end of some recently calculated primordial field strengths generated in an inflation cosmology (cf section 5.5 below).

5.2. Magnetic fields associated with absorption line systems in quasars

Having shown that the RM from a *widespread* IGM (iii) is below current levels of detectability, we now focus on what has been learned about magneto-ionic gas in discrete intervening systems (ii) at intermediate redshifts (z_a) between us and z_e, that of the emitters—the quasars. We ignore, for the moment, a *source-associated* component (i).

Independent evidence from optical and 21 cm absorption lines at intermediate redshifts (z_a), reveals that quasar lines of sight pass through intervening galaxy systems whose column densities, and excitation conditions, can be inferred from the equivalent widths at z_a in suitably chosen absorption line transitions. In a combined analysis of the best available quasar RMs and absorption line data, Kronberg and Perry (1982) found a correlation between high column depth absorbers in front of quasars, and the tendency for a quasar to have an excess RM (cf also Watson and Perry 1991). This confirmed the existence of magnetic fields in galaxy systems at large redshifts. For those quasars with good estimates of *free electron* column density, N_e, Kronberg and Perry were able to make the first crude estimates of magnetic field *strengths* in these absorber systems—which varied from a few μG to nearly a milligauss.

A small subset of quasar intervenors has high column density ($N_{\rm HI} \approx 10^{21}$ cm^{-2}) of neutral, or near neutral hydrogen, which gives rise to damped Lyman-α absorption (Wolfe 1988). This is an indicator of a galaxy disk. Combining these line equivalent width estimates with RM data, Wolfe (1988) obtains field estimates of a few μG for these systems—which are not much different from typical galactic interstellar field values.

5.2.1. The methodology of magnetic field estimates for quasar intervenor 'clouds'. The observable RM and the observationally derivable N_e, the electron column density in an intervening cloud at z_a, can be related to the cloud's magnetic field by

$$\langle B_\parallel \rangle = 2.63 \times 10^{-13}\,\mathrm{RM}\, N_e (1+z_a)^2\ \mathrm{G} \tag{5.3}$$

where $\langle B_\parallel \rangle$ is defined by

$$\langle B_\parallel \rangle = \int n_e B_\parallel \,\mathrm{d}l \Big/ \int n_e \,\mathrm{d}l \tag{5.4}$$

(Kronberg and Perry 1982). At most a small number of large galaxies will intersect a typical line of sight out to $z_e \approx 3$. the present-epoch density of galaxies having halos of $r \sim 45$ kpc is $\approx 0.017 h_{75}$ Mpc^{-3} (cf Burbidge *et al* 1977), and a fraction of current quasar samples can be expected to have no intersections with large, high column density galaxies. (For μGauss-level fields, $N_e \approx 10^{20}$ cm^{-2} at the current epoch is needed to produce a detectable rotation measure.) We can take equation (5.4) one step further to estimate the most likely actual magnetic field strength if a few (m) similar clouds (at approximately the same epoch) are intersected by a background quasar:

$$\langle |B| \rangle \sim \frac{8.37 \times 10^{12} (1 + \langle z_a \rangle)^2 |\mathrm{RM}|}{m^{1/2} N_e}\ \mathrm{G} \tag{5.5}$$

(Kronberg and Perry 1982), where N_e are the (assumed comparable) column densities in each of the m clouds near to z_a, whose field directions are randomly orientated with respect to each other. The constant includes the expectation value of 0.5 for cos θ over m randomly oriented samples.

The foregoing discussion implicity assumes a unique line of sight, i.e. that the RM (and the column density) are not averages over several different sightlines to an extended illuminating quasar. In practice, the integrated RM might represent an average over several independent sight lines, *if* the radio source has extended structure. This fact can serve to *underestimate* $\langle|B|\rangle$ as determined in equation (5.5), in that the RM in one or more of the sightlines in an extended image might be significantly larger than the integrated RM (cf Perry *et al* 1993 for a discussion of this point). Another fact to take into account is that, because the radio structure is sometimes extended over tens to hundreds of kiloparsecs, whereas the optical emission is typically <100 pc in quasars and AGNs, the line of sight which is relevant to N_e, may not coincide with that along which the RM was generated (equation (5.3) and (5.5)). For statistical estimates of magnetic fields in quasar absorption line systems, only *integrated* RMs are currently available in large numbers, so that these considerations must be allowed for in making estimates of real magnetic field strengths. Recently, high Faraday rotation images made with sub-arcsecond resolution with the VLA have provided *transverse* probes in RM along various lines of sight through an intervenor. This makes it easier to identify the appropriate sightline(s) to which (5.3) and (5.5) apply.

5.2.2. Magnetic field estimates from transverse probes of quasar intervenors. High resolution RM images of the forgoing type have been made by Kronberg *et al* (1990) for 3C191, a quasar with a rich, 'associated' absorption line spectrum, i.e. absorption virtually *at* the redshift of the emission lines. Such, relatively unusual, associated systems are not the typical intervening galaxies just discussed; in 3C191's case, it has been proposed to be a wind-driven shell of hot gas (seen in absorption *and* emission in this case) by Kronberg *et al* (1990) and Perry and Dyson (1990). The magnetic field strength in this $z = 1.945$ system was found to be in the range of 0.4–4 μG. Furthermore, it was found to maintain its prevailing direction over at least ~15 kpc—a substantial fraction of a galaxy size.

Another transverse RM probe of an intervening galaxy at $z = 0.395$, using the extended and polarized jet of the quasar PKS 1229-021 at $z = 1.038$, has recently yielded a fairly firm estimate of magnetic field strength in the intervenor of 1-4 μG (Kronberg *et al* 1992). In this case, the field direction reverses every $\approx 0.7''$, which corresponds roughly to a spiral arm separation in a galaxy at that redshift. The spectrum of the associated quasar exhibits damped Lyman-α absorption (indicative of a galaxy disk), and a combination of absorption transitions which indicate a galaxy halo and disk, where N_e in the disk is reasonably well measured. Combination of a detailed analysis of the optical and 21 cm absorption spectrum by Briggs *et al* (1985) and the RM variations established by Kronberg *et al* (1992) made it possible to give a well determined field strength, and confirm that this $z = 0.395$ quasar intervenor is very likely a spiral galaxy whose interstellar magnetic field strength is similar to that in our Milky Way.

5.2.3. Quasar intervenors as test objects for the galactic dynamo theory. Because high column density H I intervenors are probably galaxy disks, firm estimates of their magnetic field strength such as that of Kronberg *et al* (1992) above, combined with their large lookback times enables us to test current ideas of field amplification and seed fields. For the above intervening galaxy at $z = 0.395$, the cosmological lookback time is approximately 38% of the Hubble time (for $\Omega = 1$). This intervenor provides one of the first available test objects for this purpose (cf also section 2.3). The fact that the field strength in this system is comparable with typical galaxy disk fields in the local universe suggests that, *if* this object is typical, than magnetic field amplification has not occured over the past 40% or so of the age of the universe.

Additionally, the *difference* in cosmic time between the absorber-galaxy's formation time, $t_{\rm form}$, and that at its observed redshift, ($t_{\rm form} - t_{z=0.395}$ for the PKS 1229-021 intervenor), can be compared with the dynamo amplification time required to amplify the field from, say the hypothesized primordial seed field strength up to the observed value of a few μG (in this case) at $z = 0.395$. In a Friedmann ($\Lambda = 0$) universe, this cosmic time difference depends strongly on Ω, i.e. on the total matter density in the universe, and in the sense that higher Ω (e.g. in a dark-matter-dominated universe) shortens the timespan over which the galaxy can amplify its field. Supposing that the $z = 0.395$ intervenor galaxy for PKS 1229-021 formed at $z = 4$ in a $\Omega = 1$ universe, Kronberg *et al* (1992) calculate that, if the galaxy disk dynamo amplification time is larger than one galaxy rotation, then a 4 μG field requires a seed field at $t_{\rm form}$ of at least $\sim 4 \times 10^{-16}$ G. For later $t_{\rm form}$ (lower $z_{\rm form}$), the required seed fields are yet larger (unless $\Omega < 1$). Alternatively, if the dynamo amplification is 'fast', i.e. shorter than a galaxy rotation time (see section 2.3.6), then smaller seed fields would be allowed. This result does not contradict the alternative hypothesis, namely that μG-level fields have existed in galaxies since very early epochs, and even at $z \approx 0.4$ have long since saturated to the local-epoch disk field levels of a few μG.

The example of PKS 1229-021 illustrates how magnetic field strength determinations in such systems can be used to test models of slow, mean field amplification and set limits on seed fields. It shows that we are beginning to set meaningful limits at $z = 0.4$ to 0.5, so that measurements on similar systems at $z > 1$ will provide some stringent tests—especially if $\Omega \approx 1$ and $\Lambda = 0$.

5.3. Probes of cosmological magnetic field evolution using quasar Faraday rotation statistics

The fact that no Faraday rotation 'signal' has yet been detected from a widespread, all-pervading intergalactic plasma (section 5.1), whereas *discrete* 'magnetized cloud systems' have been detected over a similar redshift range (section 5.2), indicates that population models can be constructed for the latter, which can be tested against RM observations of quasars out to significant lookback times in the universe. Welter *et al* (1984) have produced comprehensive models of this type which they have tested against the best RM data available about a decade ago, and concluded that the RM intervenor population shows clear evolutionary effects out to $z \approx 2.2$. However the data were not sufficient to confidently isolate a particular preferred intervenor model.

The mathematical modelling of discrete sources of RM as a function of z is different from that of the more straightforward case of calculating the 'intersection depth' of a sample of intervenors for different cosmological geometries. The latter can be represented as an 'optical depth'

$$\tau(z_{\rm e}) = \int P(z_{\rm a})\, {\rm d}z \tag{5.6}$$

where $P(z_{\rm a})$ is the probability of intersection by a cloud which has some number density, $n(z_{\rm a}) = n_0(1+z)^3$, and a (dimensionless) cross section, $A(z_{\rm a}) = cn(z_{\rm a})/H_0\{\Sigma_0(1+z_{\rm a})^\eta\}$. Here, Σ is the physical cross section of the RM intervenor, whose cosmic evolution we parameterize by η, following the notation of Welter *et al* (1984). The subscript 0 refers to the present epoch. Consequently, $\tau(z_e)$ can be written in terms of A_0, and making use of equations (5.2) and (5.6), as

$$\tau(z_e)=\int_0^{z_e} A_0(1+z)^{1+\eta}(1+\Omega z)^{-1/2}\,\mathrm{d}z. \tag{5.7}$$

This is a purely geometrical term, applicable to the calculation of τ for any intervenor, whose electromagnetic properties have yet to be specified. If we assume $\Omega=0$, it integrates easily to become

$$\tau(z_e)=A_0(2+\eta)^{-1}\{(1+z_e)^{2+\eta}-1\} \tag{5.8}$$

(Welter *et al* 1984).

Only small numbers of galaxy-scale intersections occur per quasar out to $z\approx3.3$ (see e.g. Khari-Joshi and Perry 1982). More importantly, because of the $(1+z_a)^{-2}$ 'watering down' effect on a Faraday RM (RM_i for the ith cloud) generated at z_a, the probability density function $(R_e(\mathrm{RM}_i, z_e))$ for the total RM due to the (few) intervenors between us and z_e, must include the sum over all combinations of RM_i which, in turn, must be summed over all combinations of z_a. For example, two clouds of comparable RM_i at two large z_a's (more probable) will generate a smaller observed RM (depending on η) than the same two clouds at low z_a (less probable), assuming no cosmic evolution of RM_i.

Since the possibility of evolution needs to be introduced in a statistical model describing the Faraday RM strength of the clouds, we express the latter as an RMS (following Welter *et al* 1984);

$$\sigma_C(z_e)=\sigma_{C_0}(1+z)^{\beta_C-2} \tag{5.9}$$

and

$$\sigma_Q(z_e)=\sigma_{Q_0}(1+z)^{\beta_Q-2} \tag{5.10}$$

where C, and Q apply to RM generated in any intervening clouds, and that *associated* with the quasar, respectively. The subscript 0 refers to the present epoch, as before.

Welter *et al* (1984), using these concepts, developed appropriate general mathematical formalisms which can be used to deduce, or limit the parameters σ_C, σ_Q, A, β_C, β_Q and η. They show that the measured $\sigma^2(z_e)$, which they determined from a sample of 116 quasar RMs indicates significant evolution (namely β_C and/or $\beta_Q>0$), and that, if future RM samples enable a precise specification of the fraction of non-intersections (f_0), it should be possible in future to specify *all* of the above unknowns. This information, together with future high resolution absorption spectra for the same quasars, will provide fairly direct data on the evolution of Faraday rotating intervenors, out to the most distant quasars. This is an exciting prospect, in that it can potentially generate magnetic field estimates over >90% of the Hubble time.

The existence of a significant fraction (f_0) of quasars which do not intersect an intervenor was indicated in the analysis of Kronberg and Simard-Normandin (1976). It is additionally interesting in that, independent of the 'discrete intervenor' properties discussed here, improved precision in the measurement of extragalactic RMs may in future either lower the limit of null detection of a widespread IG magnetic field, or possiby detect such a field, if $|B_{\mathrm{igm}}|_0 \gtrsim 10^{-8.5}$ G (section 5.1).

5.4. Indirect indicators of extragalactic magnetic fields

In addition to the yet-to-be-realized possibilities for the detection of intergalactic magnetic fields through low frequency synchrotron emission (section 4.3), some recent, and quite different types of observations might give powerful, even if indirect, evidence for the strength and extent of magnetic fields in the early Universe. In the following, four different lines of observational evidence are discussed which, when combined with some of the theoretical ideas reviewed elsewhere in this paper, have the potential for yielding new clues about the strength and presence of magnetic fields in the 'quasar era' (redshifts *ca* 1 to 4) and possibly into the early galaxy formation era. It is at these epochs of the universe that we have a lamentable deficit of direct observational data.

5.4.1. The radio-far infrared correlation for galaxies in the nearby universe. Having been predicted by Harwit and Pacini (1975), a surprisingly robust correlation was discovered between the far infrared (FIR) emission from dust in starburst galaxies, and the co-extensive synchrotron emission which involves the interstellar magnetic field (Dickey and Salpeter 1984, Kronberg *et al* 1985, Helou *et al* 1985, and others). Subsequent studies of this surprisingly tight, global correlation (Völk 1989, Helou and Bicay 1990, 1993) suggest that the interstellar gas and dust 'knows' something about the magnetic field: empirically the correlation $|\boldsymbol{B}| \propto n^{\beta}$, where $\frac{1}{3} \leqslant \beta \leqslant \frac{2}{3}$ over all galaxies (Helou and Bicay 1993)—n is the interstellar gas density associated with the far infrared emission.

A key observational fact for the purpose of this discussion is that, in starburst-like galaxies, the *spectral density* of the 40–100 μm FIR emission is much stronger, hence more easily visible to larger redshifts, than cm-wave synchrotron radiation. The coming generation of millimetre and submillimetre telescopes should be able to detect FIR emission at $z \approx 5$ to 10, where the primeval analogues of starburst galaxies may be found, since this relatively strong emission would be redshifted to wavelengths at $\leqslant 1$ mm. The apparently universal empirical relationship to magnetic fields would, given measured FIR flux densities, enable us to estimate the associated magnetic field strengths in primeval galaxies out to these large redshifts. Although indirect, this is one of the few ways by which we could infer magnetic field strengths associated with primeval galaxies during and before the 'quasar epoch'.

5.4.2. Compton x-ray measurements on extragalactic sources of diffuse synchrotron radiation. Compton scattering of (especially mildly) relativistic electrons off microwave background photons to produce x-rays has been suggested and explored (Felten and Morrison 1963, Hoyle 1965, Rees 1967) in a variety of astrophysical contexts. Only recently has the quality of x-ray data 'caught up' with the theory. The morphology and spectrum of 0.1–2 keV x-ray emission of the outflow gas around M82 (e.g. Schaaf *et al* 1989) has been analysed to estimate the inverse Compton scattering component of the synchrotron-emitting electron population off FIR photons generated in the nuclear starburst region. Similar comparisons have been made for x-ray–RM comparisons in galaxy clusters (cf section 4.1), and recent ROSAT x-ray images show that x-ray emission co-exists with radio emission in the outer lobes and hotspots of some extended radio galaxies—such as Cygnus A (Harris *et al* 1994).

Whereas Kim *et al* (1990) obtained a magnetic field estimate by comparing *thermal* x-ray emission with intracluster Faraday rotation, the x-ray data can also be analysed in a different way; namely, to estimate that fraction of the x-ray emission which is due to inverse Compton scattering of microwave background photons off the same energetic electrons which produce the co-spatial synchrotron emission. Since the photon density of the μwave background is well known, the emissivity of inverse Compton x-rays can be used to compute (or limit) the number density of relativistic electrons ($n_{\mathrm{cr}0}$). Substituting this into the synchrotron emissivity equation (1.1) makes it possible to estimate

$|\boldsymbol{B}|$, or at least provide a *lower* limit to $|\boldsymbol{B}|$ corresponding to an upper limit on any inverse-Compton-generated x-rays. By isolating inverse Compton x-ray emission in the outer radio hotspots in Cygnus A, Harris *et al* (1994) have recently estimated the magnetic field strength in the Cygnus A hotspots to be $\approx 200\,\mu$G. Future generation x-ray images of extended radio lobes will permit this radio/x-ray method of magnetic field measurement to be made for other extragalactic radio sources—which can be seen over a substantial redshift range.

5.4.3. Inference of magnetic field strengths from highly redshifted metal-line QSO absorption lines. In section 3.1 we discussed recent evidence for the 'seeding' of the IGM by vigorous outflow which has recently been discovered in starburst and other galaxies with active star-forming complexes. If, at the galaxy formation epoch during the first few percent of the Hubble time, starburst activity was ubiquitous in the compact universe in which galaxies were at only $\approx 10\%$ of their current separation, a substantial fraction of the IGM at large redshifts might be filled by galactic wind plasma, consisting of magnetized gas which was enriched by heavy elements produced in the related supernovae.

This ejected, metal-enriched gas, if it exists far into galactic halos and beyond, could be the explanation of the surprising existence of heavier elements which have been seen in highly redshifted absorption lines in the spectra of some QSOs. If such enriched, magneto-ionic winds analogous to that of M82 (cf section 3.1) were produced in a compact 'volcanic', early universe of starburst galaxies, then the dynamo action associated with these winds might have provided near-μG-level fields which seem to be ubiquitous at the present epoch wherever we find intergalactic gas. If this scenario is true, then observations of heavy elements in highly redshifted QSO absorption spectra of intervening gas clouds could possibly serve as effective tracers (even if not reliable strength indicators) of magnetic fields associated with the same systems.

5.4.4. Possible future use of cosmic rays to infer the geometry and maximum strength of intergalactic magnetic fields. The observed cosmic ray (CR) spectrum of light baryons, i.e. mainly protons, is found to extend to *ca* 10^{20} eV. Recent data from the Fly's Eye detector indicate that a chemical 'switchover' occurs near 10^{18}–10^{19} eV, in the sense that CRs above this range are mostly protons and helium, whereas heavy nuclei appear more predominant below $\sim 10^{18}$ eV (Gaisser *et al* 1993). These most energetic CR protons are almost certainly extragalactic in origin. Biermann and Strittmatter (1987) and Rachen and Biermann (1993) argue that the outer *hotspots* of powerful FR II radio sources (cf section 3.2) are the most likely acceleration sites (by first order Fermi acceleration). If the universe is, as so far appears, filled with these energetic CR particles, then it is instructive to compare the *average distance* between the acceleration sites (~ 100 Mpc if luminous FR II radio sources are the origin of the CRs) with the *gyroradius* of $\approx 10^{20}$ eV protons in the presence of a widespread intergalactic magnetic field. A likely upper limit to the latter, discussed in section 5.1, is currently $\sim 10^{-9}$ G. The gyroradius, r_g, of a 10^{20} eV proton in a 10^{-9} G field is, interestingly, also of order 100 Mpc.

In the nearby universe, 10^{20} eV protons will travel in nearly straight lines for $|\boldsymbol{B}_{\mathrm{IG}}| < 10^{-9}$ G, which may be characteristic of the *interiors* (voids) of the large ≈ 100 Mpc bubbles which define the large scale distribution of optically visible matter. Around the periphery of the voids, i.e. the bubble 'surfaces' where the galaxies lie, they will be substantially deflected if $|\boldsymbol{B}_{\mathrm{IG}}| = 10^{-7\to -6}$ G, and possibly diffused in galaxy clusters and superclusters. Here, r_g will be an order of magnitude or so smaller. In any case, r_g can be approximated to a mean free path $\lambda_{\mathrm{CR}}(E, \tau, \boldsymbol{B}_{\mathrm{IG}})$, which is given by

$$\lambda_{\mathrm{CRmax}} \approx 30(E_{18}/B_{-9})(\tau_{17}/d_{\mathrm{bubble}})\ \mathrm{Mpc} \tag{5.11}$$

(Rachen and Biermann 1993) where τ is the CR particles's lifetime since acceleration to its initial (maximum) energy in units of 10^{17} s, E is in units of 10^{18} eV, and d_{bubble} is the size of the cosmic bubble in Mpc. The assumptions we made about void interior and periphery field strengths, respectively, suggest that when the CR acceleration sites are identified (thus far none has been), a combination of position differences for different directions and distances could in future lead to evidence for intergalactic field strengths. Of particular interest will be the IG field strength *within* the voids, where we otherwise have little prospect of estimating or limiting the magnetic fields.

A relevant consideration is that high energy ($\gamma > 10^{10}$) CR protons will lose energy with cosmic time, principally due to γ-p interactions (which produce pions) with the cosmic microwave background radiation (MBR) (Greisen 1966, Zatsepin and Kuzmin 1966, Stecker 1968). Since the MBR photon density decreases with time in a cosmology-dependent way, the proton CR propagation (related to τ) is complex (cf Hill and Schramm 1985, Berezinsky and Grigor'eva 1988). However the essence is that the attenuation length is very small, only $\approx$10 Mpc for $\gamma > 10^{11}$, causing a cut-off in the energy spectrum of CR from cosmologically distant sources.

These dominant energy loss mechanisms cause the universe to be opaque to high energy proton CRs beyond a few tens of Mpc. They are of interest for this discussion for the following reasons: (i) they modify the CR energy spectrum in ways which can be observationally tested, (ii) they imply that direct sources of such CRs can only be identified in the local universe, and (iii) given this 'convenient' isolation of local extragalactic CR sources, the deflection and diffusion of high energy proton CRs in the local universe will depend on the intergalactic magnetic field, as discussed above. Future observations of the locations and iostropy of proton CRs will be influenced by the strength and morphology of the intergalactic field, so that discrepencies between the arrival directions of primary CR sources and their production sites might be established in future. Field strengths $\gg 10^{-9}$ G will cause significant deflection, whereas the converse is true if $|\boldsymbol{B}_{\mathrm{IG}}| \ll 10^{-9}$ G.

5.5. Seed fields before the galaxy formation epoch

5.5.1. Magnetic field amplification between recombination and galaxy formation. The formation scenarios for the first stars and galaxies between the recombination epoch (at $z \approx 1000$), and the epoch of the currently visible quasars ($z \approx 0.2$ to 5) are not yet well understood, and as noted, there are few observations into those epochs. The role and influence of magnetic fields is likewise unclear, however this pessimistic situation has not deterred efforts to propose mechanisms for the very early generation of magnetic fields.

Zweibel (1988) has considered a scenario in which post-recombination density fluctuations, combined with tidal torques arising between mass condensations causes regeneration of a seed field. The tidal torques lead naturally to rotation, which can cause field regeneration by processes discussed in section 2; namely the toroidal field component is wound up in roatation which, in turn via the Coriolis force acting on small scale fluctuations provides the helicity, and hence the basic elements of an α-ω dynamo field regenerator. Zweibel's scenario incorporates cosmic expansion into the above scenario, and leads to estimates of up to $\sim 10^9$ G on scales of a few Mpc. This is close to current observationally established upper limits for a widespread IGM (cf section 5.1), but below what appears to be found in galaxy clusters (cf section 4.1). We might speculate that further magnetic field regeneration by, for example, matter infall along the lines of the model suggested by Pudritz and Silk (1989) might also provide interstellar-level fields already at this cosmological epoch, given a sufficient number of *e*-folding times.

If, as suggested by Kibble (1976), *strings* of supragalactic dimensions formed during the early universe then, as Osriker *et al* (1988) argue, a fossil field is an essential ingredient. When magnetic fields, along with intergalactic plasma are swept up by a moving superconducting string, reconnection of the field lines occurs behind the string, thereby trapping plasma there. A relativistic MHD wind emanates from oscillating superconducting loops, which carries a wound-up magnetic field (Thompson 1990). Such loops drive blast waves which, in Ostriker and Thompson's (1987) model, continuously heat the IGM for the recombination epoch onward. The magnetic field associated with the string-driven waves has a present-epoch value of a fraction of a μG. This proposed scenario can accommodate the experimentally established very low intergalactic density of *neutral* atomic hydrogen (Gunn and Peterson 1965), and also the current experimentally established upper limit of $\sim 10^{-9}$ G for a widespread IG field (cf section 5.3).

5.5.2. Models of magnetic field generation during the plasma epoch, before recombination. An interesting scheme for generating fields *before* the recombination epoch (at which point $z \approx 10^3$, and the universe was *ca* 10^{13} s old), was proposed by Harrison (1970, 1973). At this time, the radiation field and particles were strongly coupled, but there is a differential coupling between the intense radiation field and the electrons and ions respectively, due to the more effective Thomson scattering for the electrons. A key *proviso* for Harrisons's mechanism is that the primordial perturbations at this epoch have a non-zero vorticity. The result is that the (co-moving) eddies in the photon-electron component of the primordial 'soup' have a slower decrease in angular velocity, as the scale factor, R, increases ($\omega \propto R^{-1}$). By contrast, the *ion* component due to its larger rest mass, hence lower coupling, generates eddies for which $\omega \propto R^{-2}$. The difference between the two exponents causes an EMF, hence a current (analogous to the Biermann battery effect) and hence a back EMF which couples the electron and ion components of the eddies.

However, as Rees (1987b), and others point out, a significant vorticity at this epoch is difficult to reconcile with the expected predominance of irrotational density perturbations which, arising from initial curvature fluctuations, should become dominant in the post-recombination epoch. It is these fluctuations which are thought to be associated with the formation of protogalaxies.

Another field-generating scenario during this same, plasma epoch ($1\,\mathrm{s} < \tau < 10^{13}$ s, or $10^{10} > z > 10^3$), which does not require vorticity, has been recently put forward by Tajima *et al* (1992). Based on the fluctuation-dissipation theorem (Kubo 1957), Tajima *et al* (1992) derive an expression for the magnetic field fluctuation at spectrum (in wavenumber and frequency space) in a plasma which is in thermal equilibrium—the 'least special' *ab initio* assumption. They find that $\langle B^2 \rangle_\omega / 8\pi$ is nearly Planckian at high frequencies, but that a narrow peak in $\langle B^2 \rangle_\omega / 8\pi$ occurs near $\omega = 0$. This arises from two fundamental physical effects; first, the lifetime of the magnetic fluctuations, τ_B is $\propto \lambda^2$, λ being the scale size, so that larger 'bubbles' are favoured at any given time. Second, a reinforcement of the magnetic structures stems from the purely geometrical fact that the largest bubbles also have the greatest cross section for reconnection-inducing bubble mergers. Tajima *et al* (1992) refer to these combined processes as *magnetic polymerization*; its effect is to generate a magnetic field just prior to the recombination epoch at 10^{13} s. The field strength although difficult to quantify, could be of order 10^{-12} G, or possibly higher. The above assumptions and conditions become inapplicable *after* recombination, so that just what fields the first protogalaxies begin with is determined by other physical conditions, not specified in the above model. Tajima *et al*'s seed field mechanism appears consistent with all other evidence, scant as that is, but importantly it specifies that both the *sum* of the magnetic + charged particle pressure, and the photon pressure, are virtually constant in space. Constancy of the latter thus does not violate the recent COBE results (cf Gush *et al* 1990). Unfortunately, there appears little prospect of verifying an observational imprint of these fluctuations of B, and/or their associated density fluctuations.

The resultant magnetic field, if projected to galactic scales at the first galaxy formation epoch, is of order 10^{-18} G. Although weak, and dynamically insignificant, it could nonetheless provide the seed fields which, by *some* dynamo mechanism, might subsequently amplify up to the observed μG-level galactic fields.

5.5.3. Cosmological seed fields originating in the inflation epoch. Turner and Widrow (1988) argue that if, as seems the case, intergalactic fields exist on the scale of a few Mpc, then inflation is a good candidate mechanism for their origin. Among their reasons are that inflation provides the means, through its kinematics, of producing very large scale phenomena via microphysical processes which operate on a sub-horizon scale; that the relatively low conductivity which precedes the highly conducting plasma epoch, i.e. during the inflation epoch, permits an early increase of magnetic flux. Using this general idea, Quashnock *et al* (1989) proposed a seed field generating mechanism which is based on the assumption of a first-order QCD phase transition, which occurs during the first 10 μs at T_c, where $kT_c = 150$ MeV (cf Fukugita 1988). Here the hadronic bubbles form out of a quark-gluon plasma on scales of $10^{1\pm 1}$ cm, where the nucleation sites are separated by *ca* 10 × that scale. This quark–gluon→hadron transition possesses a characteristic temperature (T_c) due to a postulated mechanism whereby supersonic shock heating from the hadronic bubbles (which form a deflagration front) releases latent heat into the quark–gluon plasma. This heating compensates for the cooling due to cosmic expansion for the few microsecond duration of the phase transition. At this point in the model (at a Hubble time of 10 μs) the quarks and gluons have been transformed into mesons and baryons (Kajantie and Kurki-Suonio 1986). Quasnock *et al* (1989) propose that currents are set up due to the co-existence of slightly positively charged quarks and negatively charged leptons. These have different equations of state. This results in an electric field being associated with the subsonically moving hadronic shock fronts. In Quasnock *et al*'s model, the collision of these shock fronts and the consequent vorticity will, via a Biermann battery-like mechanism, cause the generation of *ca* 5 G magnetic fields on a scale of the distance between bubbles, which is $10^{2\pm 1}$ cm (see above). By invoking some further assumptions, including the local scale-related field diffusion time, they arive at a field strength of $\sim 2 \times 10^{-17}$ G on a scale of $\sim 5 \times 10^{10}$ cm at the recombination epoch. This scale is of order 1 AU at the present epoch—very small compared with galaxy scales, which makes it unclear whether such fields could effectively serve as seed fields in protogalaxy systems.

Vachaspati (1991) has suggested that gradients in the vacuum expectation value of the Higgs field give rise to magnetic fields, whose scale is related to the horizon scale after the QCD phase transition. This results in very weak fields, which could serve as seed fields. A similar scenario, though lacking firm predictions, has been proposed by Dolgov and Silk (1993). Dolgov and Silk propose that, if the gauge symmetry of electromagnetism is broken, then subsequently restored, the next electric charge density must vanish, and be compensated by heavy charged particles in the Higgs vacuum. Their decay products would cause an electric current, and a local charge asymmetry. They argue that these currents would create chaotic magnetic fields on 'astronomical' scales which could provide the seed field.

All of the above primordial field generating mechanisms predict very weak initial fields which, if they were the origin of current fields in galaxies and clusters, would need many e-folding times of dynamo amplification.

The generation of seed magnetic fields in the inflation period of the universe has also been considered by Ratra (1992a, b), who likewise proposes a sequence of scenarios beginning at the transition between the inflation and radiation eras. Ratra (1992a, b) explores the consequences of a coupling between Φ, the scalar field which is responsible for inflation, and an Abelian gauge field (A_μ), where $\alpha\Phi$ is the exponent in the inflation model. The proposed coupling is described by

$$A_\mu \propto e^{\alpha\Phi} F_{\mu\nu} F^{\mu\nu} \tag{5.12}$$

where $F_{\mu\nu}$ is the field-strength tensor of A_μ and α is a parameter. Ratra's model extends over three epochs—that of scalar field dominance, the radiation dominant era (see above), and the baryon era. Allowing for various uncertainties in the physics, especially at transition points, Ratra arrives at a range of present-epoch fields, which range from $\leqslant 10^{-65}$ G to $\sim 10^{-10}$ G on a scale of a few Mpc. The higher fields, which arise from models close to the de Sitter inflation model with relatively large α, would easily suffice to provide seed fields for subsequent regeneration during galaxy formation (e.g. through infall, or outflow), or some subsequent dynamo amplification due to outflow, rotation, etc.

5.5.4. Possible links between magnetic field generation, the masses of neutrinos, and nucleosynthesis. Enqvist *et al* (1992) present an argument, based on current-epoch galactic magnetic fields, that the magnetic moment of Dirac neutrinos has an upper limit of $\approx 2.4 \times 10^{-16}$ Bohr magnetons. This is about five orders of magnitude below current laboratory or astrophysical measurements (cf Vergados 1991), but it is scaled by a somewhat uncertain value of $B_{\rm seed}$ and hence may not be quite so stringent. Their argument limits, in consequence, the sum of the masses of the all neutrinos (including unstable ones), hence the *masses* of muon and tau neutrinos (ν_μ and ν_τ). Subject to the uncertain $B_{\rm seed}$ value, it would lead to a limit on the combined masses of the latter two neutrino flavours—if the standard model is assumed. This follows, Enqvist *et al* argue, if the successful nucleosynthesis model of helium abundance is to be preserved, *and* if very large magnetic field strengths ($B \approx 10^{23}$–10^{24} G) existed at the electroweak transition phase, which are estimated by Vachaspati (1991) (cf previous section). Such large fields are implied by cosmic expansion, even if seed fields were as weak as 10^{-30} G on a scale of ≈ 100 kpc (present epoch) (Enqvist *et al* 1992). In a more recent, similar analysis Enqvist *et al* (1993) introduce a lower limit of $\approx 3 \times 10^{-13}$ G to the seed field strength at galaxy formation, which is tied to an interpretation of the recent GALLEX neutrino experiment results (Anselmann *et al* 1992), based on the MSW theory of matter-induced neutrino oscillations. New, complementary ground-based estimates of the combined masses of all neutrino flavours, independent of oscillations between

(ν_e, ν_μ and ν_τ), might be possible with the Sudbury Neutrino Observatory (SNO) currently under construction (Ewen 1992).

The above analysis rests, of course, on the assumption of dynamo amplification in galaxies of a seed field whose origin was around the time of the QCD phase transition, when the cosmic temperature was ≈200 MeV. The above arguments would be rendered invalid if, possibly consistent with the observations we discussed in section 3, the seed fields were produced much later, in the first stars and galaxies. In other words, this particular 'link' between galactic magnetic fields and particle physics in the early universe would be broken, and the corresponding limits on neutrino magnetic moments and masses would not apply. This discussion illustrates in any case that magnetic field *generation near the epoch of the QCD phase transition is of fundamental importance* for cosmological theory and particle physics, and that the investigation of cosmic magnetic fields has potentially close connections to fundamental physics.

6. Cosmological seed fields, or galaxy-generated seed fields, or both?

Whether present day galactic magnetic fields were built up over cosmic time, or very rapidly when the first galaxies were formed, the question remains of whether the first cosmological seed fields were generated during the inflation epoch, the plasma epoch before recombination, or when the first stars were formed (cf section 5.5). In contrast to tests of the 'conventional' mean-field disk dynamo discussed above, there appears to be little immediate hope of observationally discriminating among the various early universe seed field mechanisms described in section 5.5.

We have reviewed some of the alternative possibilities for field generation which can occur in stars, galaxies and supra-galaxy phenomena, such as galaxy collisions, galaxy cluster-scale infall or 'Compton drag' on intergalactic plasma. Field-*creating battery effects are a natural consequence of the fundamental fact that electrons and* ions have the same charge but different masses. Differential Compton drag can potentially induce large scale currents in the interaction between intergalactic plasma and the photon flux of the cosmic background radiation. Large scale dynamics of plasma outflow and consequent differential ion/electron deceleration—e.g. in starburst galaxy nuclei (section 3.1)—have also been proposed to generate currents, hence magnetic fields on galactic scales. Battery effects associated with radio jets/accretion disks may also be capable of creating fields through small charge separation effects. Alternatively, possibly in addition, if extragalactic metal lines seen in QSO absorption lines trace magnetized galactic winds, as we speculated in section 5.4.3, we can extend this argument to hypothesize that the seed fields with which most galaxies formed came from *stars*. Since stars are the origin of these metal lines, and the heavy elements seen in the *ICM of galaxy clusters, then the associated magnetic fields may have been expelled stellar* fields, created by Biermann's battery, dynamo amplified, and expelled in the vigorous stellar winds from the most massive stars.

The question of what magnetic fields existed at the formation time of the earliest galaxies thus has more than one dimension: when were the first fields created—produced along with the first galaxies—or a cosmological seed field created before recombination? The second, perhaps more important question is; independent of the answer to the first, how *strong* were the magnetic fields at the first galaxy formation epoch? If they were in equilibrium with the radiation energy density or the turbulent or thermal energy density of protogalactic gas (as is the case in the galactic interstellar medium,), it is likely that galaxy formation was significantly influenced by magnetic forces. Magnetic effects were less influential, though probably not negligible if much weaker fields ($\lesssim 10^{-9}$ G) existed at the first galaxy formation time.

The magnetic field in the outflow regions of M82 and other galaxies with pronounced ouflow may be providing us with important clues about the *origin* of intergalactic fields in general. Since the starburst phenomenon is quite universal, and if most galaxies underwent at least one starburst in their lifetime, they could have 'injected' their metal-enhanced magnetoplasma into the IGM. If, in a related scenario, the very first galaxies were low mass (hence low escape velocity) starbursters, the intergalactic magnetic fields could have been largely amplified and injected into the IGM, by starbursters at redshifts greater than 3, i.e. during the first few per cent of the Hubble time, thereby 'filling' the IGM with magnetic field. In this case, most subsequently formed galaxies were born with *pre-existing* fields not much different from the present, few μG level measured in the interstellar medium of our Milky Way and other galaxies.

Another mechanism for magnetizing the IGM at earlier epochs might have been by jet-lobe radio sources (section 3.2.3), depending on their (as yet unknown) occurrence rate at $3 \leqslant z \leqslant 10$. None of these possibilities rules out the prior existence of seed fields during and before the recombination epoch.

7. Concluding remarks

Whether the first fields were self-generated in the first stellar systems, or were really primordial, it seems likely that the magnetic forces competed and interacted with gas dynamical and purely gravitational effects during the early collapse phase of galaxies. This eventuality presents a major challenge to theory, in that virtually all theoretical models of galaxy formation up to now invoke gravity and thermodynamics, and ignore the complicating effects of magnetic fields of comparable energy densities in the environment of collapsing and/or merging protogalaxies. Because magneto-plasmas are highly non-linear systems, there is an additional challenge purely from the computational standpoint to construct detailed galaxy evolution and large scale structure evolution models which incorporate magnetic fields. This is true whether such fields existed *ab initio*, or were generated and/or amplified concurrently with the formation of the first galaxies.

Although the standard α–ω dynamo theory gives first order agreement with the observations, the scenario of a *slow* galactic field build-up over several billion years from a very weak seed field in the early universe seems unlikely to the main cause of current μG fields in galaxies. The general trend of much of the observational evidence and theory suggests that (i) magnetic fields were built up over times much shorter than a galaxy lifetime, and that (ii) spiral and starburst galaxies, as well as radio jet/lobe systems and starburst galaxies are able to regenerate, and perhaps even *create* fields to near-microgauss levels in timescales $\ll 10^8$ yr.

This implies that, even if pre-galactic seed fields existed before a 'volcanic' epoch of widespread starburst-like activity in the compact, early universe, the first starbursters might have been capable of overwhelming this field with their own, stronger, ejected fields, along with metal-enriched gas, in powerful galactic winds *over a short period of cosmic time*. This proposed type of activity is the analogue of what we observe in starburst galaxies. Less certain, but also potentially effective IGM magnetizers are radio jet sources from before and during the quasar epoch, if they existed then. They have been demonstrated to effectively magnetize substantial volumes of the IGM with their own, self-amplified magnetic fields.

If the first stars and protogalaxies provided the seed fields which were quickly amplified to energy equilibrium with the protogalactic IGM, then we may have to consider a two-stage early galaxy formation scenario: the first stage of collapse occurred with very small, or no fields. Succeeding generations of galaxies then perhaps formed in microgauss-level fields which, within a few times 10^8 yr were produced, amplified and expelled by the first generation of stars and galaxies. The observations we have reviewed do not appear to rule out a scenario of this sort.

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