The Role and Influence of Magnetic Fields in Cosmology

by

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Happy New Year everyone.

Summary

The work of this thesis is concerned with the large scale effects of magnetic fields in the universe. Largely, a review has been made of the research done to date in this area, which is a recent field of research, and one not fully understood. An attempt has been made to understand the important points in this potentially enormous topic, and highlight areas which are inconsistent and those which are producing interesting results.

We begin with the standard model of cosmology and the recent work incorporating magnetic fields into this framework. In particular we look closely at the generation mechanisms of magnetic fields in the universe, since these will determine the strength of magnetic fields and the epoch in which they are generated, and hence the extent of their influence. In particular we analyse the validity of a battery mechanism for generating magnetic fields in galaxies.

Next we look to relaxing some of the constraints placed on magnetic field strength and configuration by the standard cosmological model. In particular we look at the work of Battaner et al who suggest that large scale structure could form by flux tube configurations of magnetic fields in the early universe.

Further we review the work of Peratt and others who ignore entirely the framework of the standard cosmological model, and assign much greater significance to magnetic fields on large scales. Again flux tube configurations are proposed, but now on scales of galaxies and clusters. The cosmological framework behind this work is that of Alfvén's cosmology, and this is reviewed in chater5.

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Chapter 1

Plasma Physics and Cosmology: An Overview

1.1 Introduction

This chapter is intended to give an introduction to the main ideas of plasma physics, and the application of these ideas to space plasma. The observations of space plasmas are summarised, along with the observational techniques employed. We consider briefly the regions and scales on which plasma effects have been studied and are considered significant on the basis of these observations.

The areas of astrophysics in which plasma effects are considered insignificant are the large scale phenomena, in particular the overall evolution of the universe, large scale structure formation and all aspects of cosmology. However, as the ubiquity of magnetic fields in the universe becomes increasingly clear, the influence of magnetic fields on these scales is becoming a growing area of research. Here we briefly introduce the standard model of cosmology, and the most popular model for large scale structure formation. We emphasise that gravity is considered to be the only significant force on large scales in the framework of this model, but introduce some areas where electromagnetic effects need to be considered. Finally we introduce the work of Hannes Alfvén and more recently Peratt, Lerner, Green and other plasma scientists, who have presented an interesting alternative to the evolution of the universe by considering large scale plasma effects to be more significant. In particular these ideas have addressed large scale structure formation and question the homogeneity of the universe. Specifically the non-uniform distribution of magnetic fields in the universe.

The basic ideas introduced here will be extended in the following chapters. In particular we will examine the proposed generation mechanisms for magnetic fields in the universe and the consequences of including magnetic fields in the standard cosmological model. We will also consider the influence of large scale magnetic fields in the framework of Alfvén's cosmological model, and the consequences for observational cosmology.

1.2 Occurence of Space Plasma

The study of ionized gases in space began in the late nineteenth century, when Birkland proposed that the aurora was the result of 'corpuscular rays' from space in 1896. The term 'plasma' was not coined by Langmuir until 1923. Since this time, progress in the study of plasmas has had major applications in controlled nuclear fusion research, and in space plasma research. We are concerned here with space plasma, which is observed to dominate the visible universe, with 99.99% of matter in the plasma state. In our immediate surroundings on Earth plasmas can be observed to occur naturally in lightening, and in the aurora. We find that outside the Earths atmosphere, the magnetosphere, the solar wind, stars, and the diffuse interstellar and intergalactic mediums, are all in the plasma state.

On larger scales, structures and plasma are observed to cluster into filamentary structures seperated by low density void regions. The observations of such filamentary and sheet structures are clear, extending to scales >100Mpc. Tully (1986) found galaxies concentrated into supercluster filaments $\sim$ 300Mpc long, and Gellar and Huchra (1989) confirmed this and uncovered the Great Wall, a sheet like structure of galaxy clusters extending $\sim 170 \times 60 \times 5 Mpc^3$. Szalay et al, (1993), also found filamentary structures on scales of 700Mpc. An integral part of plasma systems are magnetic fields, both external fields and those generated by the plasma motions. Hence the strength of magnetic fields and the coherence scales of magnetic fields in the universe will determine the behaviour of the plasma. Exactly the magnitude of the exent of this effect and on what physical scales it is significant, is what is in question here in this thesis.

What follows in this section is an overview of the plasma state, observations of magnetic field strengths and coherence scales in the universe, and the observational techniques used to observe these fields.

1.2.1 The Plasma State

The plasma state is often referred to as the fourth state of matter, arising when the thermal energy of the constituent particles of a gas is large enough to ionise the neutral atoms/molecules in the gas. Whilst there is no distinct phase transition between the neutral gas state and the plasma state, the nature of the interparticle interactions is very different for the two cases, and results in very different behaviour. Since the constituents of a plasma are electrically charged, coulomb forces dominate, which are weak and long ranged in comparison to the two-body interactions dominant in a neutral gas. The long range forces mean that collective behaviour is important in a plasma, involving a large number of constituent particles that is not observed in the neutral gas state. Also, the plasma will be influenced by electric and magnetic fields, and in response, produce electric and magnetic fields. Thus, description of the plasma state incorporates the electromagnetic fields as an integral part of the system.

Due to the complexity of plasma behaviour, a number of models are used to describe particular aspects of plasma phenomena. The most fundamental model is the kinetic theory of plasmas, which deals with the microscopic behaviour of the individual particles in the plasma. Statistical methods are employed to follow the evolution of the plasma as described by a distribution function. Although all plasma theories can be understood from within the kinetic theory, it is generally used to investigate high frequency phenomena, and behaviour on time scales shorter than the thermal relaxation timescale of the plasma to a Maxwellian distribution.

Another useful approach to the study of plasmas is to treat the plasma as an electrically conducting fluid. Magnetohydrodynamics (MHD) incorporates electromagnetism into the fluid equations, and gives insight into the large scale collective behaviour of the plasma. There are limitations to this approach. That the timescales of study here must now be greater than the relaxation time of the plasma. In ideal MHD the plasma is assumed to be perfectly conducting, and as a result the magnetic field lines 'move' in response to plasma motion. In this way the magnetic field is said to be 'frozen' into the plasma. Of course this assumption can be highly unrealistic in some situations. The Magnetic Reynolds number,R_M, is a dimensionless quantity that gives the ratio of the change in magnetic field due to convection and diffusion, as given by the first and second terms on the right hand side of the induction equation

$$\frac{\partial B}{\partial t} = \nabla \times (v \times B) + (\sigma)^{-1}(\nabla)^2 B \quad (1.1)$$

where v is the plasma velocity, and σ is the conductivity. An infinate Reynolds number indicates that the diffusion term can be neglected and we have ideal MHD. In astrophysics $R_M > 1$, and therefore the frozen in condition holds in most cases. However, electric fields are set up in space plasmas (not possible in an infinately conducting medium) due to, either plasma instabilities, or movement of magnetic field lines, hence MHD is not always the the most accurate treatment. For example magnetic flux tubes could not form in an infinately conducting medium. This configuration is often observed however in astrophysical systems, for example in interstellar clouds, the aurora and in solar prominences. Plasmas in relative motion are coupled by electromagnetic forces, and in nonequilibrium states tend to form current-carrying filaments. Essentially this is a minimum energy configuration, with $j \times B = 0$, i.e the Lorentz force is zero. Hence this configuration is 'force free'. The magnetic field lines in this configuration are helical, with electrons flowing along these lines. In essence, electrons towards the centre of the helix flow in straight lines, producing the helical magnetic field lines along which the outer electrons flow. The outer electrons flow in helical patterns forming the straight magnetic field lines along which the central electrons flow. Large currents can be concentrated in these filaments, and magnetic fields strengths in these structures can far exceed fields external to the filament.
Interest in such filaments in space has increased as observations in support of filamentary structures on galactic and intergalactic scales has emerged. This has also led to renewed interest in Alfvén's cosmology, in which large scale, strong magnetic fields have greater significance on cosmological scales, and a filamentary universe is a fundamental postulate.

1.2.2 Observational Tracers Of Magnetic Fields

We note here that an equivalent description of electromagnetic effects in plasmas would be to consider the electric fields rather than the magnetic fields present. However there are a number of advantages in considering the magnetic field description. From a theoretical viewpoint, the mathematical treatment of plasma phenomena is much simplified on elimination of the current. Rather we consider the current as **curl B**. We also find that it is difficult to make direct measurements of electric currents. However as noted by Alfvén (1981) and Melrose (1987), care must be taken when treating boundary conditions within the magnetic field description of plasma behaviour. It is easy to lose the particle aspect of events, which in high energy phenomena may be vital to a full understanding. Also the assumption that plasma behaviour depends only on local magnetic field parameters of a system, can result in misleading results for the global system unless boundary conditions are treated carefully

Verification for the existence of magnetic fields comes easily from the observation of synchrotron radiation emitted from relativistic electrons in magnetic fields. However, it is more difficult to obtain a reliable value for the strength of such fields.

Although we can measure the synchrotron emissivity per unit frequency interval ν, of electrons with energy E,

$$\epsilon(\nu) \propto N(E)B_{\perp}^{(\gamma+1)/2} ergs^{-1}cm^{-2}Hz^{-1}Sr^{-1}. \tag{1.2}$$

Where $B_{\perp}$ is the perpendicular component of the magnetic field, and γ describes the power law slope of the energy distribution of the relativistic electrons, a reliable estimate for $N(E)$, (being the number density of electrons per unit volume, per unit solid angle, along the line of sight moving in the direction of the observer,) is usually unknown. In the absence of direct magnetic field measurements, we usually assume that there is equipartition of energy between the magnetic field and the relativistic particles. This assumption appears to hold in the Milky Way (Heiles, 1995, 1996), but has been shown to give values of **B** which are too low in the case of M82 and the Magellanic Clouds (Chi and Wolfendale, 1993). To date the validity of such equipartition has not been determined either theoretically, or observationally.

One possible indirect method for estimating $N(E)$ in some extended radio galaxies uses the x-ray emission in the outer lobes and hotspots. The contribution to this emission from inverse compton scattering of microwave background photons off the electrons that produce the synchrotron emission, can lead to an estimate of $N(E)$, since the photon density of the microwave background is well known.

Direct measurement of the strength of the parallel component of the uniform field, $B_{||}$, is found from the measurement of Zeeman splitting of spectral lines in the interstellar medium. This method has provided considerable information on the field strength in interstellar clouds in our galaxy. Unfortunately, due to doppler smearing of spectral lines, combined with weak field strengths, this effect has not been able to be observed in external galaxies or intergalactic space.

Faraday rotation gives us another probe of magnetic fields. The direction of linear polarization of the source radiation is rotated as a result of propogation through an ionized medium, and the rotation measure (RM) is found to be

$$RM = \triangle\chi/(\triangle\lambda^2) \propto \int n_e B_{||} d\ell \; rad \; m^{-2}. \tag{1.3}$$

For the rotation angle χ of the plane of polarisation at wavelength λ, and n_e is the local density of non-relativistic electrons. $B_{||}$ is the line of sight component of the magnetic field, and ℓ the path length. Once again it is the measurement of n_e that poses the most difficulty here. In the case of our galaxy, this information is available from pulsar dispersion measures, given by

$$DM \propto \int n_e d\ell. \tag{1.4}$$

However, pulsars are too faint to observe in other galaxies, rendering this method of little use outwith the Milky Way. It may be possible to measure the dispersion measure of compact quasars in extragalactic space, owing to the increasing evidence for their intrinsic time variability (Quirrenbach et al 1991). This method has not been applied to date however.

There is also a problem with electron positron plasmas, since these do not produce faraday rotation. This limits the use of this method for AGN's, galactic and extragalactic jets, and around clouds of antimatter recently discovered in our galaxy (Chown, 1997).

Besides the prospect of measuring the Faraday rotation combined with independent electron density estimates, there seem few prospects for directly measuring field strengths in the extragalactic universe. However, magnetic fields in the pre-recombination universe could leave their mark on the cosmic microwave background as proposed by Kosowsky and Loeb (1996). They claim that the microwave background will exhibit a measurable Faraday rotation angle of the direction of polarization in the presence of a magnetic field. The polarization of the microwave background is expected to arise when an anisotropic distribution of photons scatter off charged particles before recombination. After recombination, any polarization will remain, since the photons will propogate freely along geodesics. However, if a magnetic field is present before recombination, the polarization direction will be rotated, and Kosowsky and Loeb have calculated that we should and could find an angle of $\sim 1°$ at a frequency of 30GHz. This is thought to be feasible with new maps of the microwave background.

There are also a number of indirect methods proposed for estimating, or limiting field strengths in the extragalactic regions.

We can make use of the correlation between the far infrared emission from dust in starburst galaxies, and the coextensive synchrotron emission involving the interstellar magnetic field. This was first predicted by Harwit and Pacini (1975), and since the spectral density at this wavelength is strong in starburst galaxies, this method is viable out to large redshifts. This provides a potentially powerful way of inferring the magnetic field strengths in early galaxies, although the reliability of the results is not clear.

Other indirect methods include the use of cosmic rays suggested by Biermann and Rachen (1993), for estimating a maximum strength for the intergalactic field. The method measures the deflections of high energy ($\geq 10^{19}$eV) cosmic rays in intergalactic magnetic fields. If the acceleration sites of the cosmic rays are known, then any discrepancies between their arrival directions and their production sites will give some indication of the strength and morphology of the intervening magnetic field. As yet however, acceleration sites of cosmic rays have not been determined, although these high energy cosmic rays are thought to be certainly extragalactic in origin. However the method could lead to an insight into magnetic fields in the intergalactic voids, where we have little alternative prospect of doing so.

Along with measurements of field strengths, information about the morphology and degree of ordering of these fields is also of considerable importance. Detailed studies of the polarization of synchrotron radiation at high radio frequencies can be used to estimate the relative energies of the mean and random components of the field. Rotation measures of external galaxies, radio galaxies, and clusters leads to information about field direction and field reversals.

1.2.3 Observed Values of Magnetic Fields in Astrophysics

The above methods of detecting and measuring magnetic fields have successfully revealed magnetic fields on increasingly large scales. The presence and influence of magnetic fields in the solar system and in stars is well known. Observations of the Milky Way allow the detailed study of the magnetic field structure which is not possible in other distant galaxies. However, the global features of the magnetic field can be obscured because of our observing position. Still the magnetic field strength as estimated from the RM's of pulsars in the solar vicinity is $\sim 2\mu G$, and thought to be stronger in the spiral arms. From polarisation maps of stars in the Milky Way the field is seen to lie parallel to the galactic plane (Matthewson and Ford, 1970). Simord-Normandin and Kronberg (1980), also found that the magnetic field extends out of the galagtic plane to a height of $\sim$ Kpc.

In nearby spiral galaxies the Faraday rotation measures, polarisation and intensity measurements of synchrotron radiation, has revealed that the large scale magnetic field follows closely the spiral structure of the arms. Examples are in M51, NGC5055, and NGC6946 (Neininger, 1992). The spiral structures of the magnetic fields are generally divided into two classes, axisymetric (ASS) and bisymetric (BSS) structure. This refers to the symetry of the field lines about the galactic centre as shown in fig 1.1. Although some galaxies have

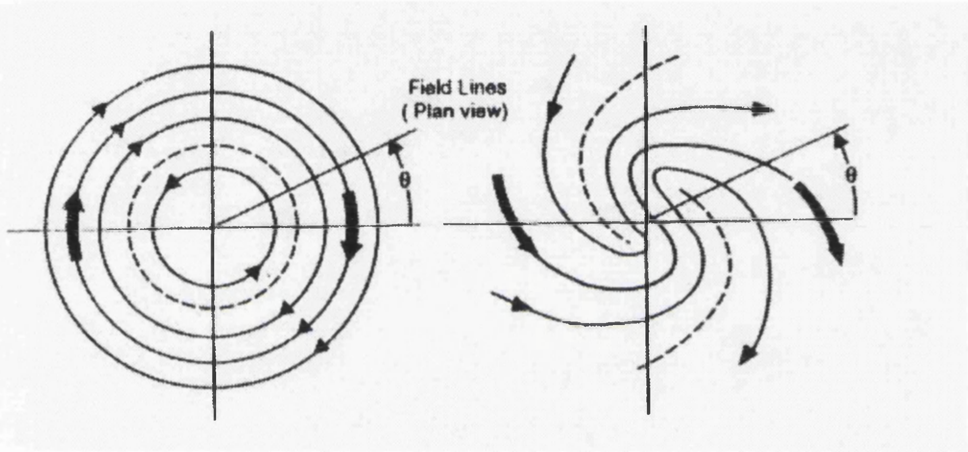

Figure 1.1: Face on view of a model axisymetric(left) and bisymetric(right) magnetic field configuration in a galactic disk. From Kronberg,1980.

been observed to conform to neither, e.g M83. The average equipartition field strengths (averaged over the volume of the visible radio disk) for external galaxies ranges from 4 μG in M33 and $12\mu G$ in NGC6946, to $\sim 19\mu G$ in NGC 2276 (Buczilowski and Beck, 1991). The fields increase towards the central galactic regions, and in some cases into the spiral arms. Some extreme fields are observed also, for example fields $\sim 20\mu G$ have been observed in the spiral arms of NGC6946 (Beck et al, 1991), and in M52 fields of the order $50\mu G$ were observed by Klein et al (1988). In short most galaxies have magnetic fields typically $\sim$ fewμG, and some have fields extending out of the plane of the galaxy, extending to 2-4 Kpc (Klein et al, 1984, Hummel, 1990), with strengths $\sim 8\mu G$.

Cosmic ray electrons emitting a diffuse 'halo' of synchrotron radiation from the regions between galaxies in clusters have revealed the presence of intracluster magnetic fields. The strength of these fields has been found in the Coma Cluster to be $\sim 3 - 4\mu G$ (Abranopoulos and Ku, 1983). More recently a study of 53 abell galaxy clusters found fields of the order $\sim \mu G$ levels (Kim et al, 1991).

The largest scale fields, and the highest energy in magnetic fields are found in cooling flow clusters, where for example in Hydra A fields $\sim 30\mu G$ are found (Taylor et al, 1990, 1993). Also from polarisation and filamentation observed in the lobes of extragalactic radio source jets, we associate magnetic fields on scales ranging from Kpcs to Mpcs.

Magnetic fields associated with filamentary structures have also been detected from radio emission by electrons in magnetic fields. Filaments in radio sources are common, and Yusef-Zadeh (1987) found filaments of radio emission extending out from the centre of the Milky Way to distances of $\sim$ 100LY.

Observations of quasar systems at high redshift has revealed the existence of magnetic fields at earlier epochs in the universe. The RM's of quasars behind high redshift galaxies has shown significant RM (Welter 1984), although the statistical significance of the results has been questioned (Perry, 1993. Oren, 1995). The strength of the fields has been estimated in a few systems. At z=1.942, Kronberg et al (1990), and Perry and Dyson (1990) found $B \sim 0.4 - 4\mu G$, and a coherence scale $\sim$ 15 Kpc.

The overall picture of magnetic fields in the universe is of μG fields in galaxies and in the intergalactic medium in galactic clusters. There is a possibility that μG fields are also present at high redshifts, and that stronger magnetic fields are present in stellar and galactic jets, and in cooling flow clusters. Filamentation of plasma has also been observed to be assossiated with magnetic fields up to scales of $\sim$ 100LY. The magnetic fields in the void regions between clusters has not yet been measured, and whilst isolated large scale fields heve been identified, the overall magnetic field configuration on cluster scales has not been identified yet.

1.3 Influence of Magnetic Fields

It is clear that magnetic fields are observed on scales up to Mpcs, and are concentrated mainly in structures such as galaxies, and in the intracluster and interstellar regions where we have noted that the density of plasma is highest. The fields in the void regions are not easily observed however with the methods available. The standard cosmological model then assumes that these low density void regions hold a uniform background magnetic field, which results from the magnetic field generation mechanisms detailed in chapter3, and which is necessary for compatibility with the assumptions of the standard model. Again this is detailed in chapter3.

The local scale magnetic fields observed are known to influence significantly small scale structures. Interstellar gas dynamics are affected, both globally in the structure of galaxies (Boulares, 1990), and on smaller scales influencing stellar formation (Heiles et al, 1993). The collapse of interstellar clouds, confinement of galactic cosmic rays, the distribution of stellar masses in galaxies are all influenced by the presence of magnetic fields. However, on scales larger than galaxies, magnetic fields are thought to be insignificant for the evolution of the universe. Although magnetic fields are observed on scales of clusters, the influence of gravity becomes more significant on these larger scales within the framework of standard cosmology. However, it has been suggested (Cheng et al, 1994. Grasso and Rubinstein, 1995. Kernan et al, 1996, Battaner et al, 1997), that magnetic fields may become increasingly important at early epochs in the universe, depending on the strength and coherence scales of the fields at this time (see Chapter2). It has also been suggested that magnetic fields may influence structure formation on large scales. The observations of filamentation on large scales in the universe may be associated with plasma filamentation and with magnetic fields. The standard model of cosmology attributes this filamented structure to gravitational clustering of matter, as will be summarised in the next section.

1.4 Cosmology

Modern cosmology has settled on the hot big bang model of the universe as the simplest consistent model that describes the begining, evolution and final fate of the universe. Although this model is not complete, and a great deal of work is still being undertaken, the general framework of the standard cosmological model is accepted by most of the scientific community, and the general public.

The model is based on the Cosmological principle, and the framework of general relativity. The symetry principle underpins the standard model and basically assumes that the universe is isotropic, homogeneous, and that we do not occupy any special position in the universe. The evidence to support such assumptions are not entirely conclusive, and are discussed in section 1.4.2. However, this principle greatly reduces the possible geometries and evolutionary paths of the universe, and hence is very desireable.

Firstly the cosmological principle coupled with the assumption that gravity is the only force significant for the evolution of the universe on large scales, leads naturally to Hubbles law of the expansion of the universe. In a homogeneous and isotropically expanding universe the distance between any two fundamental observers will scale by the same factor R(t). Then the distance, ℓ between any two observers at time t, will be given by $\ell(t) = \ell_0 R(t)$, where ℓ_0 is the initial separation of the two observers. The relative speed of the observers then yields Hubbles law.

$$V(t) = d\ell/dt = \dot{R}\ell_0 = (\dot{R}/R)\ell(t) = H(t)\ell(t) \tag{1.5}$$

Where H(t) is the Hubble constant.

The most general metric that describes the spatial geometry of a universe based on the cosmological principle is the Freidmann-Robertson-Walker metric (FRW metric), given as,

$$d\tau^2 = dt^2 - \frac{R^2(t)}{c^2}\Big(\frac{dr^2}{1 - Kr^2} + r^2 d\theta^2 + r^2 \sin^2\theta d\phi^2\Big) \tag{1.6}$$

where, R(t) is the global scale factor which describes the overall expansion or contraction. R, θ, ϕ, are the (fixed) comoving coordinates of the observers, and K is the sign of the spatial curvature. K can take the value of 0,1 or -1. This essentially presents 3 possible evolutionary paths for the universe. K=0 corresponds to flat Euclidean space, K=1, corresponds to a three-sphere geometry, and a closed universe, and K=-1, represents a 3-D analogue of the hyperbolic saddle, an open universe. The curvature parameter is related to the mass density of the universe, Ω (measured as a ratio of the density in flat Euclidean space), and in turn related to the Hubble constant. So that in principle, the entire evolution of the universe can be determined from knowkledge of these few parameters. If we introduce the cosmological constant, Λ, into the model, which acts like a negative density, allowing empty space to be curved. Then the interpretation of the curvature values are changed, and so this is another parameter that we neccessarily need to measure to determine the precise model that describes the universe.

Measurements of the Hubble constant to date have narrowed down the range of possible values to $\sim 60 - 90 Kms^{-1}Mpc^{-1}$ by various methods not detailed here (Pierce et al, 1994. Freedmann et al, 1994. Tanvir et al, 1995). The value of the cosmological constant is difficult to observe and as yet remains speculative. The total mass density of the universe is divided between the luminous matter ($\Omega_{matter} \approx 0.005$), and dark matter. From the rotation curves of galaxies, a dark matter halo is thought to surround the luminous galactic disk, bringing the estimated mass density to $\Omega_{matter} \sim 0.04$. Further, the motions of galaxies within clusters has increased this estimate to $\Omega_{matter} \sim 0.25$. However it is often speculated that $\Omega = 1$ since this helps structure formation(see following section). The uncertainty in the values of these parameters has so far not allowed any specific model to be identified, and it seems that rather than improved observational data helping to close in on the model it more causes problems for all the models! In particular the value of H^{-1} gives an upper limit to the age of the universe (when the cosmological constant is zero), and the higher values of the range of H observed to date conflict with the age of the universe as measured by alternative methods. However, if the hubble constant is in the low end of the observed range, then it is difficult to increase Ω to 1 which conflicts with structure formation models. Introducing a non-zero cosmological constant eases this difficulty by allowing a low H_0, $\Omega_{matter} < 1$ and with the contribution of Λ to the density parameter $\Omega = \Omega_{matter} + \Omega_{vacuum}$ can approach 1. However there is no theoretical/observational reason yet to suggest the value of the cosmological constant, although this option is a convenient one.

Aside from the uncertainty of these parameters the model is remarkably detailed, in particular the timescales of particular events are well known, along with the particles present at each epoch. A summary is given in fig 1.2.

Of particular importance is the epoch of recombination, occuring at a redshift $z \sim 10^3$. This is the time when the universe becomes transparent to radiation, and effectively represents the last scattering time of background photons. The cosmic macrowave backgroud radiation (CMB) is proposed to be the reminant of this epoch.

Incorporating magnetic fields into this model is not a simple task, and a very speculative one since the epoch at which magnetic fields first appeared is unclear. Hence the importance of identifying a consistent generation mechanism for magnetic fields in the universe, as will be detailed in Chater3. Regardless of this mechanism though, the configuration of any magnetic field within the standard cosmological model is restricted by the Cosmological Principle. The mean magnetic field on cosmolocical scales is zero in an isotropic universe (Battaner et al, 1997). Magnetic fields can be coherent in smaller regions, and the magnetic fields in each cell are oriented randomly with respect to each other, so that

COSMIC TIME	EPOCH	RED SHIFT	EVENT	YEARS AGO
0	SINGULARITY	INFINITE	BIG BANG	15×10^9
10^{-43} SECOND	PLANCK TIME	10^{32}	PARTICLE CREATION	15×10^9
10^{-6} SECOND	HADRONIC ERA	10^{13}	ANNIHILATION OF PROTON-ANTIPROTON PAIRS	15×10^9
1 SECOND	LEPTONIC ERA	10^{10}	ANNIHILATION OF ELECTRON-POSITRON PAIRS	15×10^9
1 MINUTE	RADIATION ERA	10^9	NUCLEOSYNTHESIS OF HELIUM AND DEUTERIUM	15×10^9
1 WEEK		10^7	RADIATION THERMALIZES PRIOR TO THIS ERA	15×10^9
10,000 YEARS	MATTER ERA	10^4	UNIVERSE BECOMES MATTER-DOMINATED	15×10^9
300,000 YEARS	DECOUPLING ERA	10^3	UNIVERSE BECOMES TRANSPARENT	14.9997×10^9
1×10^9 YEARS		10	GALAXIES BEGIN TO FORM	14×10^9
7×10^9 YEARS		1	GALAXIES BEGIN TO CLUSTER	8×10^9
1×10^9 YEARS		10	OUR PROTOGALAXY COLLAPSES	14×10^9
1×10^9 YEARS		10	FIRST STARS FORM	5×10^9
2×10^9 YEARS		5	QUASARS ARE BORN; POPULATION II STARS FORM	13×10^9
7×10^9 YEARS		1	POPULATION I STARS FORM	8×10^9
10.2×10^9 YEARS			OUR PARENT INTERSTELLAR CLOUD FORMS	4.8×10^9
10.3×10^9 YEARS			COLLAPSE OF PROTOSOLAR NEBULA	4.7×10^9
10.4×10^9 YEARS			PLANETS FORM; ROCK SOLIDIFIES	4.6×10^9
10.7×10^9 YEARS			INTENSE CRATERING OF PLANETS	4.3×10^9
11.1×10^9 YEARS	ARCHEOZOIC ERA		OLDEST TERRESTRIAL ROCKS FORMS	3.9×10^9
12×10^9 YEARS			MICROSCOPIC LIFE FORMS	3×10^9
13×10^9 YEARS	PROTEROZOIC ERA		OXYGEN-RICH ATMOSPHERE DEVELOPS	2×10^9
14×10^9 YEARS			MACROSCOPIC LIFE FORMS	1×10^9
14.4×10^9 YEARS	PALEOZOIC ERA		EARLIEST FOSSIL RECORD	600×10^6
14.55×10^9 YEARS			FIRST FISHES	450×10^6
14.6×10^9 YEARS			EARLY LAND PLANTS	400×10^6
14.7×10^9 YEARS			FERNS, CONIFERS	300×10^6
14.8×10^9 YEARS	MEZOZOIC ERA		FIRST MAMMALS	200×10^6
14.85×10^9 YEARS			FIRST BIRDS	150×10^6
14.94×10^9 YEARS	CENOZOIC ERA		FIRST PRIMATES	60×10^6
14.95×10^9 YEARS			MAMMALS INCREASE	30×10^6
15×10^9 YEARS			HOMO SAPIENS	1×10^6

Figure 1.2: Table of important epochs in the history of the universe within the standard cosmological model. From Silk, 1994.

on large scales the average field is zero. The average energy density of the magnetic fields will be non-zero however. Within these restrictions, scenarios for magnetic field generation and evolution have been proposed, and will be reviewed in this thesis. We also consider another approach made by Alfvén, who ignores these restrictions and forms an entirely new cosmological model. An entirely new model for structure formation arises from this approach, and a completely inhomogeneous matter distribution. This will be discussedin chapters 4 and 5, but firstly we consider structure and homogeneity in the standard cosmological model.

1.4.1 Structure in Standard Cosmology

One of the funadmantal questions of modern cosmology is the origin of large scale structures in the universe. Standard cosmology attributes such structure to the growth by gravitational instability (gravitational Jeans instability) of initial density perturbations. Jeans (1902) first showed that the growth of density perturbations in a homogeneous, isotropic and static fluid, would be unstable if pressure forces in the perturbation are not negligible compared to its self gravity. Essentially this leads to the criterion that the lengthscale of the perturbation (λ), should be greater than the Jeans length (λ_J), which represents the lengthscale of acoustic waves in the fluid, that would cause the perturbation to propagate away. The Jeans length is given by

$$\lambda_J = v_s\Big(\frac{\pi}{G\rho_0}\Big)^{1/2}. \tag{1.7}$$

Where v_s is the adiabatic sound speed, G the gravitational constant, and ρ_0 is the initial density perturbation.

This theory was first applied to the Freidmann models by Lifschitz (1946), and since then a number of attempts have been made to exlain the evolution of structure based on the Jeans instability within an expanding universe. Other complications arise from the different evolution of perturbations in the radiation dominated era (redshift$< 10^3$), as compared to the matter dominated era of today, and the treatment of dark matter (collisionless matter) in this model.

Firstly the form (spectrum) of the initial density perturbations must be recognised and then the subsequent evolution of this spectrum through the radiation epoch, matter epoch, and against dissipation due to radiative viscosity, thermal conduction and radiation drag is usually considered.

The radiation epoch is complicated by the fact that both adiabatic and isothermal perturbations can be generated and evole differently in this epoch. Essentially the adiabatic perturbations are time dependant and perturb the matter and radiation components both. However the isothermal mode perturbs only the matter. After recombination, both modes evolve in the same way regardless of their initial origin.

The only mechanism for producing initial density perturbations, consistent with causality arguments, in the early universe has been provided by the inflationary scenario (Hawking, 1982. Guth, 1982). Inflation can generate quantum fluctuations in the density field, which then expand faster than the hubble radius for a time, before finally re-entering the hubble radius. It is otherwise difficult to explain the causal connection of the density perturbations necessary to generate the large scale structures observed today, as the growth rate of such perturbations scale as R(t), which is slower than the hubble growth. This method produces an initial spectrum of density fluctuations in the form of a power law in wavenumber k,

$$P(K) = AK^n. \tag{1.8}$$

The relationship between the shape of the initial power spectrum and the spectrum now observed after various evolutionary processes is summarised and described by the Transfer Function T(K). This is dependant on the cosmological parameters, the form of any dark matter, and any dissipation effects, which are not discussed in detail here. The rate of evolution of the perturbations is very dependant on the cosmological density parameter Ω, with a value $\Omega = 1$ preferred for cold dark matter models. Whilst this value is flexible depending on the dark matter type, inflation and hence generation of the initial density perturbations requires $\Omega = 1$ (see section 1.4). At present, research is aimed at determining the form of the dark matter in the universe, with a mixture of cold dark matter and hot dark matter being the present trend, and in developing techniques to deal with the non-linear evolution of the perturbations which is necessary for full treatment of smaller scale structures. An explanation of the observed clustering of structures into filaments and sheets does not arise naturally from this mechanism.

1.4.2 Homogeneity and Isotropy of the Universe

The most fundamental assumption of the standard cosmological model is that the universe is homogeneous and isotropic on large scales. Hence there is an increasing foundation of observational work attempting to map the large scale structure of the universe.
Ongoing angular photometric surveys (APM and EDSGC) measure the angular pair correlation function $\omega(\theta)$. This gives a measure of the joint probability dP, of finding two galaxies in elements of solid angle $d\Omega_1$ and $d\Omega_2$, separated by an angle θ, given by

$$dP = N^2 d\Omega_1 d\Omega_2 [1 + \omega(\theta)] \tag{1.9}$$

where N is the mean surface density of galaxies in the survey.
Surveys have shown that $\omega(\theta)$ tends to zero at large angles, as expected for a homogeneous distribution of galaxies. However, it is not clear how this result should be interpretted spatially. Measurement of the spatial pair correlation function, which measures the joint probability of finding two galaxies in particular volume elements, separated by a particular distance, r, requires additional knowledge about the distances of the galaxies. This is not usually accurately known, hence we measure the angular correlation function and infer as much as possible about the spatial distribution of galaxies from this. At present we are unable to conclude that the tendancy of $\omega(\theta)$ to zero at large angles has an analogous conclusion for the spatial distribution of galaxies. This is due mainly to the fact that both these methods assume small θ and small r approximations, but a small distance does not naturally follow from a small angle approximation. In essence we are limited to a 2-dimensional distribution.
Redshift surveys provide 3-dimensional information for galaxy distributions, but not to the depth of the angular surveys. Still the rms fluctuation in galaxy number density becomes small when averaged over large scales (Fisher et al, 1993. Efstathiou et al,1990). This is consistent with homogeneous distribution of galaxies on these scales. The Las Campanas redshift survey maps galaxies out to distances $cz \sim$ 40000-50000 Km s^{-1}, and has shown no evidence for coherent structures on scales larger than the Great Wall (Schectman et al, 1992).
The most conclusive evidence for the homogeneity of the universe comes from the smoothness of the mirowave background (CMB). The temperature anisotropy is estimated by

COBE to be $\sim 10^{-6}$. However the smoothness of the CMB has caused some conflict with the age of the universe from the structure formation model reviewed in section 1.4.1

1.5 Alternative

We have reviewed here the increasing observational evidence for magnetic fields on scales of galaxy clusters, filamented plasma structures, and magnetic fields associated with these structures. All have been predicted by Alfén and incorporated into his cosmological model. His model attributes greater significance to electromagnetic effects, and naturally forms a highly inhomogeneous matter distribution, in direct contrast to the standard cosmological model. The details of this model are analysed in Chapter5. Although we find that Alfvén's approach to cosmology does not produce the complete picture that the standard model boasts, recent research has presented some interesting models for structure formation following Alfvén's basic postulates. In particular, we see that the effect of magnetic fields on early structure formation within the standard model shows similar structure evolution to that proposed in Alfvén's cosmology. The details will be reviewed in chapter4.

Chapter 2

Role of Plasmas and Magnetic Fields in Standard Cosmology

2.1 Introduction

The aim of this chapter is to consider the role and influence of magnetic fields and plasmas on all scales in the universe. Whilst electromagnetic effects are considered significant and indeed important on local scales, the role of magnetic fields is overtaken by the increased significance of the gravitational field on large scales and in cosmology. Here we investigate the reasons for this.

We then consider recent suggestions that electromagnetic effects may still affect cosmology at early epochs and in structure formation, and the physical consequences of this for the standard model.

2.2 Local Effects of Magnetic fields and Plasmas

The role and influence of magnetic fields is astrophysics is a relatively recent research field. Only since the 1950's, and the advance of radio astronomy, have observations revealed the presence of magnetic fields in the diffuse astrophysical plasmas and extragalactic radio sources, as well as in the sun and stars.

Detailed studies of the solar magnetic field, and the theory of it's origin are well known. Filaments in the solar prominences and nebula, accelaration in solar flares, and sunspots are known to be assosiated with magnetic fields.

Magnetic fields in the interstellar medium are known to play an important part in reducing the angular momentum of collapsing protostars (Mestel, 1993). Interstellar gas dynamics and molecular clouds are also influenced by the pressure of MHD waves. This is essential in supporting clouds against gravitational collapse.

Extragalactic jets and stellar jets are known to be assosiated with magnetic fields, and could possibly accelerate cosmic rays.

The intergalactic magnetic fields could similarly reduce the angular momentum of pro-rogalaxies, as suggested by Kronberg (1994).

However, as we reach scales of galaxies, already the influence of magnetic fields is thought to become increasingly insignificant. However some work has shown that care must be taken when making this assumption. In particular, Nelson (1988), Battaner et al (1992), Binney (1992), have suggested that magnetic fields may become important in galactic disks at large radii (>10Mpc). The matter density in the outer disk is much lower than that in the dense central bulge (Sancisi, 1983), yet the magnetic energy density is thought not to fall off in the outer disk. This assumption is based on the correlation of magnetic fields with the HI column density in galaxies as found by Han and Qiao (1993). HI extends to large galactocentric radii, and hence suggests that a strong magnetic field is also present at large radii. Nelson (1988) calculated that whilst in the inner galactic regions the rotational energy is $\sim$ 400 times the magnetic energy, a reduction of $\sim$ 100-500 times the matter density between 10Kpc and 20Kpc could allow the magnetic energy to compete with the rotational energy at these radii. As a result of this magnetic influence, the rotation velocity at large galactic radii increases, as the Alfvén velocity increases outwards. This effect has been suggested to explain the observed flat rotation curves of galaxies (Bosma, 1978). Magnetic fields may then reduce the need for dark matter, since flat rotation curves provide the majority of support to the presence of dark matter halos surrounding galaxies . However it is not claimed to entirely elliminate the need for dark matter. In fact some objections to this work have been made by Vallée(1994). He concludes that the magnetic field strengths required to produce the flat rotation curves is higher than observed, in particular for the Milky Way, and M31.

Magnetic fields may also have an influence on structure formation. Fermi (1953) and Chandrasekhar (1954) have considered gravitational instabilities within a uniformly magnetised medium. The direction of the magnetic field causes the Jean's instability to grow anisotropically. Also the Jean's criterion is modified in the direction perpendicular to the magnetic field, and is given by

$$\lambda_{mag} = (v_A + v_s)\Big(\frac{\pi}{\rho_0 G}^{1/2}\Big). \tag{2.1}$$

Where $v_A = \frac{B}{4\pi\rho_0}^{1/2}$ is the Alfvén speed. The magnetic Jean's length is longer than the usual Jean's length (c.f section 1.4.1).In this way magnetic fields may influence the mass distribution of structures in the universe (Kronberg, 1994). In the case of magnetic fields being amplified in galaxies (see chapter 3), a difference in stellar masses may be observed between old generation stars forming in a medium with low magnetic fields, and the younger generation within a highly magnetic medium. Lou (1996) has also analysed the effects of magnetic fields on the Jeans instability. Fluctuating and random magnetic fields have been considered here, concluding that in general the magnetic Jeans mass should be larger than the usual Jeans mass without the presence of magnetic fields. Further effects of magnetic fields on structure formation are discussed in Chapter 4.

2.3 Large Scale effects Of magnetic fields

Magnetic fields in standard cosmology are considered unimportant mainly due to the average energy density of fields being lower than that of matter. Also, since magneto-plasmas are highly non-linear systems, the mathematical difficulty of their inclusion is a real problem.

If we take the present value of matter density to be $\rho = 4 \times 10^{-30} gcm^{-3}$. This corresponds to a universe with $\Omega = 0.3$, from the lower end of the range estimated in galaxy peculiar velocity surveys. This yields an energy density for matter of $U_M = 4 \times 10^{-10} Jm^{-3}$. The present radiation energy density is effectively the contribution from the microwave background only, which is calculated to be $U_R = 4 \times 10^{-14} Jm^{-3}$. The magnetic energy density is given by

$$U_B = \frac{B^2}{2\mu_0}. \tag{2.2}$$

Where B is the present strength of the magnetic field configuration. In this case we have simply taken this to be the the value of the observed average intercluster field, $B = 10^{-7} G$. This gives a value $U_B = 4 \times 10^{-17} Jm^{-3}$.

It is clear from this order of magnitude comparison, that the magnetic fields have little significance on large scales in comparison to the gravitational force when we average the observed magnetic fields over the entire volume of the universe.

However, if we consider the evolution of these energy densities from early epochs to present day, $U_B \sim R^{-4}, U_M \sim R^{-3}$, and $U_R \sim R^{-4}$, where R is the universal scale factor. Then we find that the magnetic energy density becomes increasingly significant at earlier epochs as shown in fig 2.1. Note that we have used redshift to represent the timescale here, using $t^{3/2} \propto (1+z)^{-1}$ in a critical density universe. The move from matter domination to radiation domination can be seen to occur at a redshift of $\sim z = 10^4$, and the radiation remains the most significant to all earlier times. The magnetic energy density becomes more important than the matter contribution at a redshift of $\sim 10^7$, corresponding to the epoch of radiation thermalization, after nucleosynthesis($z = 10^9$).

However, we can note that had the energy density of magnetic fields at any time been

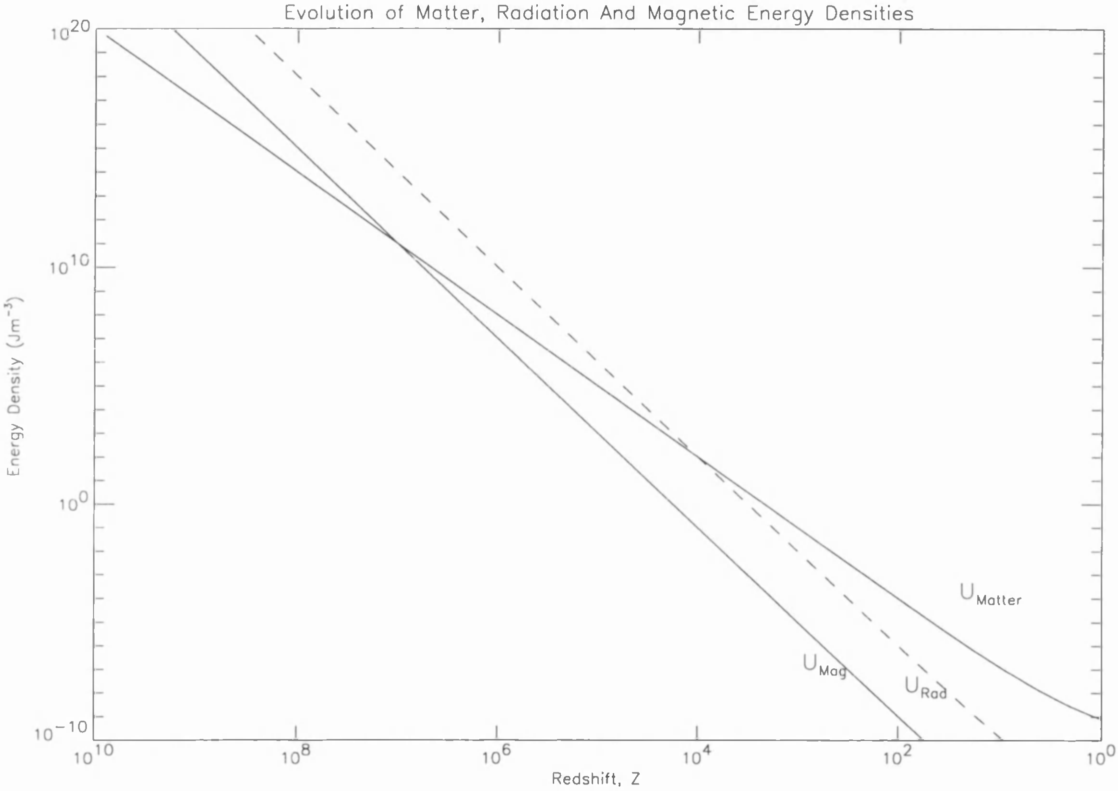

Figure 2.1: Plot of Order of magnitude energy densities of matter, U_{Matter}, radiation, U_{Rad}, and magnetic fields, U_{Mag}, from presently observed values at z=1 to earlier cosmological epochs.

higher than that of radiation, then at early epochs, the magnetic energy density would dominate all other contributions. This may be the case if some net dissipation effect has acted, to result in lower observed fields today.

From the crude calculations here, it is shown that an average field strength now of $B \geq 10^{-6}G$ would ensure U_B became dominant at sometime in the past. Indeed if turbulence was found to play an important role in field dissipation,then this scenario could well arise.

Of course we have presumed here that firstly magnetic fields were present at such early epochs, and secondly that no amplification or dissipation of the field has occured since generation of the field.

The first assumption will be discussed in Chapter3, when the proposed generation mechanisms of magnetic fields in the standard cosmological model are reviewed. The second assumption is not well understood, and section 2.4 gives a brief review of field dissipation effects.

2.3.1 Physical Consequences of Magnetic Fields at Early Epochs

Magnetic fields effect the standard cosmological model only at early times in the evolution of the universe. This is because the very framework of the standard model dictates that isolated (hence possibly large magnetic energy density) magnetic fields, cannot exist until structures begin to form, freezing in and possibly amplify the background field. It is necessary then to provide a consistent mechanism for generating such a background magnetic field, and evolving this field into the isolated filamented structures observed today. The presently proposed generation mechanisms for magnetic fields are analysed in chapter3, and many inconsistencies with theory and observations are highlighted. We will however continue here to consider the effects on the early universe of magnetic fields within the standard cosmology, and in chapters 4 and 5 consider Alfvén's ideas, which although can solve some inconsistencies, generate more in the process.

The relative importance of the magnetic, radiation and matter energy densities here determines the dominant contribution to the expansion rate of the universe at these early epochs, since the energy densities contribute to the curvature of space-time in the framework of General Relativity. The effects of the magnetic fields in terms of the electromagnetic force, such as for nuclear reaction rates, is dependant on the strength and the coherence scale of the field also.

The effects of a magnetic field in the early universe depends crucially on the strength and coherence scale of the field at this time, hence the importance of determining a consistent generation mechanism of magnetic fields in the universe which will then determine or at least limit these parameters. In Chapter3 we discuss the mechanisms for generating magnetic fields in the universe. All but one of these mechanisms takes place in the pre-recombination epoch. In this one case no magnetic field at such early epochs is required, and so the consequences of the fields generated in this mechanism are only seen in galaxy formation and on local scales.

For the pre-recombination universe, the presence of a magnetic field can necessitate significant corrections to nucleosynthesis models, the time-temperature relationship, expansion rates and even the geometry of the universe. All of which contribute to the standard cosmological models predictions, and used to argue its validity.

Some restrictions on the early magnetic field configuration can be formed instantly in the standard cosmological model. Firstly, a magnetic field coherent on scales larger than the horizon scale, such as would be produced in generation mechanisms during or prior to inflation, cause an anisotropic expansion of the universe (Cheng et al, 1994). Models of anisotropic universes have been studied, although are not considered here. If this anisotropy persists then Thorne and later Hawking and Taylor have shown that the helium abundance of the universe reduces to just a few percent, contrary to observation. Hence generation mechanisms after any inflationary epoch seem preferable.

Secondly, in the case of non-uniform magnetic fields strengths from region to region across the universe, particle reaction rates in the early universe will vary spatially, and inhomogeneity of element abundances would result (Cheng et al, 1994). A similar result would arise if the coherence scale of the fields is much smaller than the horizon scale at the generation epoch. In this case the magnetic domains will be disconnected from each other, and again the reaction rates would fluctuate from place to place.

Consequently, it is assumed generally that the magnetic field is uniform throughout the universe, and is coherent on scales smaller than the horizon scale, and the magnetic domains are connected. With these assumptions Cheng et al (1994), and subsequently Kernan et al (1996), have considered the two primary effects of a primordial field on the early universe to be (a) The magnetic field energy density contribution to the expansion rate of the universe, and (b) The field changes to the electron phase space, which affects the weak interaction rates at nucleosynthesis.

Both of these have consequences for the abundance of light elements produced in the early universe due to the changes induced in the time-temperature relationship , although the relative importance of the two affects is unsure. Recently, Keran et al argue that (a) is the more significant affect, contrary to cheng et al's findings.

The general result of Kernan et al is that with the exception of β decay, the effects of the magnetic field on the electron phase space is to decrease all the weak interaction rates. On the other hand, changes in the time-temperature relationship due to the contribution of the magnetic field to the energy density, serves to increase the neutron fraction. The overall affect is most noticeably seen in the helium production rate, as a net increase in the helium fraction at nucleosynthesis.

These analyses, along with the observations of light element abundances in the universe today, have allowed constraints to be placed on the field strength present at the nucleosynthesis epoch. Cheng et al allow $B \leq 10^{11}G$ at the nucleosynthesis epoch for consistency with observations, and warns that if the field reaches $10^{13}G$ at this time, drastic affects to element abundances will arise because the neutron will decay quicker at this field strength. Grasso and Rubestein(1995) show a limit of $B \leq 10^{10}G$ at nucleosynthesis is necessary.

It has also been suggested that magnetic fields may influence the formation of density inhomogeneities in the pre-recombination universe. Recent work by Battaner et al (1997) has attempted to incorporate magnetic fields into the evolution of density inhomogeneities in the early universe. Firstly they introduce the general equations, which differ from previous treatments of MHD in an expanding universe (Brandenburg,Enqvist and Olesen, 1996), by accounting for magnetic fields perturbing the metric. They conclude that fields $\sim 10^{-8}G$ are able to generate density structures initially, and modify their evolution at later times. However we note, that as previously mentioned, the average magnetic field in the universe must be zero in the Robertson Walker metric. Since this means the magnetic fields must be uniform throughout the universe, the observed energy density of magnetic fields in the universe restricts this model. In fact Battaner et al calculate strict limitations on the magnetic field strength allowed, and conclude very little deviation from $10^{-8}G$ is allowed for consistency. In a follow up paper, Battaner et al consider the specific magnetic field configuration of flux tubes. They find that primordial magnetic flux tubes in the epoch from $z \sim 10^8$ to $z =\sim 10^5$, can produce filamentary density inhomogeneities, and suggest that this is a valid alternative way of forming the observed matter distribution on large scales, or at least a mechanism for reinforcing other gravitational effects. This is further discussed in Chapter 4.

2.4 Evolution of magnetic fields

It is important to consider the effect of diffusion on the evolution of the field. The rate of dissipation of a primordial field is of great consequence here since the extent of dissipation will determine the initial magnetic field strength neccessary at early epochs to account for the observed magnetic fields today. Of course the amplification mechanisms discussed in Chapter3 will also affect this. The extent of diffusion is described by the diffusion term in the magnetohydrodynamic induction equation

$$\frac{\partial B}{\partial t} = \nabla \times (v \times B) + (\sigma)^{-1}(\nabla)^2 B \tag{2.3}$$

Where v is the plasma velocity, and σ is the conductivity. In the pre-recombination epoch the conductivity of the universe is very high, and the diffusion term in 2.4 can be neglected. The first term on the right hand side of 2.4 represents the tendancy of the magnetic field to move with plasma motions, hence in the case when the diffusion can be neglected we consider the field to be 'frozen' into the plasma.

However, when the number of charge carriers decreases dramatically after recombination, the conductivity drops and we can no longer consider the field to be frozen in on all scales. We can estimate the scale below which the diffusion of the field becomes significant after recombination to be

$$\ell(t) \approx \sqrt{\frac{t}{\sigma}} \tag{2.4}$$

Dimopoulos and Davis (1997) have estimated the plasma conductivity to be

$$\sigma \simeq \frac{e^2}{mv\sigma_c} \tag{2.5}$$

Where,

$$\sigma_c \simeq \frac{e^4}{T^2} ln\Lambda \tag{2.6}$$

is the collisional cross section of the plasma particles. Hence they obtain an estimate for the length scale at low temperatures (taken here to be after the epoch of electron-positron annihilation), of

$$\ell(t) \sim 10^8 T^{-7/4} GeV^{3/4} \tag{2.7}$$

Where T is the temperature in GeV.

At the recombination time ($t = 10^5$ years), $T \approx 1eV$, and the diffusion length scale is therefore $\ell \sim 5 \times 10^{-3} AU$.

At the time of galaxy formation, ($t = 10^9$ years), $T \approx 0.01eV$,and the diffusion scale $\ell \sim 15AU$. We can then consider the field to be frozen into the plasma from recombination to the galaxy formation epoch for scales larger than $\ell(t)$.

Since in this analysis we are only considering galactic scales and larger, the assumption of frozen in fields is valid.

We should also take account of any field diffusion due to turbulence , since this may cause dissipation of the primordial field in the pre-galactic epoch also. In essence, our understanding of magnetic diffusion and turbulent mixing is incomplete, and objections to both assumptions of low and high turbulent diffusion have been voiced with consequences for the generation mechanisms in Chapter3. Not only is this mechanism poorly understood, the circumstances to which we apply it here are so uncertain as to make the problem far from trivial.

Chapter 3

Generation Of Magnetic Fields In Cosmology

3.1 Introduction

The purpose of this chapter is to consider the proposed generation mechanisms for magnetic fields in the universe. Having noted that within the standard cosmological model magnetic fields are expected to become increasingly significant at earlier epochs in the evolution of the universe, then the question of magnetic field strengths and coherence scales at these epochs is of fundamental importance in determining the extent of this significance. The primary problem of determining the effect of magnetic fields in standard cosmology is then one of the fields origin, the scenarios for generating magnetic fields then will prescribe the strength and configurations of the initial fields.

This chapter discusses the approaches made to this fundamental cosmic question. Firstly the primordial origin, possibly requiring amplification by dynamo action, and secondly, battery generation of fields in stars and galaxies, with outflow phemomena seeding the intergalactic medium. The second scenario here is particularly important since it offers a possible method of generating magnetic fields at later epochs, and alleviates the effects of magnetic fields in cosmology mentioned in chapter2. This approach is examined closely here, following the work of Lesch et al (1989), and comparison of the results reveals some inconsistancy in the treatment given in the Lesch paper. The consequences for the standard cosmological model are discussed for both approaches.

It becomes clear that in all of these approaches, whilst the theory behind the mechanism is sometimes well established, the circumstances to which we apply them are badly understood, and so the value of the conclusions we draw is unclear.

3.2 Primordial Origin

The first case to consider is a magnetic field originating in the pre-recombination epoch. There are two scenarios which require a field at such early epochs. Firstly, the simplest case of a purely primordial field, generated prior to recombination, diluting with the universal expansion until present day. Secondly, a primordial seed field generated at early times, then maintained and amplified at a later time by the dynamo mechanism.

The two approaches differ enormously in the strength of initial field required, which is of paramount importance to the standard cosmological model. A strong field will have significant consequences for the early universe models. In particular for nucleosynthesis rates and abundances, and even the expansion rate of the universe, and structure formation at early epochs, as detailed in Chapter 2.

It becomes clear however from the work done to date, that both scenarios are inconsistent from a theoretical and observational view point. This tends to favour the theory which places the least restrictions and causes the least disruptions of the present cosmological model. As already mentioned, the difference of the two approaches for the standard model is in the importance of the initial field strength and configuration. The dynamo allows the present day fields to be essentially independent of the initial field strength and coherence, whilst a purely primordial origin requires much stricter constraints on the initial conditions and generation mechanism.

For this reason it is easier to dismiss the primordial origin theory in favour of dynamo amplification of a weak seed field, as it causes less disruption of the present cosmological models, and generation mechanisms of weak seed fields are more abundant.

We consider here all the work done to date on both mechanisms. We trace the evolution of the field backwards in time from the presently observed fields, and consider the effect on the standard model as discussed by Cheng et al (1994).

The proposed generation mechanisms of the initial field are also investigated.

We note here that assumptions are made about the diffusion and turbulent effects of magnetic fields for all the generation mechanisms presented here (see Chapter1 for brief discussion). In primordial theories to date, turbulent diffusion is assumed to play no part, indeed the survival of the field relies on this effect being negligible. In the case of dynamo theories, the effect is again considered negligible before the dynamo begins to ensure the survival of the required seed field. Yet, the dynamo mechanism itself needs a high resistivity to allow the field strength to increase without a progressive tangling of the field (see section 3.4). Effectively the turbulent diffusion needs to be switched on at the onset of galaxy formation.

Our understanding of magnetic diffusion and turbulent mixing is incomplete, and objections to both assumptions of low and high turbulent diffusion have been voiced.

Parker(1979) showed that on inclusion of turbulent flows, a primordial field dissipates on a time scale shorter than even the galactic lifetime. Also, Catteneo(1991) has questioned the extent of turbulent mixing for the dynamo model.

In the following sections we will consider primordial fields and then add in a dynamo. In both, the effect of turbulence will be mentioned briefly.

3.3 Primordial Field Generation

We begin by noting that the word primordial here does not refer to a field created in the very beginning. Rather the primordial field is only considered to appear between the inflationary and nucleosynthesis epochs, depending on the mechanism proposed. A truly primordial field is never discussed.

A number of scenarios have been proposed for the generation of the first magnetic fields, all of which are somewhat esoteric. A brief review of the most recent and popular mechanisms follows.

Magnetic fields have been generated (on paper) during phase transitions in the early universe.

Quashnoke et al (1989), and later Cheng and Olinto(1994) considered the first order quark-hadron transition when the universe had cooled to a temperature $T \sim 100MeV$. As bubbles of hadronic phase are formed and grow at the expense of the quark phase, shocks form. Quashnoke et al postulated a Biermann battery machanism that relies on the different responses of the positive and negative charges to these shocks, and produced a field $B \sim 5G$. Cheng and Olinto have since shown that stronger fields can arise after the brief nucleation period, when the two phases coexist. This mechanism is based on the charge seperation occuring at the interfaces between phases, due to the different baryon susceptibility of the two phases. Perculiar flows are then introduced to mix the plasma and produce currents. The field strength estimate in this scenario is considerably larger than in Quashnoke et al, $B \sim 10^6 - 10^8G$.

A second order phase transition at the electro-weak epoch ($T \sim 200GeV$), has been considered firstly by Vachaspati(1991). The important idea in this transition is to give the Higgs field different phases in neighbouring regions of space. Then the resulting gradients in phase between causally disconnected regions may produce magnetic fields. However, Vachispati found the field generated by these gradients to be negligible ($\sim 10^{-30}G$). Since then, Enqvist and Olesen (1993), using different assumptions about the correlation domains, have generated fields $B \sim 10^{-18}G$ at present day with this mechanism. Although this is more promising, the correlation scales of these fields is a problem. These mechanisms cannot create a field coherent on scales larger than the horizon scale at the epoch of formation. At the electro-weak epoch the hubble radius corresponds to a comoving scale today of $\lambda_E W \sim 10AU$, which is comparible to the diffusion scale already mentioned. Hence, fields coherent on such small scales will not be frozen into the primordial plasma, and diffusion becomes important.

Harrison(1970,1973), proposed a very different model for generating fields in the recombination epoch. By postulating that the electrons and photons couple, and the protons couple with the neutrons before recombination, then in the event of vorticity, the two 'couples' would behave as seperate fluids. They would acquire different angular velocities and a circularly rotating electric field would be set up. However, Harrison found that primordial vortices, limited by COBE results, would have decayed by the recombination epoch. More recently, Sicotte(1997) has considered dynamically generated vortices caused by the collapse of dark matter(DM). The DM must collapse before recombination however, and this rules out the standard cold dark matter model preferred today. Even so the mechanism gives a field of only $B \sim 10^{-20}G$ at epoch of generation

The mechanisms so far considered generate fields with very short coherence lengths. This conflicts with the scales of fields observed today, unless we can generate order at a later time, for example with the dynamo (see later). In an attempt to overcome this problem, a number of mechanisms have been proposed to generate fields in or before the inflationary epoch. To date the attempts have been unsuccessful since the field is inevitably diluted enormously in the rapid expansion. Unless we break conformal invariance of electromagnetism this problem remains. A number of mechanisms for doing so have been proposed, but the result is very model dependant. In any case, the coherent scale of the fields produced during inflation would be larger than the horizon scale. This has been shown/calculated to produce such inhomogeneity in the matter density as to cause an anisotropic expansion of the universe (Cheng et al,1994).

Another mechanism proposed to overcome the problem of small coherence scales has recently been suggested by Dimopoulos and Davis(1997). They have considered the possibility that correlated domains of magnetic field may grow faster than the hubble growth due to turbulence at domain interfaces. They argue that the assumption that the correlated domains of field expand only due to the hubble expansion is too simplistic. Infact, since the causally connected domains grow faster than the expansion rate, then two initially uncorrelated regions will become causally connected much faster. The field would re-arrange and untangle in order to avoid creating magnetic domain walls which are energetically unfavourable. Hence the field becomes correlated over the causal length scale, larger than the scales growing with the hubble expansion. This could solve the problem of coherence scales facing the primordial origin theory. However, if we introduce turbulence for this mechanism we then risk losing the field due to turbulent diffusion.

Finally we mention the possibility of thermal fluctuations in the pre-recombination plasma generating magnetic fields, as suggested by Lemoine (1995). The fields so far produced are very small however ($B \sim 10^{-33}G$).

With these available field strengths and correlation lengths in mind we now consider the evolution of the field from the generation epoch to the observed fields of today. Since the generation mechanisms discussed produce a range of field strengths, and are somewhat speculative, we will begin from the observed field values today and extrapolate backwards in time. This will allow us to determine the consistency of the various mechanisms with observations.

We have seen in Chapter2 the evolution of the average magnetic field energy density observed today, extrapolated to earlier epochs (fig 2.1), assuming no amplification or dissipation of the field. From this order of magnitude estimation, we can gain an estimate of the field value at the time of nucleosynthesis from Fig 2.1. The value here is $\sim 2 \times 10^{11}G$. The effects of such a field on nuclear reaction rates will be considered later, along with the effect of U_B on the expansion rate of the universe, and on early structure formation. We can see at this stage however that there is some difficulty in generating a $10^{11}G$ field at this epoch. From the generation mechanisms already discussed in section 3.3, none can produce a field of this strength by the nucleosynthesis epoch.

If we now consider galactic magnetic fields, fig 3.1 shows the evolution of a typically observed galactic field strength of $B = 10^{-6}G$. In this simplest case, we consider there to be no dissipation or amplification of the field at any time. Tracing backwards in time, the observed field strength remains constant until the epoch of galaxy formation, when the field is frozen into the protogalactic cloud as it collapses. Prior to this, the graph illustrates the field frozen into the universal expansion.
The initial value of U_B at $z = 1$ is taken from the observations of galaxies at this redshift. The validity of this observation is not entirely clear, as discussed in chapter1. However, in this case with no amplification or dissipation of the field after galaxy formation, the redshift of this observation has no effect on the value of U_B at earlier times.
We can again obtain an estimate of the field strength at the epoch of nucleosynthesis. The graph gives $U_B = 2.65 \times 10^7 Jm^{-3}$ at $z = 10^9$, so that $B \sim 10^5 G$.
We note that in order to obtain a timescale for this analysis a particular cosmological model must be chosen, since this dictates the relationship between real time and redshift. The simplest relationship to consider is that of a critical density universe, where, $t^{3/2} \propto (1+z)^{-1}$. Field dissipation at any time during or prior to galaxy formation would only serve to increase the initial field strength present in the pre-recombination poch. On the other hand, the primordial field strength would be considerably decreased if some amplification mechanism is introduced, as we see in the next section.

3.4 Dynamo

The dynamo mechanism seems to have first been proposed by Larmor(1919). The basic idea is that differential fluid flow can increase the energy in an existing magnetic field by doing work against the Lorentz forces exerted by the field. The dynamo mechanism is most easily visualized by considering the evolution of magnetic field lines. A non-uniform plasma flow can distort the existing field lines, and if the conductivity of the plasma is finite (most astrophysical situations), reconnection occurs where the field changes direction over a short distance. A particular velocity field of the plasma can stretch, twist and reconnect the field lines in such a way as to increase the energy and order of the field. A number of velocity fields have been proposed depending on the situation to which they are applied, i.e stellar, planetary or galactic dynamos.

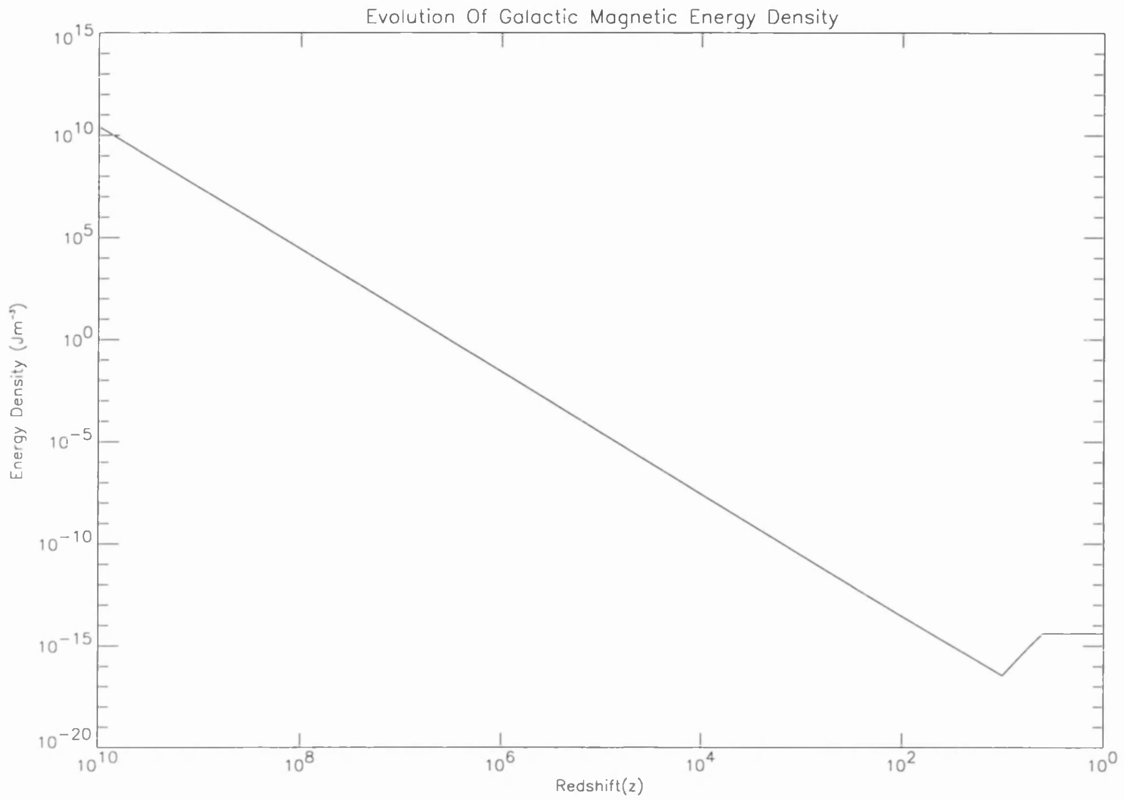

Figure 3.1: Graph to show the evolution of the magnetic energy density of a galaxy, from the observed values at z=1, to earlier cosmological epochs (higher redshifts). No amplification or dissipation of the magnetic fields are considered here, only the flux freezing of the fields as the universe expands, and the protogalaxy collapses($z \sim 10$).

A crucial element of the dynamo for all situations is the finite conductivity requirement of the plasma. This allows the reconnection of field lines to occur, which is vital for the amplification of the field. However, the usual molecular resistivity is too small for this purpose, and so dynamo must introduce turbulence to provide the resistance. Not only is the theory of turbulence in astrophysics incompletely understood as mentioned in chapter1, but this also complicates the mathematical treatment of the mechanism.

The mean field dynamo avoids tackling the problems of turbulence to some extent by averaging over large scales. By assuming that the turbulence scale is very much smaller than the coherence scale of the initial magnetic field, and that there is a lack of symetry in the small scale motions, averaging yields a mean induced current,

$$J_{ind} = \sigma \alpha B_0 \tag{3.1}$$

where σ is the conductivity, and α measures the proportionality of J_ind and B_0.
Ohms law then becomes

$$\bar{J} = \sigma(\bar{E} + \bar{V} \times \bar{B} + \alpha\bar{B}) \quad (3.2)$$

It becomes clear that the dynamo properties depend on α and the spatial gradient of the velocity field of the plasma(Ω). Hence the term '$\alpha\Omega$' dynamo.

The theory is incomplete however.

The lorentz force can drive large scale flows which are not included in the mean field approximation.

Also there is the problem of 'α-quenching', were the turbulent motions are increasingly inhibited by the amplified field. This reduces α and the dynamo reaches saturation. This could significantly reduce the efficiency of the dynamo (Kulsrud and Anderson, 1993.

The assumption that the turbulent length scales are very much less than the coherence scales of the mean field, is simply not valid in most astrophysical situations. This also leaves the dynamo with the same scale problem as the primordial origin theory. Where initially the dynamo is thought to overcome the small coherence scales by generating order on large scales, it now appears that the seed field coherence length must be much greater than the turbulent eddie scales for the mean field dynamo to apply.

From an observational view point the theory is inconsistent for major features of the solar dynamo. For example, predicting that sunspots migrate in the opposite direction to observed during the solar cycle. Dynamos for other stars have recently emerged, but the predictions and observations are obviously less detailed.

Work has been done on dynamos without the mean field approximation, since all the problems seem to be absorbed in the co-efficients and turbulence. However the computational difficulty of including turbulence is great, and to date only simple simulations have been attempted. Glatzmaier and Roberts(1995) have modelled the earths dynamo and have recovered some correct details, e.g polarity changes on correct timescales. Also, simulations of the solar dynamo show some new information, such as the formtion of vortex tubes. However thay show no evidence of large scale mean fields, although this could be a computational problem.

For the purposes of this chapter, we are considering the dynamo in the galactic enviroment. Differential rotation in the disk, along with the coriolis force provides the necessary velocity field for amplification of an initially weak seed field. The models incorporate an '$\alpha\Omega$' dynamo for the outer disk, whereby an initially radial field, and differential rotation cause an azimuthal field to grow. A small poloidal field is also generated by the action of the coriolis force on turbulent motions perpendicular to the disk. In the inner galactic regions, where Ω is independant of galactocentric radius, the conditions for amplification of the disk fields no longer apply. However, a poloidal magnetic field component is generated as in the outer disk regions, and a poloidal current, which reinforces the toroidal magnetic field. This is called the α^2 dynamo.

The final field structure of these models is predominantly azimuthal in the disk, with quadrupolar symetry about the galactic plane. In the inner regions a dipolar field dominates. The primordial field generation mechanisms discussed are still required here, since the dynamo can only amplify an existing field, no self-starting dynamo exists. The problems of field scales are reduced for the dynamo, since the mechanism generates order. However as mentioned above, the approximation of mean field dynamos can limit the seed field scale relative to the turbulent length scale. The second problem of the strength of the seed field produced in these mechanisms is also reduced, since the required seed field for dynamo amplification can be as low as B$\sim 10^{-20}$G. (Zel'dovich et al, 1983)

Still the question remains, is the dynamo amplification mechanism efficient enough to account for todays observed galactic magnetic fields strengths from even this minimum seed field?

We have extended fig 3.1 to account for dynamo amplification after galaxy formation, replacing the condition of no dissipation or amplification. The dynamo is considered to be entirely efficient, producing exponential growth of the magnetic field strength over the galactic rotation period ($\sim 10^8$Years) i.e the best case scenario.

Fig 3.2 shows that the field strength at nucleosynthesis is then much reduced from the case of no dynamo amplification to B$\sim 10^{-7}$G.

Comparing this value with those generated by the mechanisms at early cosmological epochs discussed earlier, we find that only one scenario can claim to generate a field consistent with this picture. The quark-hadron phase transition is shown to generate fields as large as 10^8G at a redshift $z_{QCD} \sim 10^{15}$. By the time of nucleosynthesis ($z_N \sim 10^9$),

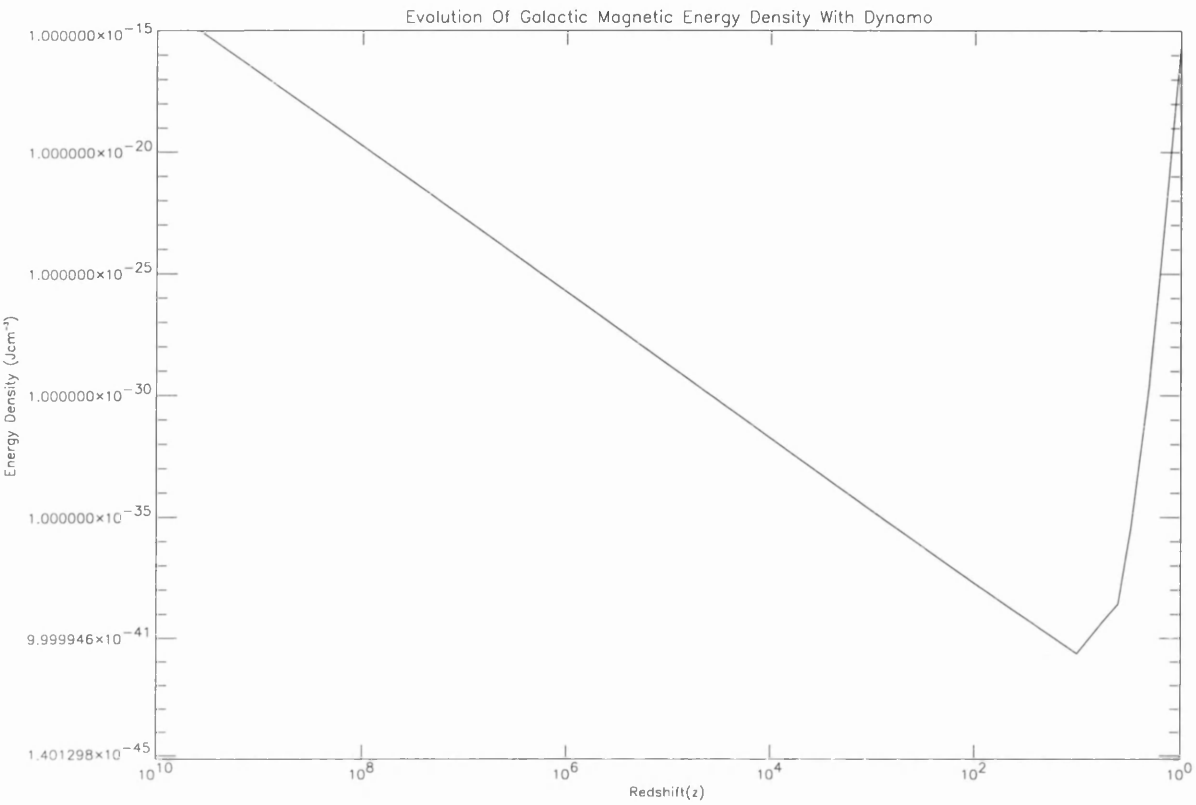

Figure 3.2: Graph to show the evolution of the average galactic magnetic energy density fromthe values observed at z=1, to earlier epochs. Here amplification of the magnetic field by dynamo, after galaxy formation is shown, but no dissipation of the magnetic fields is considered.

this frozen in field will have strength

$$B_N = B_{QCD} \left(\frac{1 + z_N}{1 + z_{QCD}} \right)^{3/2} \sim 0.1G \tag{3.3}$$

This is several orders of magnitude higher than that required for the galactic dynamo. Also, with such a high field generated at QCD, there can be some flexibility in the efficiency of the dynamo mechanism, and even some dissipation of the field prior to dynamo action. On the other hand, such a high field would generate density inhomogeneities in the early universe, and cuse structures to form too quickly for consistency with the standard cosmological model.

The evolution of the galactic magnetic field strengths in fig 3.1 depends crucially on our observations of filed strengths in galactic systems today. As already noted, we have taken the observations at z=1 as the starting point of the graph, and extrapolated backwards in time to earlier epochs. The high redshift of these observations does put a strain on the mechanism, leaving a shorter timescale for amplification, which drives up the strength of the required seed field for the dynamo. In this case of observed fields at z=1, the graph shows that a seed field of $5 \times 10^{-18}G$ is required at the onset of the dynamo mechanism. This is small but not negligible, and is significantly higher than the minimum seed field required for dynamo action ($\sim 10^{-20}G$), and preferred for the standard model.

If instead we begin with the condition of minimum dynamo seed field before the onset of dynamo action, we expect the field strength at earlier epochs to be again reduced. Fig 3.3 illustrates this scenario, and shows the minimum field at nucleosynthesis that is consistent with dynamo action after protogalactic collapse around z=10, is $\sim 10^{-9}G$.

However, if the observations of fields in galactic systems at high redshift are shown to be statistically significant, then the dynamo is somewhat pushed for time, and the consequences for the early universe are greater due to the higher field strengths present.

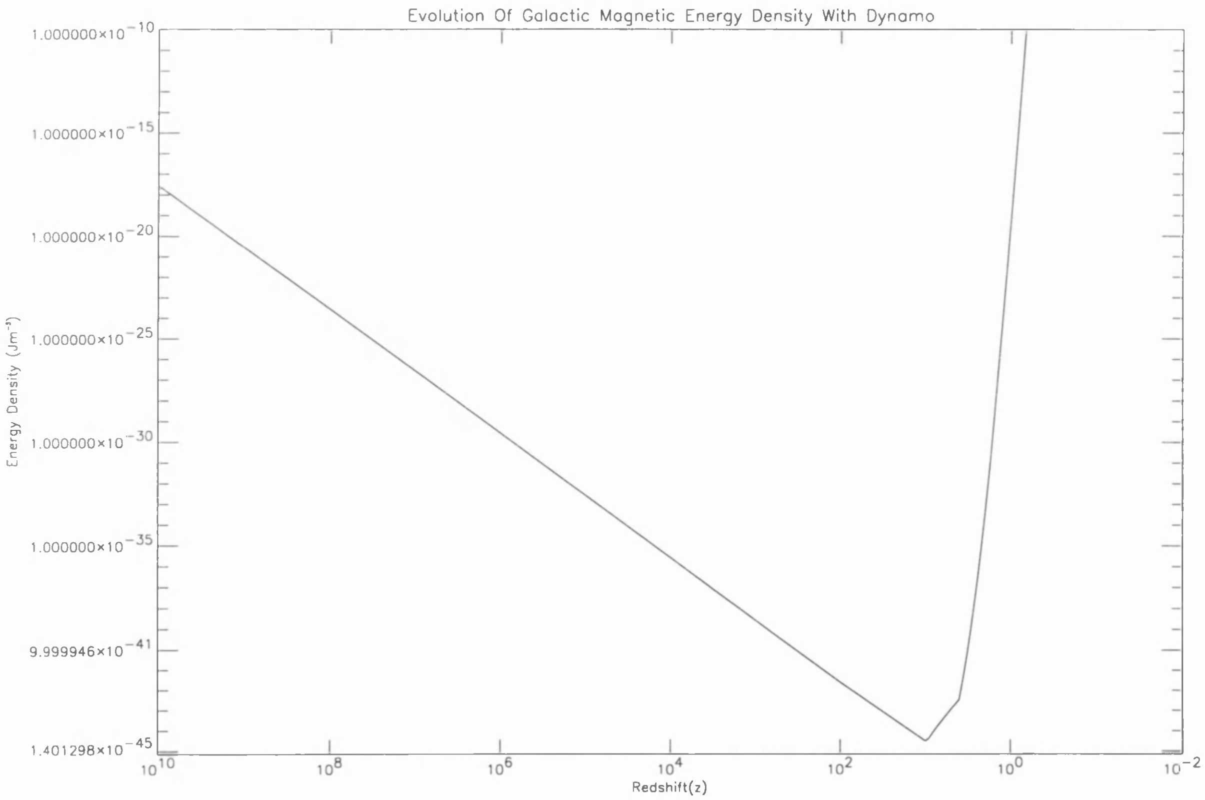

Figure 3.3: The evolution of average galactic magnetic field with redshift. In this case the minimum required seed field for dynamo is assumed at z=5(after galaxy formation).

3.5 Battery Mechanism

A second scenario for the generation of magnetic fields in galaxies originates from the work of L.Biermann (1950), and could elliminate the necessity of a primordial magnetic field. Biermann tackled the problem of toroidal field generation in rotating stars, by considering the unbalanced forces on electrons and ions, due to their different masses. In this case, the gravitational force and the coriolis force act differentially on the two species, resulting in a partial-pressure gradient of the electrons. This is balanced by an outward movement of electrons, hence a drifting charge separation, which produces a toroidal magnetic field. More recently, a form of battery mechanism has been proposed on galactic scales by Lesch et al (1989) in order to ensure the existence of a large scale field in the inner galactic regions, for amplification by dynamo action. In this case, the separation of electrons and ions is the result of differing collisional deceleration rates, when a fast, neutral plasma beam, is injected into a cold gas ring, orbiting around a galactic centre. The collision rate for protons is a factor m_p/m_e lower than that for the electrons, as discussed by Emslie (1978), hence the electrons tend to fall behind the protons. If the plasma flow is continuous, it is claimed that a charge separation current may build up in the ring, so that an associated magnetic field will be produced.

A somewhat similar problem of neutral beam interaction with a gas, has been discussed as a mechanism for the acceleration of electrons in the solar chromosphere, in an attempt to explain the hard X-ray bremmstrahlung produced at the onset of solar flares (Simnett and Haines 1990).

Here we have undertaken further work on the solar flare problem, with applicable results to the field generation problem considered here, in collaboration with Karlicky, Brown and Conway. Electrostatic particle codes were used to examine collective effects, such as particle trapping, along with the mean particle behaviour discussed in this analysis. These numerical results were compared with analytical approximations.

In the galactic case, the physical picture for this mechanism is based on observations of rotating gaseous tori and plasma outflows such as around the central regions of M82 and NGC 3628. Strong star formation occurs in the centre of the rings, and a number of supernova remnants and gas outflows with high velocities (200-500kms) have been detected. A schematic view of this situation is shown in fig 3.4.

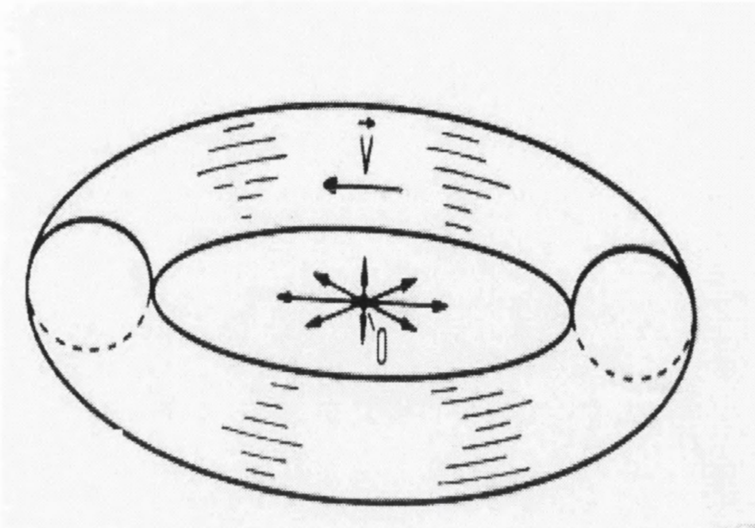

Figure 3.4: Schematic diagram of rotating gaseous tori, with orbital velocity V, around the galactic centre, O. From Lesch et al, 1989.

Lesch et al discussed the possibility of such outflows exciting compressional sound waves in the surrounding medium, which push the radially flowing plasma into the azimuthally rotating gas torus. The electrons in the outflow fall behind the protons in the beam, as mentioned above and Lesch et al argue, neglecting the displacement current, that "by amperes law", a current density $j = ne(v_p - v_e)$ implies that $\nabla \times B \neq 0$, with v_e and v_p the electron and proton velocities in the beam respectively, and B the magnetic field. However, in the analysis that follows, we show that the assumption of ignoring the displacement current is incorrect. In fact the displacement current plays a crucial role in determining the behaviour of the components of the beam, and the generation of electromagnetic fields in the system. We conclude that no magnetic fields are generated after inclusion of the displacement current.

3.5.1 Formulation Of Problem

The problem adressed involves the injection of a 'blunt beam' of neutral plasma (equal electron and proton densities) across a boundary, into a moving background gas. We shall first consider a simpler formulation of this, by ignoring the azimuthal rotation of the background plasma, so reducing the problem to that of a beam injected into a stationary background gas. Although this appears to alter the problem at hand, we show later in section 3.5.2 that in fact the results deduced for this case apply directly to the moving background case. Furthermore, we begin with the beam head already some distance ($\gg$debye length) into the plasma, before any significant deceleration occurs. Then one can conjecture that the behaviour of electron proton pairs behind the beam front will be essentially as if the pairs are launched with the same initial velocity (v_0) at time $t = 0$, at every point in an infinite homogeneous background plasma.

Homogeneity in the beam dictates that $n_e(t) = n_p(t) = n$, a constant, where n_e and n_p are the electron and proton number densities respectively. Hence the charge density in the beam is always zero. From Maxwell's equations, we can then conclude as follows:-

$$\nabla \cdot E = 0 \tag{3.4}$$

i.e any electric field produced must be homogeneous. Also

$$\nabla \times E = 0 \tag{3.5}$$

since the electric field must be 1-Dimensional if the beam is of very large width, due to the symmetry and homogeneity of the problem. It follows that, since

$$\nabla \times E + \frac{\partial B}{\partial t} = 0 \tag{3.6}$$

then

$$\frac{\partial B}{\partial t} = 0 \tag{3.7}$$

and so $B = 0$ for all t if $B = 0$ initially. It seems clear then that no magnetic field will result in this case. Infact the displacement current originally neglected by Lesch et al ensures that no magnetic field appears.

There will however be an electric field, E, (produced by the charge density at infinity, i.e by the sheet charges formed at the beam head and tail). The evolution of this field, and the mean motions of the ions and electrons in the beam are investigated in section 3.5.3.

3.5.2 Generalising To Moving Background Gas

We now show that the results of this section still hold for the real case of a moving background plasma. The direction of motion of the beam components for injection into a moving background is shown in fig 3.5. From this picture it is unclear that the electric field produced will be 1-dimensional and homogeneous as for the stationary case. However, by transforming to the rest frame of the background plasma, as illustrated in fig 3.6, it is easily seen that the injected beam now simply enters the background obliquely rather than at right angles, and the particle motions remain unidirectional. The only effect is thus to alter the direction of the electric field, but since it still remains 1-dimensional, the results of section 3.5.1 still hold.

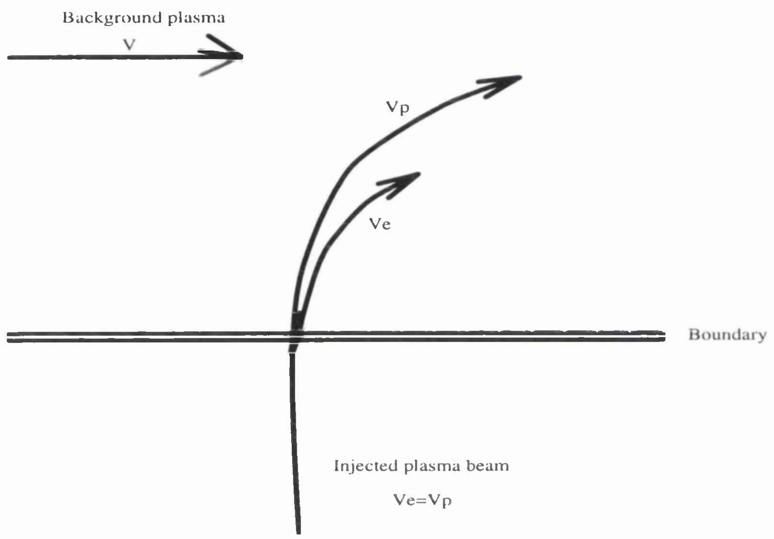

Figure 3.5: Diagram showing flow directions of electrons,V_e, and protons,V_p, in neutral beam injected across a boundary into a moving background gas (velocity V).

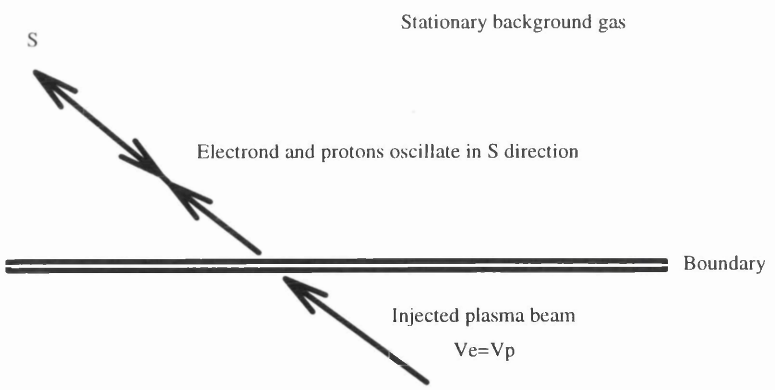

Figure 3.6: Diagram showing motion of electrons and protons in neutral beam injected into background gas. This time transformed to the rest frame of the background gas. This illustrates the motion of electrons and protons in 1-D only.

3.5.3 Investigation Of Particle Behaviour In Beam

The following analysis leads to both analytical and numerical descriptions of the motions of the electrons and ions in the injected plasma beam. We begin from the equations of motion for 'mean' particles in the beam,

$$m_e \frac{dv_e}{dt} = -eE - C_e(v_e) \tag{3.8}$$

$$m_p \frac{dv_p}{dt} = eE - C_p(v_p) \tag{3.9}$$

$$\frac{dE}{dt} = -j(t) = -\frac{ne}{\epsilon_0}(v_p - v_e) \tag{3.10}$$

Here $v_e(t), v_p(t)$ are the electron and proton velocities respectively, e is the electron charge, and n is the beam density, m_e and m_p are the electron and proton masses, and C_e, C_p are the coulomb collision forces on the electrons and protons respectively. Here it is assumed that the background gas is neutral insofar as it will not react to any large scale field which appears, i.e does not contribute to j.

The analytical solution of these equations is obtained by considering a short enough time scale so that the electron speed varies by only a small fraction of the initial beam speed, hence C_e is constant. Then, since the proton collision time is much longer than the electron collision time, the proton speed can be assumed to remain constant. Then these equations simplify to:-

$$m_e \frac{dv_e}{dt} = -eE - C_e \tag{3.11}$$

$$\frac{dE}{dt} = -\frac{ne}{\epsilon_0}(v_0 - v_e) \tag{3.12}$$

where v_0 is the constant proton speed. We can rewrite these equations to give:-

$$m_e \frac{d^2u}{dt^2} + \frac{ne^2}{\epsilon_0}u = 0 \tag{3.13}$$

where $u = v_p - v_e$. The solution of this is

$$u = \frac{C_e}{\omega m_e} \sin \omega t \tag{3.14}$$

where ω is the angular beam plasma frequency. From this the corresponding electric field can be expressed as

$$E = \frac{C_e}{e}(\cos \omega t - 1) \tag{3.15}$$

It follows that the electrons are fully dragged by the protons due to the mean electric field as stated by Simnett and Haines(1990), whilst oscillating about them with very small amplitudes and angular frequency ω.

The full numerical treatment now follows. The results, showing the oscillatory motion of both species, are displayed graphically.

Again we rewrite equations 3.8,3.9 and 3.10 into that for oscillatory motion to give

$$\left(\frac{m_e}{ne^2}\right)\ddot{v_e} + \left(\frac{C'_e}{ne^2}\right)\dot{v_e} = \frac{1}{\epsilon_0}(v_p - v_e) \tag{3.16}$$

$$\left(\frac{m_p}{ne^2}\right)\ddot{v_p} + \left(\frac{C'_p}{ne^2}\right)\dot{v_p} = \frac{1}{\epsilon_0}(v_e - v_p) \tag{3.17}$$

where $C'_e = \frac{dC_e}{dv_e}$ and $C'_p = \frac{dC_p}{dv_p}$.

The collisional terms C_e and C_p are calculated by considering coulomb collisions in a fully ionized hydrogen plasma. In the case of the electrons, the rate of kinetic energy loss is given by

$$\frac{d\mathcal{E}}{dt} = -\frac{e^4 ln\Lambda v_e n_0}{8\pi\epsilon_0^2\mathcal{E}} \tag{3.18}$$

where $ln\Lambda$ is the coulomb logarithm, and n_0 is the background plasma number density.

Also since $\mathcal{E} = \frac{1}{2}m_e v_e^2$

$$m_e v_e \frac{dv_e}{dt} = -\frac{e^4 ln\Lambda n_0 v_e}{4\pi\epsilon_0^2 m_e v_e^2} \tag{3.19}$$

and

$$C_e = -m_e\frac{dv_e}{dt} = \frac{e^4 ln\Lambda n_0}{4\pi\epsilon_0^2 m_e v_e^2} \tag{3.20}$$

furthermore,

$$C'_e = \frac{dC_e}{dv_e} = -\frac{e^4 ln\Lambda n_0}{2\pi\epsilon_0^2 m_e v_e^3}. \tag{3.21}$$

Similarly for the protons

$$C_p = \frac{e^4 ln\Lambda n_0}{4\pi\epsilon_0^2 m_p v_p^2} \tag{3.22}$$

and

$$C'_p = -\frac{e^4 ln\Lambda n_0}{2\pi\epsilon_0^2 m_p v_p^3} \tag{3.23}$$

Substituting into equations 3.16 and3.17 gives

$$\left(\frac{m_e}{ne^2}\right)\ddot{v_e} - \left(\frac{e^4 ln\Lambda n_0}{2\pi\epsilon_0^2 ne^2 m_e}\right)\frac{\dot{v_e}}{v_e^3} = \frac{1}{\epsilon_0}(v_p - v_e) \tag{3.24}$$

and

$$\left(\frac{m_p}{ne^2}\right)\ddot{v}_p - \left(\frac{e^4 ln\Lambda n_0}{2\pi\epsilon_0^2 ne^2 m_p}\right)\frac{\dot{v}_p}{v_p^3}\frac{m_p}{m_e} = \frac{1}{\epsilon_0}(v_e - v_p). \tag{3.25}$$

If the velocities are measured with respect to the initial velocity v_0, by defining $u_e = \frac{v_e}{v_0}$ and $u_p = \frac{v_p}{v_0}$, then eqns 3.24 and 3.25 become,

$$\left(\frac{m_e}{ne^2}\right)\ddot{u}_e - \frac{e^2 ln\Lambda}{2\pi\epsilon_0^2 m_e v_0^3}\frac{n_0}{n}\frac{\dot{u}_e}{u_e^3} = \frac{1}{\epsilon_0}(u_p - u_e) \tag{3.26}$$

$$\left(\frac{m_p}{ne^2}\right)\ddot{u}_p - \frac{e^2 ln\Lambda}{2\pi\epsilon_0^2 m_p v_0^3}\frac{n_0}{n}\frac{m_p}{m_e}\frac{\dot{u}_e}{u_e^3} = \frac{1}{\epsilon_0}(u_e - u_p). \tag{3.27}$$

Also measuring time in units of the beam plasma period $\tau_{pe} = \left(\frac{4\pi^2\epsilon_0 m_e}{ne^2}\right)^2$, and defining $\tau = \frac{t}{\tau_{pe}}$, we finally obtain,

$$u_e'' = \frac{e^3 ln\Lambda n_0^{\frac{1}{2}}}{\epsilon_0^{\frac{3}{2}} m_e^{\frac{3}{2}} v_0^3}\left(\frac{n_0}{n}^{\frac{1}{2}}\right)\frac{u_e'}{u_e^3} + 4\pi^2(u_p - u_e) \tag{3.28}$$

$$u_p'' = \frac{e^3 ln\Lambda n_0^{\frac{1}{2}}}{\epsilon_0^{\frac{3}{2}} m_e^{\frac{3}{2}} v_0^3}\left(\frac{n_0}{n}^{\frac{1}{2}}\right)\left(\frac{m_e}{m_p}\right)\frac{u_p'}{u_p^3} + 4\pi^2\left(\frac{m_e}{m_p}\right)(u_e - u_p). \tag{3.29}$$

Where u_e', u_p' are the derivatives with respect to τ.

Numerical solution of these two equations is required, as described in the following sections.

3.5.4 Numerical Solutions For Particle Motions

Reducing equations 3.28 and 3.29 to four first order differential equations as follows,

$$u_e' = y_e \tag{3.30}$$

$$u_p' = y_p \tag{3.31}$$

$$y_e' = u_e'' \tag{3.32}$$

$$y_p' = u_p' \tag{3.33}$$

allows the implementation of a Runge-Kutter numerical integration routine with adaptive stepsize, to solve for u_e and u_p. The values of n, n_0 and v_0 are altered in order to adjust the ratio, R, between the collisional drag force and the electrostatic force between the beam electrons and protons.

The results of the numerical integration are shown in figures 3.7-3.10 for a range of initial values of beam and background plasma densities.

It is clear that the initial separation of electrons and protons in the beam is short lived, and in fact both species display oscillatory behaviour at the plasma frequency. The amplitude of the oscillations increases as both species slow down resulting in increased collisional forces, and separation of the electrons and protons.

The effects of altering the ratio between the collisional force of the background gas, and the electrostatic force of the seperated components in the beam is demonstrated.

When the collision timescale $\ll$ the oscillation timescale, negligible separation of the two species occurs. At the other extreme, the collisional drag is so effective that the electrons are stopped before any oscillatory behaviour appears. For ratios in between, the amplitude of the oscillations increases as the ratio decreases (i.e the collisional drag force increases the initial separation of the species).

Note that the integration routine stops before either species reaches zero velocity. This is due to the approximation of a $\frac{1}{v^3}$ dependence of the collisional force, resulting in this term blowing up as the velocities tend to zero. Hence we see the electron velocity drop to $0.2v_0$ before the programme ends. Even including the thermal speeds in the collisional term, so that the collisional drag becomes constant at this velocity, makes little difference. Since this velocity is reached just prior to stopping, the routine stops even before this velocity is reached. This oscillatory motion of the electron component of the neutral beam with the beam plasma period is also seen in the simulations of Karlicky, which deal with the more complex problem of a finite beam, and includes some randomisation of particle speeds.

3.5.5 Edge Effects

The analysis of section 3.5 has shown that no magnetic field arises in the body of the plasma beam when the often ignored displacement current is included. i.e j is entirely matched by $\frac{\partial E}{\partial t}$ with no $\nabla \times B$ or $\nabla \times E$. However, our treatment of this problem is only valid away from the boundary where the injected beam initially enters the azimuthally rotating background gas. We simplified the problem to one of launching electron proton pairs within an infinite background gas, hence we do not consider events at the interface between the rotating torus and the injected plasma beam.

The treatment of this more complex problem is beyond the scope of this thesis. Certainly,

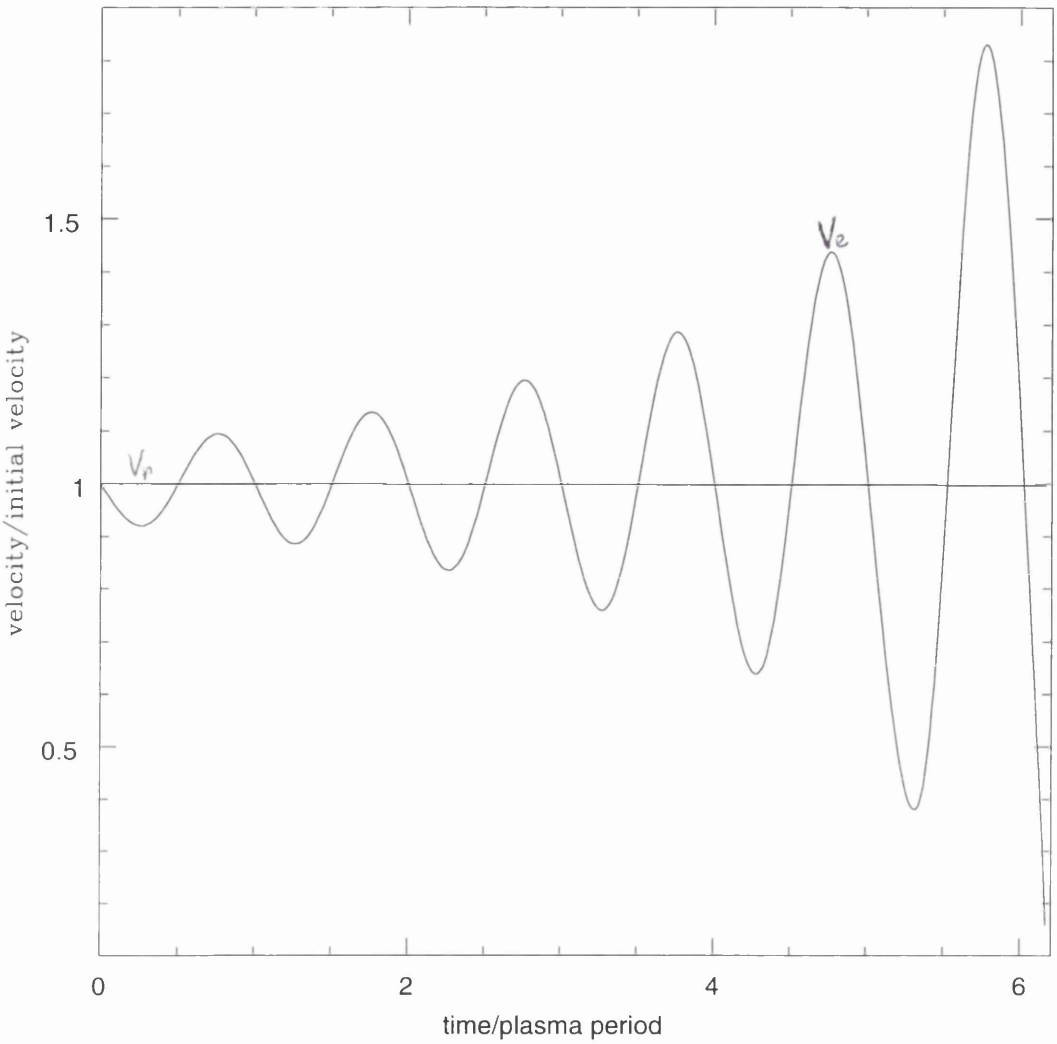

Figure 3.7: Plot of evolution of beam electron and proton velocties for ratio $R \approx 1$

it is not obvious what effect, if any, inclusion of the boundary will have for this problem. We have shown there to be a time varying electric field in the plasma ahead of the boundary, but it would also be necessary to consider the electric field in the beam before the boundary, and to what extent the constituents of the beam here would respond to the varying field. This would determine whether $\nabla \times E$ would be non-zero at the boundary, and hence $\frac{\partial B}{\partial t} \neq 0$. For the application of field generation considered in this chapter there is then a possibility that a magnetic field may grow at the boundary.

Further analysis of this problem is required before we can conclude the validity of the mechanism for magnetic field generation in Galaxies.

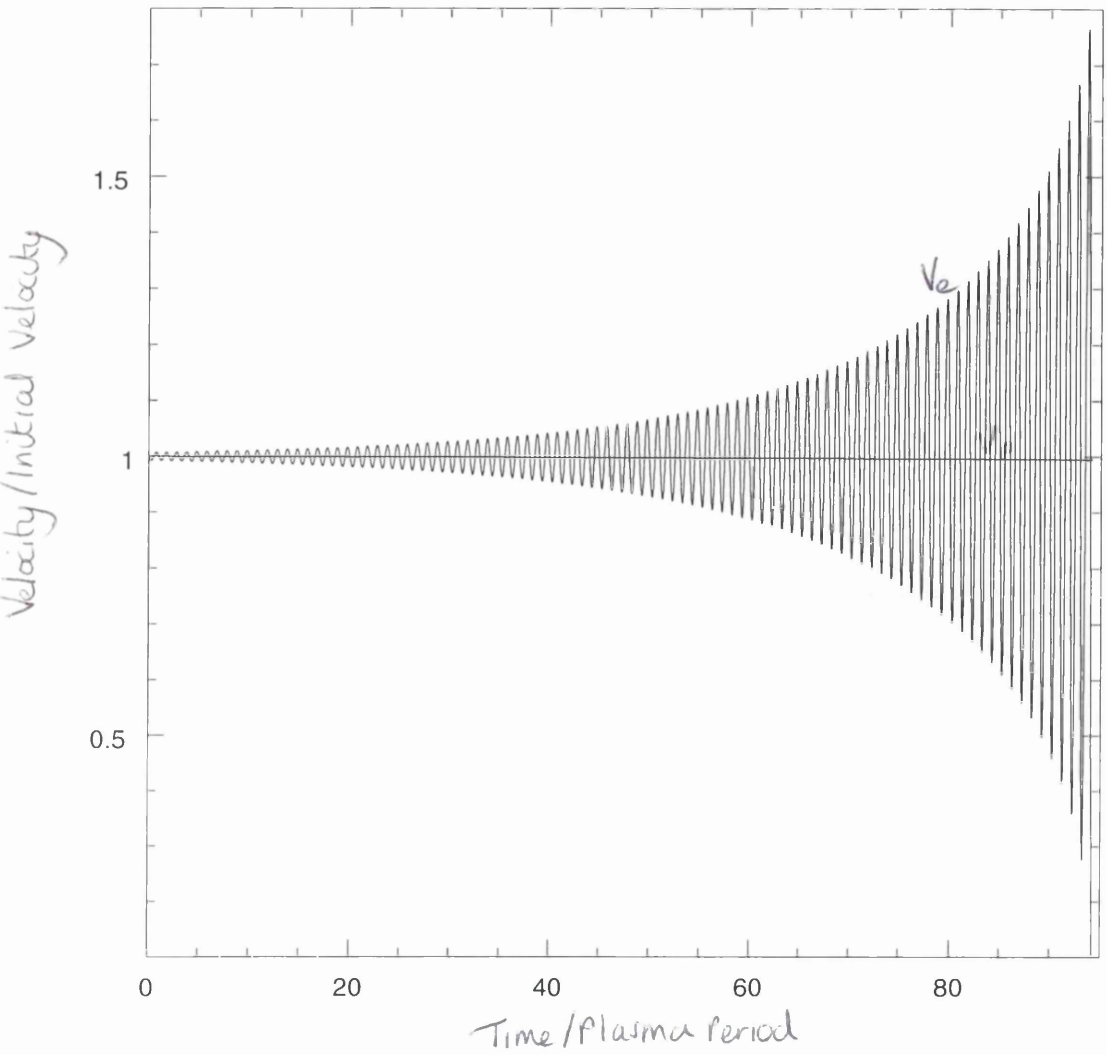

Figure 3.8: Plot of evolution of beam electron and proton velocties for ratio $R \approx 0.1$

3.5.6 Inclusion Of Background Plasma

So far in this analysis all background plasma effects have been excluded for simplicity, by considering the background to be an unionised cold gas. This has confined all electrodynamic effects to the beam, providing a purely collisional background.

Recent work by Karlicky and Brown using electrostatic particle codes, has shown that an ionised background plasma reacts to the electric field produced in the beam, generating neutralising currents. The effect of this is that the electron and proton components of the beam become spatially separated, since the growth of the electric field which effectively ties the two species together in the previous analysis, is neutralised by the background

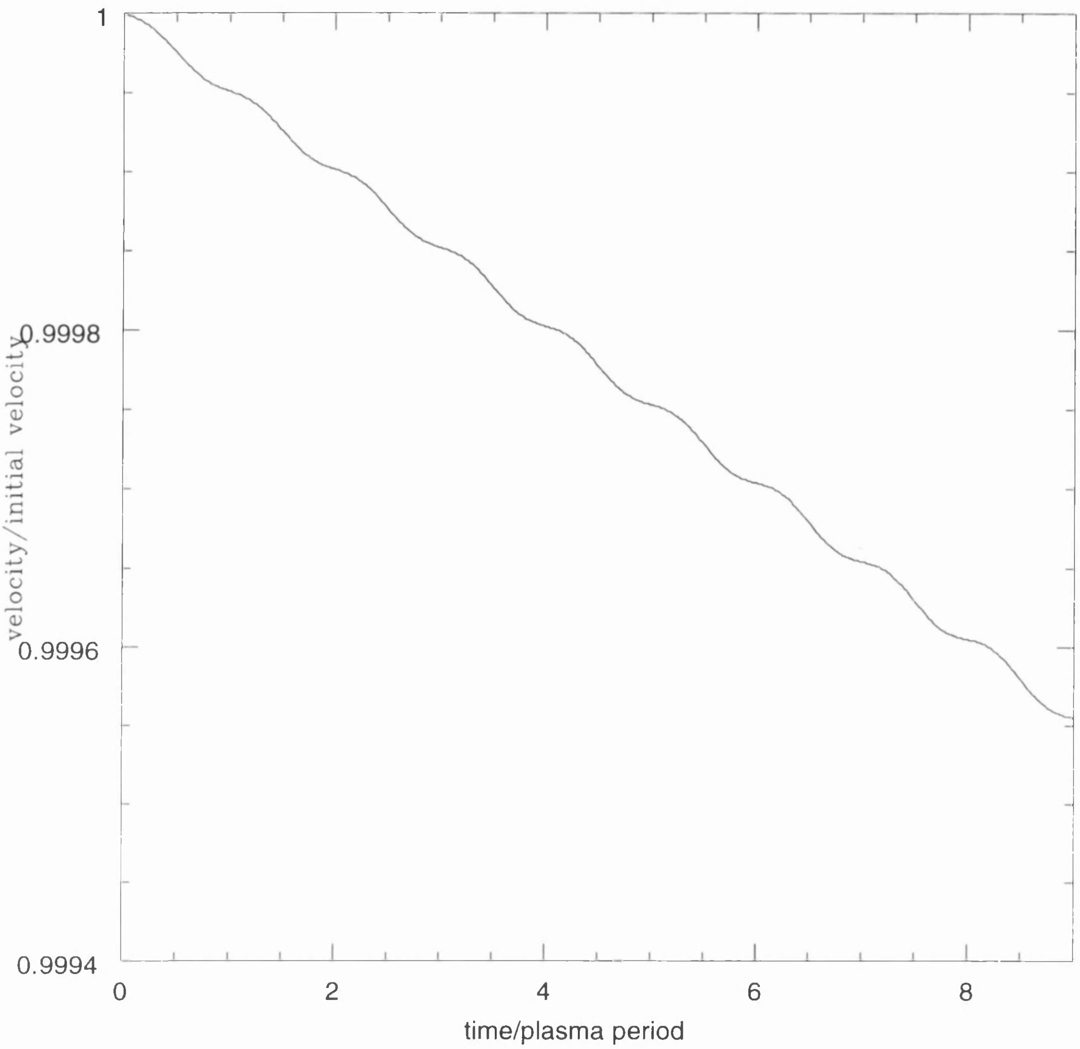

Figure 3.9: Plot of beam proton velocities only for $R \approx 0.01$

current.

As was argued by Simnett and Haines (1990), the effectivenes of the background neutralisation is dependant on the ratio of beam and plasma number densities n_b/n_p. In fact for $n_b/n_p \gg 10^{-3}$ the neutralisation effect becomes insignificant, and the beam propagates as in a cold gas.

In the case of M82 the ionised component of the background plasma has a number density $n_p \sim 10^2 cm^{-3}$ (Kronberg et al., 1985). The number density of the ionised plasma in the gas outflow from the central galactic regions is estimated at $n_b \sim 10^{-3} cm^{-3}$. We then see that in this case the background gas will act to neutralise the fields produced in the

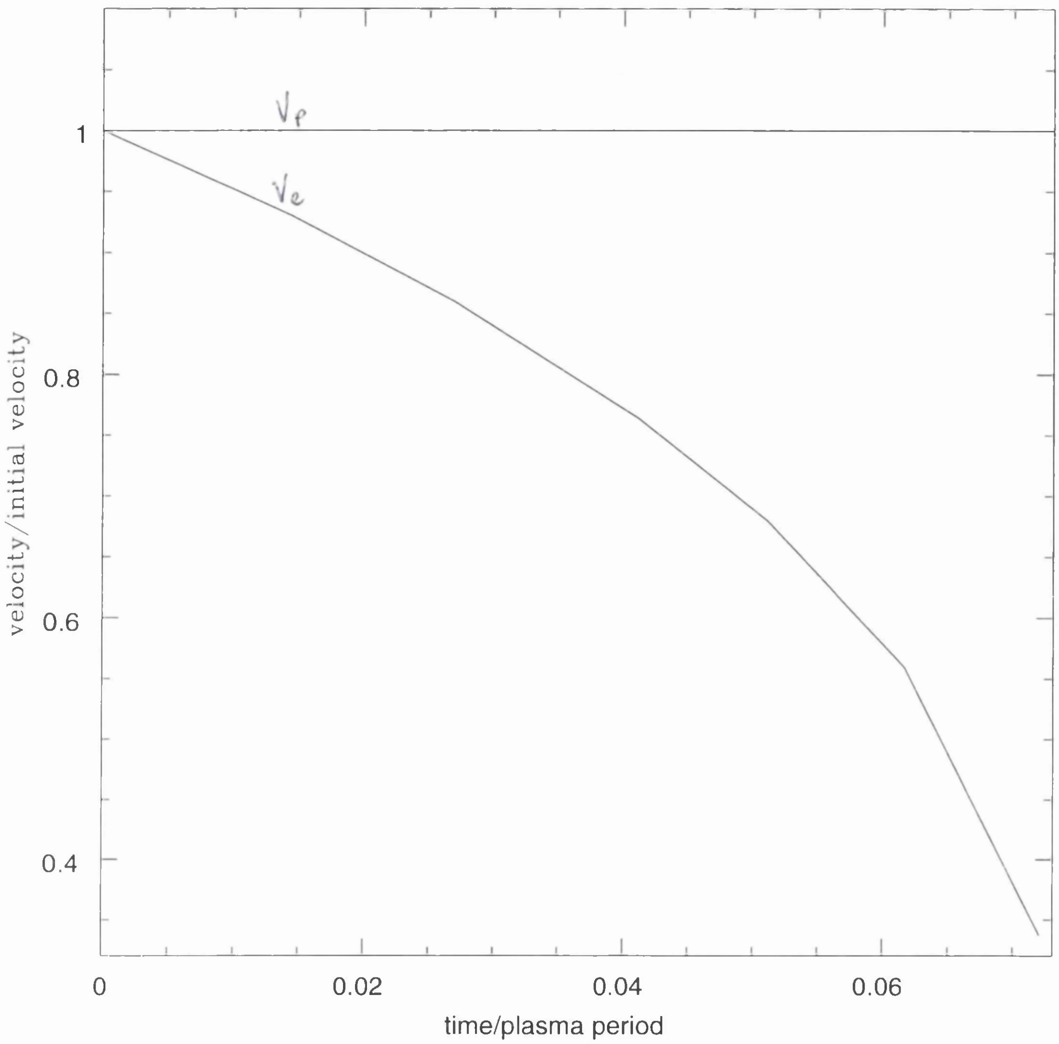

Figure 3.10: Plot of evolution of beam electron and proton velocties for ratio $R \approx 10$

beam, and there is a possibility that the ionised components in the outflow may become spatially seperated. The full analysis of this effect and the fields produced, is beyond the scope of this analysis. However we note that there is a possibility for magnetic field generation in galaxies with a form of the Biermann battery mechanism. This is not due to any space charge density produced by collisions in the background gas as proposed by Lesch et al, but due to electrodynamic effects in the background counteracting the electric field produced by the displacement current in the beam.

3.5.7 Outflow Phenomena

We have considered the possibility of galaxies generating the first magnetic fields of the universe. The mechanism itself is somewhat speculative, and still it must explain the observations of intergalactic and intercluster fields.

Outflow phenomena from galaxies provides one way in which an initial galactic field can be introduced into the surrounding medium. The outflow is generally thought to be associated with stellar winds pushing matter and fields into the galactic halo and beyond.

There is evidence in certain galaxies that this is indeed happening. With synchrotron emitting halos observed in a subset of spiral galaxies, e.g M82 and NGC4631. The field lines in these cases, as mapped by polarisation studies, are directed out of the galactic plane, and the field strengths suggest that a dynamo hasn't sufficient time to generate such fields before the outflow. In the case of M82 in particular, the starburst activity in the central regions, rules out the α^2-dynamo mechanism proposed for 'quiescent' galaxies. It remains an open question however as to whether such outflows alone can account for the observed intergalactic field strengths. Some dynamo may be required in clusters, and some contribution to the field may be made by extraglactic radio jets, although their existence at early epochs is uncertain. However it is clear from observations that outflow phenomena do contribute to the redistribution of magnetic energy in the universe, independantly of the mechanism that originates the galactic fields. Hence they are relevant for all the mechanisms discussed in this chapter.

3.6 Conclusions

This chapter has discussed the research done to date on the evolution of magnetic fields in the universe, from their initial generation to the observed fields today. This area is somewhat speculative, particularly at early epochs due to restrictions on observations at such high redshifts. Usually the approach then is to rely to some extent on the standard cosmological model, in particular Big Bang Nucleosynthesis, to probe the conditions of the early universe. Since the presence of a magnetic field in the pre-recombination universe has been shown to effect particle reaction rates, the universal expansion rate, and the generation of density inhomogeneities, these effects can place limits on magnetic field strengths at early epochs.

Comparing the magnetic field strengths obtained from the various scenarios discussed in this chapter, with the limits set by Cheng et al and Grasso and Rubenstein, we see that a purely primordial magnetic field will effect the early universe as detailed in Chapter 2. If a dynamo mechanism can amplify smaller initial magnetic fields these effects can be avoided however. Although even these smaller fields effect structure formation are discussed in Chapter4. In effect we are attempting to add magnetic fields to the cosmological model without altering the models predictions since they constitute vital proof of the models success. What we have then is an inferred limited initial field, observed galactic, intergalactic, and intercluster fields, and essentially three scenarios for the field evolution inbetween.

We have considered the present state of all three scenarios. This task is not helped by the existing literature, which tends to discuss sections of the field evolution in isolation. For example, the dynamo mechanism is widely discussed and documented, yet the origin of the seed field which is fundamental to the theory is unquestioned in the dynamo context. The result is that the sections don't fit. No primordial generation mechanism is consistent with a purely frozen in field scenario. Only the fields proposed from the Quark-Hadron phase transition can provide fields compatible for dynamo amplification, but these fields are then incompatible with structure formation models.

From a purely theoretical argument, all approaches suffer from inconsistencies. As previously mentioned, recent studies have shown that the dynamo should saturate as a result of the growth of a small-scale field component, before it can produce the coherent scales observed (Vainstein and Rosner 1991). Coherence scales also causes problems for the primordial origin, although the work done by Dimopoulos and Davis (1997), may partly solve this. The inconsistencies in the analysis of the battery mechanism proposed by Lesch et al have also been highlighted here. Although our analysis is somewhat simplified, it is not clear that the mechanism will produce magnetic fields at all. Even if the mechanism is successful, observations suggest that outflow from galaxies cannot account for the intergalactic and intercluster fields alone, and one/both of the other two mechanisms would still be necessary. This would elliminate the only mechanism that does not require a primordial field.

Furthermore, it is worrying that all of the scenarios considered here depend critically on physical parameters that are ill-understood in astrophysical situations. For example the extent of turbulent diffusion is critical for all of the proposed mechanisms, a theory whose application in the astrophysical context is highly speculative. Certainly a more consistent theory of turbulence in astrophysical systems would give a firmer grounding for these theories, and perhaps force the rejection of at least one scenario.

Unfortunately to date there is little direct observational evidence to prove either theory. The future however, holds some possibilities.

It is possible that the structures of galactic fields may allow a decision to be made more definately. The primordial origin predicts a bisymetric field configuration due to differential rotation in the galaxy. In direct contrast, the dynamo generally produces an axisymetric structure. Observations of galactic field structure to date is limited, and cannot at the moment conclusively reject either model. This field structure is best revealed by mapping the synchrotron polaristion, Faraday rotation and Zeeman splitting, which have limited sensitivity. Improved observational capabilities could improve the results of this test.

The observations already mentioned of magnetic fields in QSOs at redshifts of $z \sim 2$, would strain the dynamo model, and tend to favour a primordial origin. However, the statistical significance of the current data on these systems is unsure, and conclusions therefore await more data.

Also Kosowsky and Loeb (1996) have recently proposed a direct empirical probe of primordial magnetic fields. They claim that the microwave background will exhibit a measurable Faraday rotation angle of the direction of polarization in the presence of a magnetic field. This method is detailed in Chapter1, and would effectively determine the presence of any fields in the pre-recombination universe, giving clearer requirements for the seed field generation mechanisms, and perhaps eliminating the need for them at all.

In the meantime, we must be careful to realise the limits of the current field generation models. All have problems, and the good points of each are not assessed by their predictive powers yet, but in how well they tessellate with the standard cosmological model. There is little to be done about this until we can test specific models with improved observational work however. Sugggestions have also been made that the presently observed fields may be the result of a mixture of all/some of these mechanisms. This could indeed solve some of the problems that individual mechanisms have, and satisfactorily leave an enormous spectrum of possible initial and final states for the field. However this doesn't solve any of the theoretical inconsistencies of any model, just consentrates them all in to one large mess!

Chapter 4

Large Scale Structure Formation and Magnetic Fields

4.1 Introduction

Having briefly considered the effects of magnetic fields on the Jeans instability for structure formation in chapter2, and introduced the magnetic Jeans length for gravitational collapse in a magnetised medium. We noted that the mass distribution of structures in the universe could be affected by the presence of magnetic fields, and that measuring the mass distribution of different generation objects could reveal the history of magnetic field strengths in galaxies for example. We now consider the mechanism for generating and evolving intial density perturbations in the early universe, and the role of magnetic fields in this process. In chapter2 we highlighted that one of the effects of magnetic fields on early cosmology would be in forming initial density inhomogeneities that could later be amplified by gravitational clustering. This provides an alternative to the standard mechanism reviewed in chapter1, that is purely gravitational. This could be a positive effect for the standard cosmological model, producing filamented density inhomogeneities which if amplified describes well the distribution of structures observed today. Although we have noted in chapter2 that the field strength for this mechanism is highly restricted in the standard model.

This chapter is intended to consider the evolution of these density inhomogeneities. In particular, large scale filamented structures formed by electromagnetic effects have been proposed by Lerner, Peratt and other plasma scientists. This requires magnetic fields being more significant on larger scales than proposed by the standard cosmological model however. In fact these ideas stem from an entirely different cosmological model proposed by Hannes Alfvén. The details of Alfvén's model will be discussed in Chapter5, however it is interesting at this stage to consider these models of structure formation, and the similarities with those proposed for the early standard cosmological model. The approach is very different in Alfvén's cosmology, and in light of the difficulties highlighted in the previous chapters of the standard models approach to magnetic fields, are an interesting alternative.

4.2 Large Scale Structure In Standard Cosmology

In chapter1 we briefly reviewed the formation of large scale structures in the universe by the growth of quantum generated density perturbations by the gravitational instability, and in chapter2 we considered briefly the correction made to the Jeans instability for gravitational collapse in a magnetised medium. In chapter3 we considered the influence of magnetic fields in the pre-recombination epoch. The result of Battaner et al (1997) showed that magnetic fields could induce perturbations in the density field at early epochs and therefore influence the generation and evolution of structures in this epoch.

The mechanism proposed by Battaner et al assumes the presence of magnetic fields in the radiation dominated epoch, more specifically in the post annihilation and pre-recombination epoch. This assumes the primordial field generation mechanisms reviewed in chapter3, although the strength of the field is not assumed initially. Essentially the analysis focuses on the contribution of the magnetic energy density to the overall energy density of the universe. Whilst it is thought that this will have little effect on the overall expansion of the universe, the internal motions of the universe are shown to be affected. A magnetic field strength at nucleosynthesis of $\sim 10^9 G$ would in the radiation dominated era,(assuming the frozen in condition) be sufficient to perturb the metric and generate photon inhomegeneities. Not only will random magnetic fields generate perturbations in the photon energy density in this epoch, they are shown to influence the perturbations after their generation. In particular the magnetic field vector highlights a preferred direction, and this can lead to anisotropic evolution of the perturbations. The initial pattern of the magnetic field will determine the nature of the perturbations also, and this magnetic pattern will be preserved today, although diluted by the expansion. This does assume no dissipation or amplification of the magnetic field. In particular Battaner and Florido (1997) have considered the initial magnetic configuration to be a flux tube, and have shown that the resultant inhomogeneities are filamentary in shape. The evolution of these radiative filaments after radiation domination is estimated to be linear and unaffected by dissipation effects for large scale structures ($\geq$10Mpc), and could therefore be identified with matter filaments observed today. However the evolution is thought to become non-linear for smaller scales (c.f structure formation by gravitational instability, section 1.4.1). This means that large scale matter filamentary structures can be associated directly with the initial magnetic field configuration in this scenario, whereas smaller scale structures may not mimic the initial magnetic field pattern entirely. These results are intersting in light of the observations of large scale filamentary structures in the universe.

The evolution of structure in the presence of magnetic fields has been studied in the post recombination era by Coles(1992), and Kim et al (1996). The matter dominated era brings additional complications, which produce the non-linear evolution of perturbations. Kim et al have considered magnetic fields to be one such complication that is usually omitted from the analysis of structure evolution, and analysed the influence of magnetic fields on structure formation in the non-linear regime. They conclude that magnetic fields can influence the generation of structures on scales of galaxies and clusters, but that the spectrum of the perturbations does not fit well with that observed. This is assuming however that the perturbations were generated only after recombination.

Peratt(1988) has also considered the effect of magnetic fields in the post-recombination epoch. His analysis looks at the evolution of large scale structures due to large scale magnetic flux tubes. Whilst this is similar, if on larger scales, to the ideas introduced by Battaner et al (1997), it differs in that it does not attempt to be consistent with the standard cosmological model. In fact this scenario for structure formation is based on the cosmology of Alfvén, which is detailed in Chapter5. Rather than attempting maintain the minimum significance of magnetic fields possible on large scales, Peratt's approach is to assume magnetic fields are significant on all scales and postulate the structures formed, as described in the following section.

4.3 Large Scale Structure from Large Scale magnetic Fields

The analysis of Peratt are based on extrapolation from laboratory observations and on numerical simulations of plasma filaments. This approach has its origin in Alfvén's cosmology.

Initially magnetic fields are considered to be significant on large scales which is in direct contrast to the assumptions of the standard model of cosmology. This however does not necessarily clash with observations, since this does not require the magnetic energy density to be very large nor that the average magnetic field be non-zero. Only that the distribution of magnetic fields in the universe is non uniform, and that magnetic fields form force free configurations randomly oriented on large scales and the intermittent regions (voids) have a very low/zero magnetic field. Essentially this is also proposed by Battaner et al (1997), who argue that magnetic field loops could form the large scale pattern of magnetic fields which will be observed as filamented field structures in isolated regions and still allow the average magnetic field to be zero on large scales.

Peratt's analysis does not describe the generation of the initial density perturbations, nor the evolution of these perturbations in the early universe. The focus is specifically on galaxy formation and the resultant alignment of galaxy clusters along filaments. This is the fundamental difference of the approach, is that the large scale magnetic fields are assumed to be present on scales of galactic clusters before any glaxies have formed. Clearly this is not consistent with the standard cosmological model. We note also that Alfvén's cosmological model cannot provide a consistent framework for these ideas either (see chapter5). The results of the simulations are described in the next section.

4.3.1 Galaxy Formation

Peratt et al (1980) proposed that galaxies could be form when two plasma filaments merged. Peratt had been one of Alfvén's graduate students and was well aware of Alfvén's theories of the importance of filamentary currents in the universe. He had also been observing the behaviour of plasma in a large pulsed-power generator, and found that plasma filaments formed and tended to move towards each another. They then merged into a spiral structure from which a burst of X-rays emanated, similar to small scale spiral galaxies. This was further studied using 3-D particle in cell computer simulations by Peratt and Green(1983). The simulations involved two force-free plasma filaments, with the gravitational force omitted for simplicity. The filaments were found to move slowly towards each other, then to rotate and stretch the plasma, creating a perfect spiral galaxy form, at the point of the merger . Also, by varying the distance between the filaments, different classes of 'galaxy' could be seen at various stages in the simulation. Figure 4.1

shows the results of these simulations.

The interaction of the filaments can be understood by considering the attraction between

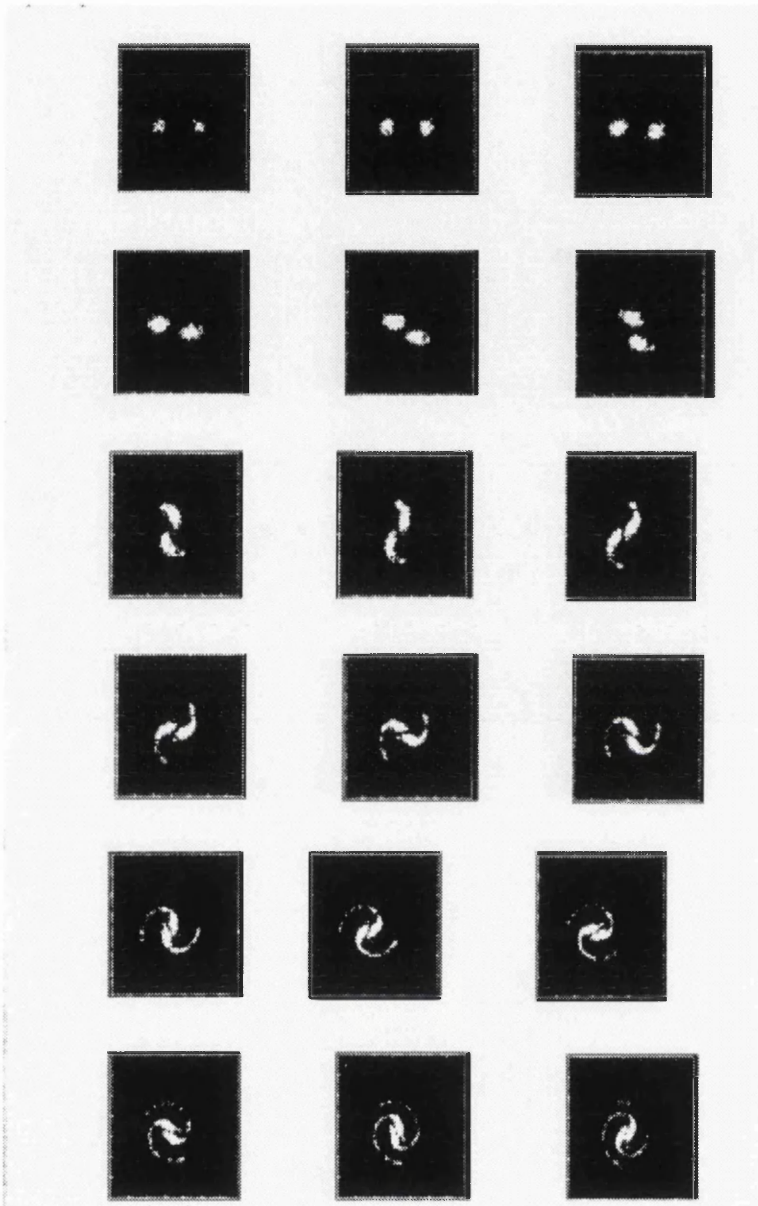

Figure 4.1: Computer simulation of the electromagnmetic interactions of plasma filaments in space (the cross section is shown here). From Lerner, 1991.

currents flowing in the same direction. The two filaments have an axial current flowing parallel to the external magnetic field, which produces a long range attractive force between them, causing the filaments to move towards each other. There is also a radial component of current which produces a short range repulsive force, causing the converging filaments to move obliquely, rotating around each other and forming one large twisted filament

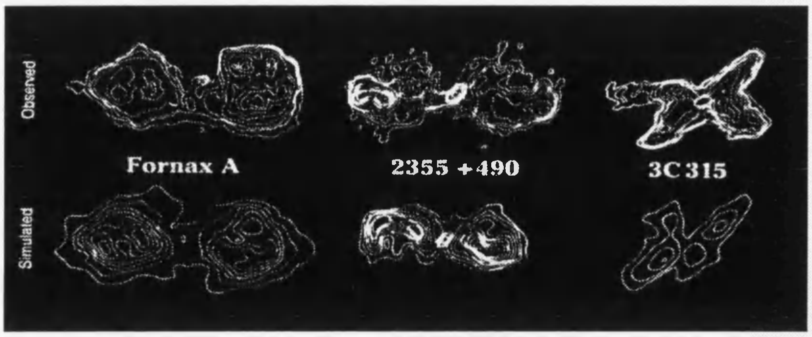

Figure 4.2: Brightness maps of observed double radio sources are shown on top row. Below are the results of one computer simulation of two interacting galaxy-sized plasma filaments. Time increases towards the right plot. The similarities of the observed plots and those simulated suggest that apparently unrelated radio galaxies could be showing different stages in the development of one process. From Peratt, 1992.

when the forces reach equilibrium. Taking a cross section through the merging filaments, the plasma moving through the background magnetic field merges also to form one single rotating object. The oblique motion of the filament causes the plasmoid to rotate and to stretch. The object is observed in these simulations to take on the same structure as that of spiral galaxies. By scaling up the parameters of the simulation to filaments $\sim 10^8$ LY long, galaxy scale objects were found to occur. The central regions of these objects were observed to emit radio waves, due to synchrotron emision from electrons in the strong central magnetic field. Also the magnetic pressure causes some fragmentation of the central region, which flows out along the rotation axis in both directions. Such 'jets' are characteristic of active galactic nuclei and quasars. Some characteristics of double radio sources can also be seen in the simulations at earlier stages of the filaments collision (see fig 4.2 and fig 4.3). The simulations have also produced flat rotation curves for galaxies shown in fig 4.4. This is explained by Lerner (1991). The spiral arms are large filaments radiating from the galaxies core. Since these arms are magnetic structures the rotation velocity will be equal along its entire length, and these filaments are found in the simulations to roll as they rotate around the galactic centre.

The simulations also showed that once the galactic structure had formed, the rotation induced currents to flow in opposing directions along the 'spiral arms', pinching the plasma into smaller scale filaments. This leads naturally to Alfvéns original theory of solar system formation from density perturbations caused by electromagnetic fields (Alfvén, 1981).

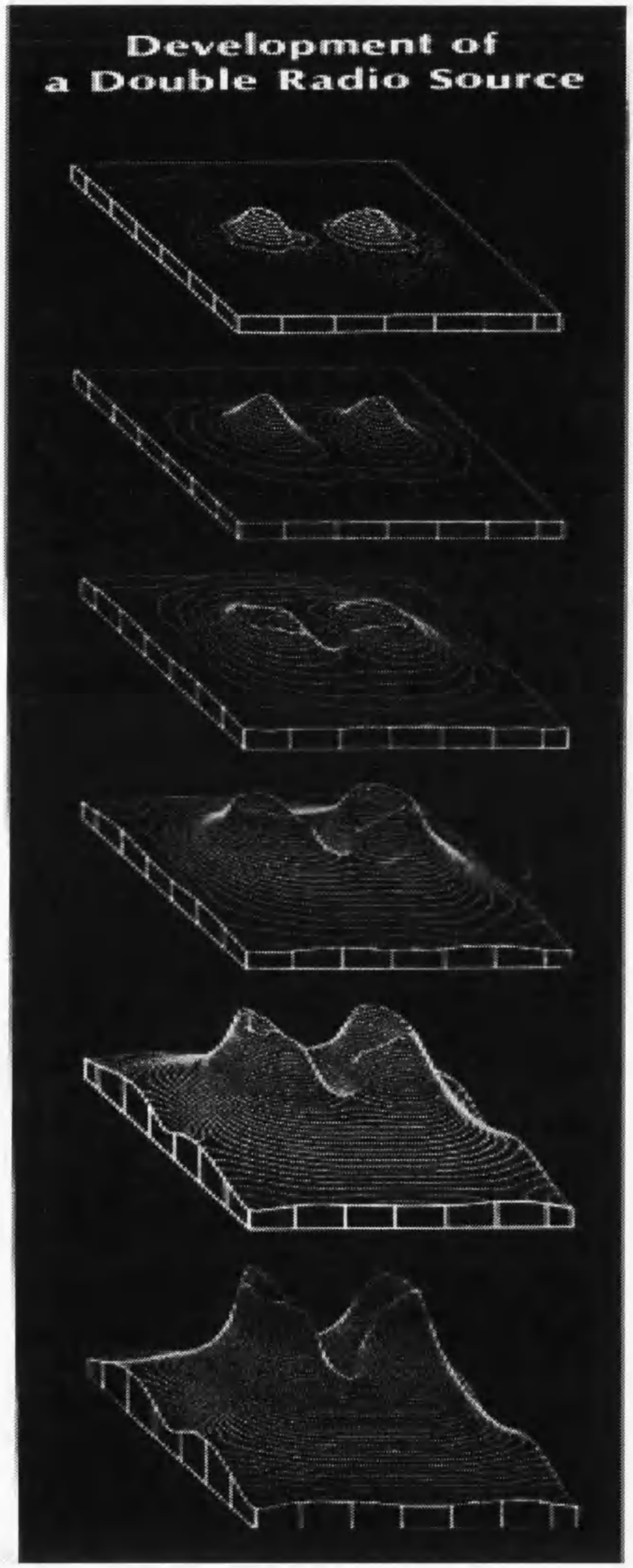

Figure 4.3: Computer simulation showing the development of the magnetic field configuration in two interacting plasma filaments. The base of each plot is the plane of the sky; and the higher contours indicate stronger fields. Time increases downwards. From Peratt, 1983.

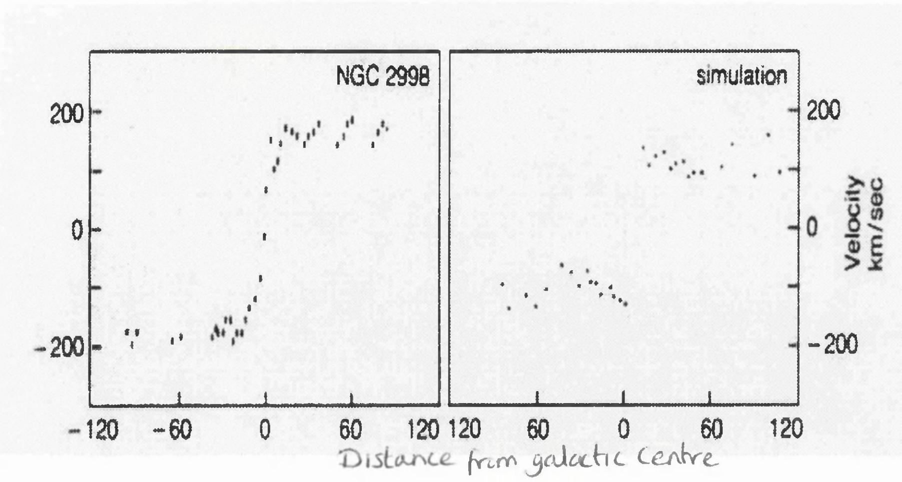

Figure 4.4: Comparison of the observed flat galactic rotation curve of NGC 2998, with computer simulations produced by Peratt, 1992. The simulation shows the rotation curve of a galaxy formed by electromagnetic interaction of plama filaments. The rolling motion of the spiral arms around the galactic centre are thought to produce the detail in the plots. From Lerner, 1991.

On larger scales still, this model also predicts that since galaxies form when two filaments collide, that galaxies should be found to cluster along filaments. This is precisely what is observed as discussed in chapter 1.

4.4 Conclusions

Magnetic fields have been shown to influence and perhaps generate initial density perturbations in the pre-recombination era of the standard cosmological model. The strength of the magnetic field is required to be $\sim 10^9$G at nucleosynthesis for this effect to be significant. The generation mechanisms for primordial magnetic fields, as detailed in Chapter3, produce fields at nucleosynthesis much lower than this value, except for the mechanism at the quark-hadron phase transition, which can generate fields of this order. Concluding that the influence of magnetic fields is then insignificant for all but one of these mecanisms is not instructive, since the mechanisms themselves are inconsistent with observed magnetic fields today, even with dynamo amplification. It is clearer to compare this magnetic field value with the necessary values required for both magnetic field evolution scenarios of primordial origin, and dynamo amplification of a primordial field. If the observed field is purely primordial the effect of magnetic fields on structure will be very significant, since a field $\sim 10^{11}$G is necessary at nucleosynthesis, but for dynamo amplification this effect can be avoided since lower field strengths are allowed in the early universe (see Chapter

2). Of course for the case of the Battery mechanism also discussed, no primordial field is necessary.

It is however difficult to reach meaningful conclusions since the strength of magnetic fields at early epochs is so speculative, and the mechanisms for generating these fields and the subsequent evolution of the fields are so inconsistent. However, the observations of filamentary and sheet structures are clear, extendng to scales >100Mpc. Magnetic fields associated with filamentary structures have been detected from radio emission by electrons in magnetic fields. Filaments in radio sources are common. These models then provide a natural explanation of these observations. Battaner et al calculate strict limitations on the magnetic field strength allowed, and conclude very little devation from $10^{-8}G$. Battaner et al have shown that generation of density perturbations by magntic fields can provide an interesting alternative to the quantum generated perturbations of inflation, and could at least aid gravitational clustering in the evolution of these perturbations to form large scale structures.

The results of Peratts simulations are interesting, particularly the prediction of Peratt and Green's simulation, of magnetic filaments and high powered jets emerging from the central galactic regions, precisely as observed in quasars and active galactic nuclei. For larger scale structure, it is a natural consequence of the magnetic field generation mechanism proposed by Peratt et al that galaxies should cluster long filaments and sheets as observed. The model assumes the existence of large scale magnetic fields before structure formation though, which is not consistent with the standard cosmological model, even with magnetic fields being significant at early times. Alfvén's cosmology does not have a beginning in time, and so the 'chicken and egg' problem does not arise in this model. Still, as we conclude in chapter5, the model avoids discussing the origin of the magnetic fields, or their evolution to large scales, and finally this provides it's own problems.

Chapter 5

Alfvén's Cosmology

So far in this thesis we have considered the possible influence of magnetic fields on the standard cosmological model of the universe. Based on the observations of magnetic fields on increasingly large scales, we have considered the possible generation mechanisms of these observed fields, and the difficulty of incorporating these fields into the cosmological model. We have noted that on cosmological scales, electromagnetic effects are often given little significance, mainly due to the relatively small energy density of magnetic fields in the universe, and the mathematical complexity caused by their inclusion (Chapter 2). However, as the importance of electromagnetic fields becomes more apparent on larger scales, it is interesting to consider the work done by a small group of plasma scientists who believe that the electromagnetic force is important on galactic scales and larger.

In this chapter we introduce an alternative view of the universe, in which the electromagnetic force is given much greater significance. This approach was pioneered by Prof Hannes Alfvén in the 1960's. In collaboration with Oscar Klein, he formulated a cosmological model describing a universe continuously evolving, with no beginning or end in time. The basis of this model and the motivation behind it stems from Alfvén's belief that plasma processes are important on all scales in the universe.

Having already discussed the recent developments within this model made by Peratt concerning large scale structure formation, we look at Alfvén's cosmology, and the postulates behind it which are the basis of Peratt's approach. We consider briefly the recent developments by Lerner, who has proposed an alternative exlanation for the CBR. The consequences for the standard cosmological model are discussed, and the inconsistencies of the model.

5.1 Alfvens Postulates Reviewed

The basic hypotheses of Alfvén's plasma cosmology are that the universe is continuously evolving, with no beginning or end in time, and that plasma processes are important on all scales in the universe.

Both of these postulates stem from Alfvén's methodology of observing and extrapolating laboratory plasma physics to larger scales. He has argued that observations of plasma behaviour in the laboratory, and in regions of space available to measurement, must be assumed to be representative of regions outwith observational reach - essentially the perfect cosmological principle. Otherwise our model of the universe becomes divided into two regions with different physical laws. This is of course an important, if not obvious, basis for any scientific theory, especially in such a speculative field as cosmology. For Alfven, this led to the idea that the universe has a cellular structure.

The behaviour of plasma in the laboratory, has been observed to have direct analogies in our observable region of space. Birkland (1896) essentially modelled the earth's auroral system with his famous terrella experiment which demonstrates the effect of immersing a magnetized body in plasma. An electron beam was fired at a magnetised metal sphere painted with a phosphor. In line with Birkland's ideas, and the now accepted theory of the aurora, the electrons in the beam followed the magnetic field of the sphere, and hit the sphere at its poles. The phosphor was observed to glow at the same latitudes as the real aurora on earth.

The pinching of plasma into filaments, observed in fusion experiments, can be seen in solar prominences, spicules, plumes and streamers. Also, filamentary structure is observed in the aurora, the ionosphere of Venus, cometary tails, and in the interstellar medium and clouds. On still larger scales there is well established observational evidence to suggest that filamentation is observed in larger scale structures (Oort, 1983; review by Einasto, 1992). This structure is associated with magnetic field aligned currents. These form force-free filaments in which the plasma itself is pinched together by the magnetic fields and the current flowing in the plasma is concentrated in vortices. This behaviour creates inhomogeneity in the plasma density, and plays a major role in Alfvén's cosmological model. As Alfvén extrapolates these ideas outwards in space, he concludes that space should exhibit a filamentary structure on large scales and hence plasma naturally enhances the density of matter in some regions at the expense of the regions surrounding the filaments. This essentially is also Peratts motivation for postulating large scale magnetic filaments, and their significant effect on structure formation.

Plasma is also seen to form discontinuous interfaces between regions of plasma with different physical parameters. Rather than a continuous spatial variation of temperature, density, magnetization, chemical composition etc, plasma moves to set up boundaries between regions with different physical properties. This phenomena is clearly seen in the earths magnetosphere. The magnetopause is a current layer, $\sim$ few cyclotron radii thick, separating regions of opposite magnetic field orientation. Similar current sheets have also been observed in the magnetoshere of Jupiter and Venus, on the sun, and in cometary tails. Large scale sheets have also been observed (Einasto, 1992). Observation of such interfaces is difficult for regions outwith spacecraft measurement however, because they are too thin to be spatially resolved. The conclusion when we extrapolate outwards is that space everywhere should exhibit a cellular structure.

Further, Alfven proposed that the localised release of energy observed in circuits on earth when a sudden drop in current occurs, could explain explosive events in the cosmos. Of course the generally accepted formalism for the description of plasma phenomena in space, is to describe the magnetic field configuration as opposed to a current description. This is the most natural presentation because of the difficulty of making direct measurements of electric currents, as noted in chapter 1. The mistreatment of boundary conditions pointed out in Chapter 1, is easier to avoid in the current description advocated by Alfvén, as in a non curl free plasma the properties of the whole circuit in which the current closes are also considered. Within the current description Alfven demonstrates the transfer of energy from one region of space to another, and explosive events occuring when a break in the circuit causes a drop in current (Alfvén, 1981). He has proposed that in this way solar flares may be described in terms of the current description rather than magnetic reconnection.

In short, Alfven applied the plasma behaviour observed in the laboratory, and in our solar system to cosmological scales. His conclusion is that space everywhere must exhibit a cellular structure, where regions of differing physical parameters are separated by current sheets. He proposes that most of space is filled with 'Passive' plasma, associated with only weak fields, and transient currents. These regions will be interspersed with and separated by 'active' plasma, where filaments and current sheets form, and explosive events occur

Since Alfven suggested these ideas there have been further observation in support of this picture. Filamentary structures have been observed on scales of $\sim 100LY$ by Farhad Yusef-Zadeh eta l (1984), also on larger scales by Gellar and Huchra (1989), and Tully (1986). Alfvén's second postulate that the universe is continuously evolving, with no beginning or end in time is not clearly reasoned. Following his methodology of extrapolating from everyday science, he argues that nowhere do we observe something created from nothing, and hence we should not consider this as a possibility for the universe. A similar philosophical stance is taken by Hoyle and Narlikar (though without magnetic effects).

5.2 The Model

We have overviewed the standard cosmological model in chapter1, and Alfvén's cosmology clearly differs in both approach to the subject, and the model itself. Alfvén's universe is governed by gravity and the electromagnetic force on every scale. Structure in the universe is formed primarily by electromagnetic forces. Alfvén's model is inhomogeneous on large scales, in direct contrast to the smooth homogeneous distribution of matter on large scales, advocated by the standard cosmological model. On smaller scales Alfvèn proposed that formation of the solar system, stars, galaxies and quasars are governed by electromagnetic forces also (Alfvén (1981)). Rather than trying to incorporate these ideas into the standard cosmological model, Alfven then continued from this point to develop an entirely new cosmological model. His motivation is somewhat unclear from the literature, although his frustration with the Big Bang model is clear! He argues that continuous additions to the standard model of new physical theories far from application to our local world of experience, in order to explain away the new problems that arise from new observations, comes somewhere near to the epicycles of Ptolemy!

The cosmological model brings together Alfvén's ideas already discussed, with a model proposed by Oscar Klein in the 50's to explain the Hubble expansion of the universe. In 1962 a collaboration between the two scientists produced a model of the universe governed by the electromagnetic force, with no beginning in time, and consisting of a very tenuous mixture of matter and antimatter (alfvén and Klein 1962). The density of the universe is taken to be the density of visible matter ($\sim 0.1\Omega$). Our observable part of this universe is named the Metagalaxy, and this, along with presumably other matagalaxies, is contracting under gravity.

Since Alfvén's scientific approach is of explaining individual observations primarily, and then piecing together to gain a bigger picture, the literature/model is somewhat stochastic. However, this is one of Alfvéns primary criticisms of the standard model, that it tries to prescribe a complete model of the universe first and then alters the parameters to fit observation.

The details of Alfvén and Klein's model, in as complete form as the literature allows, and discussion of recent developments follows. Clearly the global structure of the universe is an important factor, but the observational results as discussed in Chapter 1, are still inconclusive.

5.2.1 Antimatter

Antimatter is introduced into Alfvén's cosmological model in order to explain the observed expansion of the universe. Here we describe the method proposed by Alfvén and Klein to initially separate matter and antimatter, followed by the annihilation explosion (Alfvén and Klein, 1962). A number of problems with the model are noted, and the observational consequences of antimatter in the universe are considered briefly in section 5.4. Little research continues on this part of the Alfvén Klein model, and it is generally accepted that the mechanism cannot explain sufficiently the Hubble expansion. However, recent observations in our galaxy have revealed the presence of antimatter extending more than 3000LY from the centre of our galaxy, and perpendicular to the galactic plane (Chown, 1997). The consequences of these recent observations on the Alfvén Klein model are considered here. Although these observations could lend support to the alfvén Klein model, they do not help to overcome the problems which are summarised in this section.

The process of separating the initial mixture of matter and antimatter begins with some gravitational clustering of matter which creates a gravitational field. The model proposes that sufficiently frequent collisions between particles in the mixture can equalise the energies of all the particles. Then the gravitational field will differentiate the mixture by mass. If a magnetic field is present parallel to the motion of particles in the gravitational field, then electrons and protons travelling in opposite directions in the gravitational field will move in the same direction in the magnetic field. Similarly, the positrons and antiprotons moving in opposing directions in the gravitational field will move in the same direction

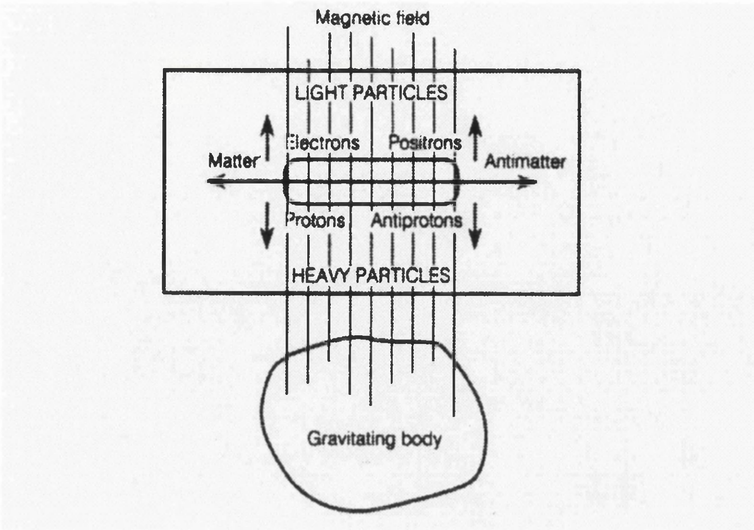

Figure 5.1: Diagram illustrating Alfvén's proposed mechanism for matter antimatter separation in the matagalaxy. The motion of the constituent particles in the gravitational field, and the background magnetic field results in the overall motion in opposing directions of matter and antimatter. From Lerner, 1991.

in the magnetic field. This mechanism is illustrated in fig 5.1, and results in matter and antmatter separation.

There are however a number of confusing points about this argument:

1. The origin of the initial density perturbation is not discussed. The universe in Alfvén's model is highly inhomogeneous, but this is due to the formation of plasma filaments and sheets. These are thought to form in regions of matter or antimatter, but they're formation in a mixture of matter and antimatter is not discussed. If such structures formed in this mixture, the annihilation rate would increase in the denser regions, and the overall motion of the constituent particles could be disrupted.

2. The model deals with protons and electrons and their antiparticles, and relies on these moving in opposite directions in the magnetic field. Alfvén and Klein propose that the electrons and positrons rise and the other particles fall in the gravitational field due to the different masses of the particles. However it is not clear why this motion in opposite directions should occur. If the matter antimatter mixture is attracted towards a higher density region, then all particles will move in the same direction, towards the dense region. In the case when collisional effects slow down the lighter particles more efficiently than the heavier particles, as proposed here, then separation by mass may occur. But all

particles in the mixture 'fall' into the denser region. This motion would not cause the desired separation of mater and antimatter in the magnetic field.

3. The origin of the magnetic field essential to this mechanism is not dealt with at any time. The initial separation of the mixture by the gravitational field relies on the two separating parts being electrically neutral, otherwise the electrostatic force would prevent separation. Hence the magnetic field cannot originate from the initial motions of charges in the gravitational field. We find in fact, that the question of origin of magnetic fields in Alfvén's cosmological model is not clearly answered. The mechanisms discussed in chapter3 for magnetic field generation in the early universe, within the standard cosmological model, do not apply in this model, since there is no early, hot, dense phase in the evolution of alfvén's model. Also the generation of magnetic fields in galaxies, and in dynamo mechanisms leaves us with a 'chicken and egg' situation! However, since Alfén's cosmology, has no beginning in time, we are not limited to a particular timescale. The question remains as to whether in an unlimited timescale a large scale coherent magnetic field can permeate a mixture of matter and antimatter.

4. The rate of annihilation of the matter, antimatter mixture is not discussed quantitatively. Although this cosmological model is based on a very low density universe ($\Omega \sim \Omega_{visible}$), the velocities of the particles in the mixture will increase as they move in the gravitational and magnetic fields, and the density of the mixture will increase. This will effectively increase the collisional rate between particles, ans hence the annihilation rate will increase also. Even in the case where a fraction of the initial mixture survives the annihilation, the motions of these particles will be far from the unidirectional flow necessary for the separation mechanism proposed here.

Aside from these problems, we continue with Alfén and Klein's model. Once the matter and antimatter are seperated, they are proposed to remain seperated by a hot plasma layer that forms at the interface between the matter and antimmater regions. This mechanism is similar to the formation of a thin layer of water vapour at the interface between a water droplet and a hot surface at a temperature above the boiling point of water. This layer, referred to as a Leidenfrost layer, isolates the two components and allows the water droplet to survive evaporation for several minutes. In this way, annihilation at the interface between regions of matter and antimatter produces a layer of high energy electrons and positrons, (Alfvén and Klein, 1961). A pressure gradient in the boundary layer is balanced by the magnetic force which tends to push the two regions apart (if the magnetic field is assumed to be parallel to the interface). On reaching a quasisteady balance the rate of annihilation is greatly reduced, and Rogers and Thompson (1982) calculated that such layers would form on a relatively short timescale ($\sim$ 10 years). Lehnert (1977) established that these layers need only be 10^8m thick. The sizes of the cells is not clearly stated by Alfvén, although it is suggested that galaxies may contain both matter and antimatter regions.

The idea of matter and antimatter coexisting in the universe again emphasises the idea of a cellular structure of space. Space is then separated into regions of matter and antimatter by Leidenfrost layers, and these seperate regions are also divided into areas of differing physical parameters by current sheets and filaments.

5.2.2 Hubble Expansion

Alfvén has suggested that at earlier times our metagalaxy contained regions of matter separated from regions of antimatter by stable Leidenfrost layers. However, as the metagalaxy continues to contract under gravity, the seperated regions are compressed together. High energy particles, electrons and positrons, in the layer absorb a higher fraction of the annihilation energy, due to the relative inefficiency of heat transfer by coulomb collisions in the hot plasma. The plasma pressure of the high energy particles increases at a faster rate than the magnetic pressure in the layer, and once the quasisteady balance between the two pressures is disturbed, the layer disrupts, and the matter and antimatter regions become mixed. Lehnert (1987) calculated the ratio between the plasma pressure and the magnetic field pressures in the layer, and the limit of this ratio for disruption of the layer. He found that for disruption to occur, the energy density in the magnetic field must increase at a lower rate than the matter density. This is the case for a frozen in magnetic field, as $B^2 \sim 1/r^4$ and $n \sim 1/r^3$. The energy released in the annihilation causes an explosion of the two regions. In this way, the model attributes the observed expansion of the universe to an explosion of matter and antimatter in metagalaxies. Another possible mechanism, which may disrupt the layers even before the equilibrium condition described above, is violated, could be turbulence in the separated regions of plasma. However, Lerner (1991), has raised a number of objections to this and the overall mechanism (see later). A number of detailed models of this explosion were proposed by Alfvén and Klein, (1962), and later developed by Laurent et al (1987) and Laurent and Carlqvist (1990). All find that one such explosion cannot account for the observed redshifts of todays universe. In fact several explosions are required to accelerate matter in stages, to eventually reach velocities of a significant fraction of the speed of light. This model was first presented as a simple Newtonian model in the original paper by Alfvén and Klein (1962), and Laurent et al have extended this to a relativistic treatment, and the model was named the 'fireworks' model. Alfvén (1983) suggested that this multistage acceleration could occur, if successive fragmentation of increasingly smaller fragments of the metagalaxy occured. Alternatively, annihilation of the metagalaxy could occur successively in shells, starting from the inner regions around the layer. The result would be a hierarchy of structures (Alfvén, 1983), and an observed motion of these structures away from each other. Still, Lehnert (1994) found that this model cannot produce the observed high recession velocities of objects in the universe, and it is not clear as to why we would not equally observe blue shifts. A number of further problems exist with the model. Lerner (1991) has pointed out in particular, that no structure would be preserved in such an explosion. The energy released in such an explosion would tend to blow structures apart, and certainly not preserve the hierarchical structure that Alfvén suggests. More seriously, the rate at which this energy is released would blow the metagalaxy completely apart before producing any considerable expansion.

It thus seems that antimatter alone cannot provide an explanation for the expansion of the universe, and without it, Alfvén's cosmological model is not complete. However, the recent work done by Peratt et al (see chapter4), developing the filamentary, cellular structure of space idea has shown some interesting results. We will discuss Peratts structure formation scenario within Alfén's cosmological model, and other developments within this model in the following section.

5.3 Modern Developments Of Plasma Cosmology

Developments recently in plasma cosmology have centred around Alfvéns posulate that space should exhibit a cellular structure. A small number of plasma scientists have extrapolated the observations of plasma filamentation in laboratory fusion plasmas to larger

and larger scales, to postulate a highly inhomogeneous universe of plasma filaments and current sheets separating regions of different physical parameters.
We have already discussed these ideas as applied to large scale structure formation in Chapter 4. Antimatter is never discussed within this work however, and in fact there are difficulties in combining the two. If we introduce antimatter to the universe, we require that the filaments transverse regions of matter and antimatter. Since the universe in this model is hierarchical, the size of the matter antimatter regions makes no difference to this problem. There will always be some scale on which a filament must run through a leidenfrost layer. This has not been addressed in the literature to date, but instinctively one envisions matter and antimatter moving in opposite directions in the magnetic field of the filament disrupting the quasisteady balance in the boundary layer. Alternatively this could be a desireable mechanism for disrupting the layer to initiate the Hubble expansion already discussed in section 5.2.2.

5.3.1 Cosmic Microwave Background Radiation

Alfvén has not proposed any consistent explanation of the microwave background radiation (CBR) within his model. However, in 1988 E. Lerner, and then Peratt and Peter(1990), presented such a mechanism which still remains unrefuted. They propose that dense magnetic filaments in the IGM will be opaque to radiation with wavelengths longer than 100-400um,and essentially transparent to shorter wavelengths. They would thus be capable of isotropizing and thermalizing CBR by synchrotron absorbtion and re-emission of background photons at radio frequencies. High energy electrons spiralling around B-field lines in the filaments can absorb photons and reradiate them in random directions, hence scattering the radiation. Rees (1978) had already calculated that the helium abundance observed today could have been produced by massive stars formed during galaxy formation. These stars would convert hydrogen to helium in their cores, and produce the observed 24% helium abundance on a timescale of the order of 10^8 Years. The energy released in producing the helium, he calculated was of the correct order of magnitude to account for the energy in CBR.
Lerner (1988), found that efficient smoothing of the radiation requires lots of small filaments with strong B-fields. He suggested a possible candidate for such structures are the

jets emerging from galactic nuclei. In fact, in more recent research by Lerner (1992), it was found that these jets will spontaneously break up into finer and finer filaments, each pinching itself into stronger and stronger fields (a phenomenon observed in the lab and in the sun). These finer and denser filaments increase the efficiency of the scattering process. So, it is proposed that most of the scattering occurs in tiny subfilaments $\sim$ few km across, with fields $\sim 10^3$ gauss. On average, Lerner calculated that a photon of background radiation would encounter one of these filaments every few million years, and isotropy would be complete after several billion years. He found that filaments ranging from radii of 32m and fields of 6T, to those of radii 6×10^9km with fields of 0.14G will be highly opaque to radiation in the region from 400μm to 200cm. At shorter wavelengths a rapidly declining opacity will be provided by filaments ranging down from 2m radius and fields of 25T, with complete transparency below 100um. Lerner calculated that the energy of the electrons in such filaments, and the scale of the filaments are consistent with the jets emitted by quasars, AGN's and Herbig-Haro objects (the hot spots formed when the jets from very young stars, T-Tauri stars, hit the surrounding nebulosity). This highly inhomogeneous collection of filaments will be stable against collisional and synchrotron processes for many Gy's. Such a mechanism can account for the isotropy and spectrum of the CBR even with large scale structures in the univese. We must also consider that this model of the IGM absorbing radio frequency radiation from galaxies, predicts that the radio luminosity of galaxies will decrease with increasing distance. The observational consequences of this have been considered by Lerner (1990), and will be discussed in section 5.4

5.4 Observational Consequences

The main consequences of Alfvén's model and the recent work on galaxy formation and larger structure formation, are that the universe is highly inhomogeneous, and that magnetic fields have played a significant part in forming this structure, and phenomena such as double radio source jets, and active galactic nuclei.

We have mentioned the observations of sheet and filamentary structures in acessible regions of the universe. Most noteable are the observations of the Great Wall, extending $\sim 170 \times 60 \times 5h^{-3}Mpc^3$ (Gellar and Huchra, 1989). We have also noted in chapter1 that the standard cosmological model based on the Freidmann Robertson Walker metric can incorporate local inhomogeneities, but requires that the universe be isotropic and homogeneous on very large scales, and the observational evidence for this in chapter 1.

These observations are not entirely conclusive although do suggest that the universe is homogeneous and isotropic on large scales. We also note that the large angle isotropy of CBR is probably the best indication of the isotropy of the universe, within the standard cosmological models interpretation of the CBR. However this also places some difficult constraints on models of structure formation.

It seems that there is a wealth of observational support to the idea that on large enough scales the universe becomes homogeneous and isotropic. This would rule out Alfvén's original postulate that the universe is inhomogeneous on all scales. However, the formation of galaxies and clusters of galaxies, and structures on scales of the Great Wall by electromagnetic forces, are not inconsistent with these observations. However, we then require some explanation for this distribution smoothing out on very large scales. Lerner has suggested such a reason (1992).

We should also consider the consistency of the observed energy density of magnetic fields in the universe with the proposed significance of electromagnetic effects in plasma cosmology. In Chapter1 we find that when the energy density of magnetic fields is averaged over the entire universe, then the matter density in the universe is several orders of magnitude greater. However, this assumes that magnetic fields are isotropic throughout the universe, and that there is no mean magnetic field, only a mean magnetic energy (necessary in the Freidman Robertson Walker metric (Battaner et al, 1997)). If for the case of Alfvén's model, magnetic fields are not uniformly distributed, and are concentrated into 'active' plasma regions, then the average magnetic energy over the whole universe may be small, but electromagnetic effects could still play an important part in the evolution of these active regions.

A direct consequence of Lerner and Peratt's explanation of the CBR, as already mentioned, is that radio frequency radiation emitted from galaxies will be absorbed by the IGM. The mechanism therefore predicts that the brightness of galaxies at radio frequencies should decrease with increasing distance. Lerner (1990), has measured the radio absorption of intergalactic space, using the esablished correlation between the radio luminosity (L_R) and infrared luminosity ($L_I R$) of spiral galaxies discovered by Dickey and Salpeter (1984). For galaxies with a particular $L_I R$, the L_R should decrease with increasing distance from

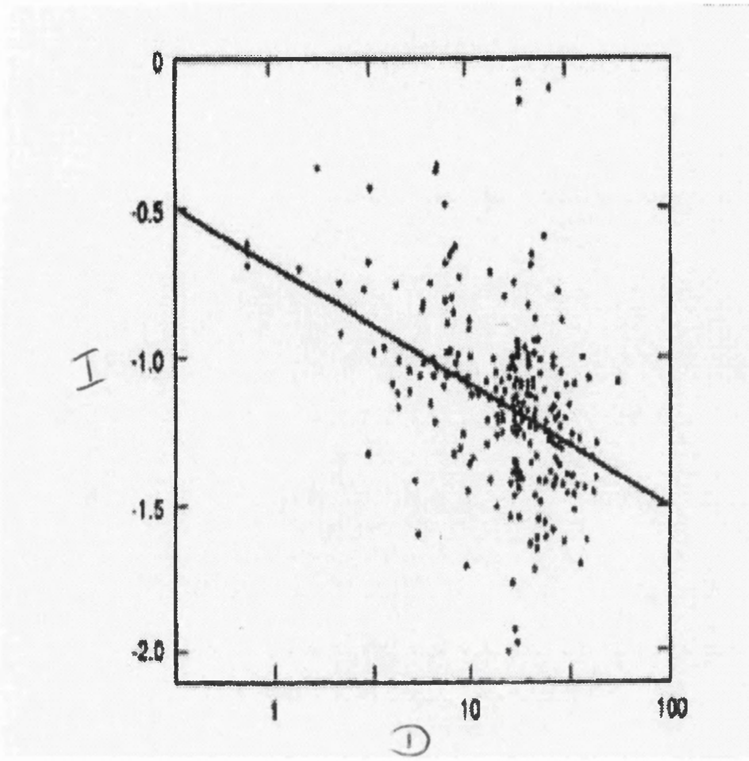

Figure 5.2: The correlation between radio luminosity index $I = 0.43 + \log(L_R) - 1.41\log(L_I R)$, and distance D from earth. Each point represents a galaxy, and the least squares fit of the data is shown. From Lerner, 1990.

Earth. Lerner uses a sample of 237 spiral galaxies, out to distances $\sim 40Mpc$, and the results are displayed in fig 5.2. The index I, gives the difference between $L_I R$ and L_R effectively, and this is plotted against distance D in Mpc. The least squares fit of this data shows a decrease in L_R with $D^{0.41}$, and a zero slope is excluded at a 7σ level. Possible biases that may spuriously produce this correlation are dealt with, and the conclusion of Lerner, is that the result is still highly significant statistically. Some further work has been presented on this problem, extending the correlation to larger distances (Lerner, 1993, 1995). Not only was this predicted by Lerner and Peratts model of the CBR, but this result has important consequences for the standard interpretation of CBR. This data contradicts the assumptions made by the standard model of CBR, which assumes that radio frequency radiation can transverse the IGM with such insignificant absorption as to not effect the high degree of CBR isotropy. This work suggests this is not the case, and remains unrefuted.

The consequences of large scale structure formation by magnetic filaments has been discussed in Chapter4. The difficulty of incorporating this idea into either the standard cosmological model or alfvén's model are noted.

5.5 Conclusions

This chapter has reviewed an alternative cosmology which is interesting in view of the difficulties of incorporating magnetic fields into the standard cosmological model as catalogued in the previous chapters.

It is clear however that the model has some serious problems, most noteably in being unable to produce the observed hubble expansion. Nevertheless the ideas of extrapolating physics to increasingly large scales is emphasised within this model, which apears to have somehow been lost in standard cosmology. The filamentation of space is a very resonable assumption to make then, and has led to the most interesting developments of Alfvén's Cosmology. As already discussed, observations of magnetic fields does not rule out this filamentation idea.

Ideas for structure formation lead to some surprising correlations with observations, but without a cosmological model, or at least a consistent generation mechanism for the large scale magnetic fileds, the model remains only 'interesting'. However, still the origin and evolution of magnetic fields is not even asked, let alone answered in Alfvén's model, being avoided perhaps because the universe is infinate in time for this model! The explanation of the CMB has presented a possible problem for the standard interpretation of this observation, which still remains refuted. However again the mechanism itself is lost without a cosmological framework around it.

Chapter 6

Conclusions and Future Work

The purpose of this brief chapter is to provide an overview of the work covered in this thesis, and to assimilate the results of the collective research reviewed here, and the analysis of chapter3. In general there is certainly a great deal of further work neccessary in this field of research, and a need for different areas to collaborate.

The attempt made to incorporate magnetic fields in standard cosmology generally presumes in the first instance that magnetic fields are insignificant in cosmology, and hence limits the strength and configuration of the fields within this prescription. Although this approach is often neccessary here since we have little data to guide us, we should be careful not to conclude that magnetic fields are insignificant simply because we have assumed them to be initially! Especially since here there appears no consistent model for generating the magnetic fields observed today from an initial seed field that does not disturb the balance of the early universe.

In chapter3 we reviewed the present state of the mechansms for generating magnetic fields in the standard cosmology. These are important in determining the effect of magnetic fields, since they should determine to some extent the strength of magnetic fields and the epochs in which they appear. However, again this is mostly determined by the assumptions of the standard model itself. Still we conclude that all suffer from inconsistencies in both theory and observations. All mechanisms expect very different levels of turbulence in the space plasma, none of which are as yet clearly justified. This highlights one area of research that requires further work, and could lead to the demise of at least one of the proposed generation mechanisms.

A purely primordial magnetic field can only account for the magnetic fields of today if the field strength at nucleosynthesis was $\sim 10^{11}G$. This would influence nucleosynthesis reaction rates, structure formation rates, and the expansion rate of the universe. Further, the coherence scales of the magnetic fields produced prior to nucleosynthesis are incompatible with the observed field scales today.

Dynamo amplification of an initial seed field would allow the standard cosmological model to remain unaffected, and could account for the strength and coherence scales of the observed fields today. However, the only generation mechanism proposed that provides a magnetic field of the strength required for dynamo amplification, would also effect structure formation.

Further theoretical work is needed on the seed field generation mechanisms, and on the dynamo mechanism itself. Possibly more important is improved observational work. In particular, the preferred magnetic field structure (ASS or BSS) could determine whether dynamo amplification has occurred in galaxies. Observations of magnetic fields in high redshift systems could restrict the dynamo further, and polarisation of the CMBR could provide an important insight into the magnetic field at the time of recombination.

Also in chapter3 we analysed a third generation mechanism. Although this battery mechanism would provide a way of producing magnetic fields and avoiding entirely the effects on the early universe, the results here show Lesch et als' treatment to be inconsistent. The overall conclusions from our analysis are restricted, and we can not conclusively reject or enforce the possibility of magnetic field generation by this mechanism. However, any magnetic fields arising in this scenario will not be due to the space charge distribution as suggested by Lesch et al.

Extending this analysis to a fully 3-D treatment, and taking account of the edge effects in this problem would allow one to reach a more precise conclusion. To date Brown and Karlicky have used electrostatic particle codes to introduce a finite injected beam, a background plasma, and some randomisation of particle speeds. They find the same result as here, of oscillating electrons and protons in the beam, and also reveal other particle effects.

In light of the problems that the restrictions of standard cosmology generate, we have also considered the approach of Hannes Alfvén. Chapter5 reviews this alternative cosmology and it's shortfalls, and we can conclude that the model is unsatisfactory. However, Alfvén's idea that space is filamented and interwoven with magnetic fields has it's appeal in being an extrapolation of the physics of our immediate surroundings. And it is this

idea that has been further developed recently to produce the alternative models for large scale structure formation, and the CMBR. However we note that the generation of these magnetic fields is not considered in Alfvén's cosmology, and perhaps would suffer the same problems as in standard cosmology.
The model for structure formation produces some suprising correlation with observations of galactic nuclei and radio jets, and of course accounts specifically for the observed filamented matter distribution on large scales. The generation of the CMBR within this model offers a challenge to the standard cosmological model in explaining the possible absorption of radio frequency radiation by the IGM. This is still unrefuted and should be considered by Big Bang cosmologists.

Essentially two different approaches to magnetic fields in cosmology have been reviewed here, and neither has presented satisfactory results. Fixing a standard model of cosmology, and attempting to add magnetic fields as an after thought results in speculative theories of magnetic field generation mechanisms and evolution, which incorporate concepts that are badly understood in the situations to which they are applied, and still the picture is inconsistent.
Attempting to explain isolated observations firstly, beginning with magnetic fields on all scales, and making them central to models of structure formation and the CMBR results in an incomplete picture, with no consistent cosmological framework to support it.
In addition, the two approaches continue with sometimes little awareness of the others ideas and results, accentuated by the fact that each publish in entirely different journals! At present then this field is a difficult one to follow and understand. Even within the seperate approaches, work is often focused on perfecting isolated parts of a mathematical theory, when the basic assumptions and conditions of this theory are not questioned.
Perhaps however this is the only option at present for such a large topic, which can still afford the luxury of pure speculation. The increase of observational data within this field will change this.

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