JOURNAL OF THE KOREAN ASTRONOMICAL SOCIETY
29: S155 ~ S158, 1996

THE ORIGIN OF LARGE SCALE GALACTIC MAGNETIC FIELDS

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ABSTRACT

Magnetic fields correlated on several kiloparsec scales are seen in spiral galaxies. Their origin could be due to the winding up of a primordial cosmological field or due to amplification of a small seed field by a turbulent galactic dynamo. Both options have difficulties: There is no known battery mechanism for producing the required primordial field. Equally the turbulent dynamo may self destruct before being able to produce the large scale field, due to excess generation of small scale power. The current status of these difficulties is discussed. The resolution could depend on the nature of the saturated field produced by the small scale dynamo. We argue that the small scale fields do not fill most of the volume of the fluid and instead concentrate into intermittent ropes, with their peak value of order equipartition fields, and radii much smaller than their lengths. In this case these fields neither drain significant energy from the turbulence nor convert eddy motion of the turbulence on the outer scale to wave like motion. This preserves the diffusive effects needed for the large scale dynamo operation.

Key Words : Magnetic fields; galaxies:magnetic; galactic dynamos

I. INTRODUCTION

Magnetic fields in galaxies have strengths of order few $10^{-6}G$, and are coherent on scales of several kpc (cf. Beck et al 1996). How such ordered, large scale fields arise is a problem of considerable interest. They can arise in principle, due to dynamo amplification of a weak but nonzero seed field $\sim 10^{-19} - 10^{-23}G$, if the galactic dynamo can operate efficiently to exponetiate the field by a factor $\sim 30-40$ (cf.Zeldovich *et al.* 1983). But the origin of even such a small seed field needs some physical explanation. We review here some of the issues relevant to galactic magnetic field generation, in particular, the galactic dynamo theory, its problems and possible solutions.

The evolution of the magnetic field is generally described by the induction equation $(\partial \mathbf{B}/\partial t) = \nabla \times (\mathbf{v} \times \mathbf{B} - \eta \nabla \times \mathbf{B})$, provided one assumes the usual form of Ohms law and neglects the displacement current term in Maxwells equation. Here $\mathbf{B}$ is the magnetic field, $\mathbf{v}$ the velocity of the fluid and η the resistivity. If $\eta \to 0$ the magnetic flux through any area in the fluid can be shown to be conserved during the motion of the fluid. The presence of a finite resistivity allows for a violation of such "flux freezing" and the magnetic reynolds number $R_m = vL/\eta$ measures the relative importance of flux freezing versus resistive diffusion. (Here v and L are typical velocity and length scales of the fluid motions.) In most astrophysical contexts flux freezing greatly dominates over diffusion with $R_m >> 1$.

Since $\mathbf{B} = 0$ is a perfectly valid solution of the induction equation, there would be no magnetic fields generated if one were to start with a zero magnetic field initially. It is generally believed that the universe did not start with an initial magnetic field. So one needs some way of violating the induction equation and produce a cosmic battery effect, to drive curents from a state with initially no current. There are a number of such battery mechanisms which have been suggested (see Rees 1994; Subramanian 1995 for reviews). All of them lead to only small fields much smaller than the galactic fields. Therefore, it would be good to find velocity fields, which can act to exponentiate the small seed fields efficiently. Some form of dynamo action is needed to explain the observed magnetic fields. We will discuss below the possiblities of galactic dynamos after touching briefly on one battery mechanism, which appears capable of seeding the whole IGM with ordered fields, albiet with a small value (Subramanian et al 1994).

II. A BATTERY MECHANISM

The basic problem that any battery has to address is how to produce finite currents from zero currents? Most mechanisms use the fact that the positively and negatively charged particles in a charge neutral universe do not have identical properties. For example if one considered a gas of ionised hydrogen, then the electrons have a much smaller mass compared to protons. This means that for a given pressure gradient of the gas the electrons tend to be accelerated much more than the ions. This leads in general to an electric field, which couples back positive and negative charges, of the form $\mathbf{E}_T = \nabla p_e / e n_e$, where p_e and n_e are the electron pressure and number density, respectively. If such a thermally generated electric field has a curl, then by Faradays law of induction a magnetic field can grow. Taking $p_e = n_e kT$ with T the electron temperature we have $\nabla \times \mathbf{E}_T = -(ck/e)(\nabla n_e/n_e) \times \nabla T$. So $\mathbf{E}_T$ has a curl only if the density and temperature gradients, are not parallel to each other. Biermann (1950) and Mestel and Roxburgh (1962) applied this idea to stars. Subramanian et al (1994) have applied it to cosmic ionisation fronts, which are produced when the first UV sources turn on to ionise the intergalactic medium.

The temperature gradient in a cosmic ionisation front is normal to the front. However, a component to the density gradient can arise in a different direction, if the ionisation front is sweeping across arbitrarily laid down density fluctuations, associated with protogalaxies/clusters since these in general have no correlation to the source of the ionising photons. The resulting thermally generated magnetic fields on galactic scales turn out to have a strength $B \sim 3 \times 10^{-20} G$. This field by itself is far short of the observed microgauss strength fields in galaxies, but it can provide a seed field for a dynamo. Recently Kulsrud et al (1996) have suggested that the Biermann battery can also operate in collapsing protogalaxies/clusters.

III. THE GALACTIC DYNAMO

Spiral galaxies are differentially rotating systems. Also the magnetic flux is to a large extent frozen into the fluid. So any radial component of the magnetic field will be efficiently wound up and amplified to produce a toroidal component of the field. But this results in only a linear amplification of the field and to obtain the observed galactic fields starting from small seed fields one should find a way to generate the radial components of the field in the galaxy from the toroidal one. If this can be done, the field can grow exponentially and one has a dynamo.

A mechanism to produce the radial components from the toroidal field was originally invented by Parker (1955) (cf. Zeldovich et al 1983). The essential feature is to invoke the effects of cyclonic turbulence in the galactic gas. The galactic interstellar medium is assumed to be turbulent, due to for example the effect of supernovae randomly going off in different regions. In a rotating, stratified (in density and pressure) medium like a disk galaxy, such turbulence becomes cyclonic and aquires a net helicity. Helical motions of the galactic gas perpendicular to the disk can draw out the toroidal field into a loop which looks like a twisted Ω. Such a loop is connected to a current and because of the twist this current has a component parallel to the original field. Since the gas has a net helicity, in the presence of such motions a toroidal current can be produced from the toroidal field, Hence, poloidal fields can be generated from toroidal ones. In quantitative terms isotropic and homogeneous turbulence with helicity, in the presence of a large scale magnetic field $\mathbf{B}$, leads to an extra electromotive force of the form $\mathbf{E} = \alpha\mathbf{B} - \eta_t \nabla \times \mathbf{B}$ where α depends on the helical part of the turbulence and η_t called the turbulent diffusion depends on the non helical part of the turbulent velocity correlation function.

A physics comment is in order at this stage. When one considers the effect of turbulent fluid motions on say smoke, one only gets a mean diffusion of the smoke particles, associated with the random walking nature of turbulent fluid motions. But for magnetic fields the induction equation has terms which not only imply a body transport due to the random motions of the fluid, but also a term which describes the generation of magnetic fields due to velocity shear. It is this qualitative difference between magnetic fields and smoke that leads to an alpha effect, over and above turbulent diffusion (and also leads to the small scale dynamo action discussed below). Note that both these effects also crucially depend on the diffusive (random walk) property of fluid motion. So if due to some reason (see below) the fluid motion becomes wavelike, then the alpha effect and turbulent diffusion will be suppressed.

The induction equation, with the extra turbulent component of the electric field, with a prescribed large scale velocity field, can have exponentially growing solutions for the large scale field. These have been studied extensively in the literature (cf. Beck et al. 1996 for a review). One can even modify it to discuss the possible reasons why large scale magnetic fields in spirals are sometimes bi-symmetric and why these bi-symmetric magnetic spirals are correlated with the optical spirals (cf. Mestel and Subramanian 1991; Chiba and Tosa 1990). We have assumed here that the turbulent velocities do not get affected by the Lorentz forces due to the magnetic field, at least not until the mean large scale field builds up sufficiently. However this does not turn out to be valid due to the more rapid build up of magnetic noise compared to the mean field, a problem to which we now turn.

IV. PROBLEM OF MAGNETIC NOISE

Suppose one splits up the magnetic field $\mathbf{B} = \mathbf{B}_0 + \delta\mathbf{B}$, into a mean field $\mathbf{B}_0$ and a fluctuating component $\delta\mathbf{B}$. Here the mean is defined either as a spatial average over scales larger than the turbulent eddy scales or more correctly as an ensemble average. The dynamics of the fluctuating field has been worked out in detail by Kulsrud and Anderson (1992) (KA) in fourier space and by Subramanian (1996) using a complimentary coordinate space approach. We summarise some of the results drawing mainly on the later work.

This analysis shows firstly that the fluctuating field, tangled on a scale l, can grow on the turn over time scale of a turbulent eddy of scale l, with a growth rate $\Gamma_l \sim v_l/l$, provided the magnetic reynolds number on that scale $R_m(l) = v_l l/\eta$ is greater than a critical reynolds number $R_c \sim 100$. Here v_l is the velocity associated with eddies of scale l. For Kolmogorov turbulence, since $v_l \propto l^{1/3}$, $\Gamma_l \propto l^{-2/3}$. If the magnetic reynolds number associated with eddies at the cut-off scale (inner scale), say l_c, of the turbulence is larger than R_c, then these eddies will themselves be able to exponentiate the magnetic field first on these scales. Since the time scale for mean field growth is $\sim 10^9 yrs$, of order a few rotation time scales of the disk, is much larger than the turn around time scales of the turbulent eddies in the galaxy, the magnetic field will be rapidly dominated by the fluctuating component. KA argued that as the small scale field builds up it will drain energy from the turbulence, mainly due to the friction of the ionised gas and the neutrals resulting from ambipolar drift. Also once the energy density in the small scale component achieves equipartition with the turbulent energy density, the turbulence will become weak, a more wavelike "alfven" turbulence, than an eddy like fluid turbulence resulting in a suppression of the alpha effect. All this happens much before the mean field has grown appreciably. So KA speculated that the galactic field is primordial in origin.

V. A POSSIBLE SOLUTION

Before accepting the above conclusions, it is worth re-examining carefully the dynamics of the small scale fields and its back reaction on the turbulence. We had pointed out earlier (Subramanian 1995) that if the small scale field is intermittent in space, then it may saturate without drastically draining the power from the turbulence. This idea has been now investigated more thoroughly (Subramanian 1996), taking into account in a quantitative fashion the effects of ambipolar drift in the galaxy as well. We summarise below some of the relevant results.

For this it is useful look at the behaviour of the magnetic correlation function, say $w(r,t) =< \delta\mathbf{B}(\mathbf{x},t).\delta\mathbf{B}(\mathbf{y},t) >$, where $r = |\mathbf{x}-\mathbf{y}|$ and the angular brackets $<>$ indicates an ensemble average. Suppose the turbulence was initially isotropic and homogeneous. Then in the kinematic regime, if $R_m(l_c) > R_c$, the fastest growing $w(r,t)$ has a form $f(r)e^{\Gamma t}$ with $f(r)$ strongly peaked within $r = r_1 = l_c/R_m^{1/2}(l_c)$, and a negative tail extending to $r_2 \sim l_c$. Zeldovich et al. interpret such a correlation function as implying that field is concentrated into ropes of thickness r_1 and radius of order r_2. There can be slower growing higher order modes w with more complicated structure for the field but all with a ropy structure with rope thickness of order r_1. The question arises as to how such ropes evolve in the non-linear regime when the lorentz force due to the generated field reacts back on fluid motions?

We show that, in a partially ionised plasma, due to ambipolar drift, the effective diffusivity changes to $\eta_{eff} = \eta + < \delta\mathbf{B}^2 > /(6\pi\rho_i\nu_{in})$, where ρ_i is the ion density and ν_{in} is the neutral-ion collision frequency. So, as the energy density in the fluctuating field increases, the effective magnetic reynolds number, for fluid motion on any scale of the turbulence say $R_{ambi}(l) = v_l l/\eta_{eff}$, decreases. Firstly, this makes it easier for the field energy to reach the diffusive scales $r_d \sim l/R_{ambi}^{1/2}$, from a general initial configuration. Subsequent field amplification, leads to a decreasing R_{ambi} and an increase in r_d and hence the thickeness of the flux ropes. However for the galactic turbulence with say an outer scale $L \sim 100pc$ and $v_L \sim 10$ km s^{-1}, $R_{ambi}(L) \sim n_i f^{-1} 10^6$, where n_i is the ion density in units of cm^{-3}, and f is the ratio of the magnetic to the turbulent energy density E_T. The flux ropes then remain relatively thin with a thickness at most a value of order $L/R_{ambi}^{1/2} << L$, even taking account of the ambipolar drift. The volume filling fraction of the field depends not only on the thickness of the rope but also on its total length. In the kinematic regime, a rough estimate of the length of the rope is $\sim NL$, where N is related to the number of higher order modes excited. For $R_{ambi} \sim 10^6$, only a few higher order modes can be exited. In this case the volume filling factor of the field is $\sim N/R_m$. How this changes as the field reaches a stationary state is more difficult to quantify. (cf. Vishniac 1995, in a different context).

Since $R_{ambi} > R_c$, ambipolar drift alone cannot lead to a saturation for the small scale dynamo. The field keeps building up until the effects of the magnetic pressure in the ropes acting on the fluid as a whole becomes important. Due to the increasing importance of this pressure, stretching of field lines can lead to a partial decrease in fluid density in the ropes rather than a decrease in the rope cross section and the associated increase in the rope magnetic field. An upper limit to the magnetic pressure in the ropes is given by the external pressure P_{ext}. This implies that the field in the rope, say B_r is limited to $B_r < (8\pi P_{ext})^{1/2}$. In the interstellar medium, the ratio of the gas pressure to the turbulent energy density $P_g/E_T \sim 1.7(T/10^4K)(v/10kms^{-1})^{-2}$. If P_{ext} in the galaxy is dominated by the gas pressure, the peak field in the ropes will not be much larger than the equipartition field. [Vishniac (1995) has also discussed the ropy nature of the magnetic field in accretion disks. There are however crucial differences due to the dominance of ambipolar drift in the galaxy. Also in the case considered here, when the field grows from a small seed field, the kinematic evolution naturally leads to an initial ropy structure for the field which can be preserved when the field becomes strong].

The above considerations lead us to conjecture that when the small scale dynamo saturates, 1. The magnetic noise generated by the small scale dynamo is ropy and does not fill the volume of the fluid. 2. The peak fields in the ropes are not much greater than equipartition fields. Given these conjectures one can show that the power dissipated in ambipolar drift is much smaller than the turbulent power. Also, from the conjectures 1 and 2 one can see that the average energy density of the generated small scale field is much smaller than the average energy density in the turbulence. So any wave-like motion induced by the presence of the field will have a period larger than the eddy turn around time. This implies that such tangled small scale fields do not change the diffusive nature of the turbulence. Due to the above reasons the large scale dynamo can still operate to grow the mean field. More details of the above work can be found in Subramanian (1996). In conclusion, it seems that an understanding of how galactic magnetic fields originate, is far from complete and is still a challenging problem.

ACKNOWLEDGEMENTS

I thank the SOC/LOC of the Asia-Pacific IAU meeting for support. Periodic discussions with T. Padmanabhan and a brief one with Ethan Vishniac were very helpful.

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