THE PRESENT STATE OF A PRIMORDIAL GALACTIC FIELD

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ABSTRACT If the galactic field arose from flux imbedded in the protogalactic-galactic medium, then one would expect this field to be strongly wound up by the differential galactic rotation once it had formed into a disk. This process is balanced by the buoyancy forces lifting the flux out of the disk. The resulting field turns out to be only slightly wound up. Further, its magnitude depends only on properties of the ISM provided that the primordial field exceeds 10^{-13} gauss.

1.Introduction

Two separate theories have been put forward to explain the origin of the galactic magnetic field. These are a primordial origin, and a dynamo origin. In order to decide between these two theories, one must derive the present state of the field predicted by each one. Considerable effort has gone into deriving the fields predicted by the dynamo origin. In this note we consider the field that should result if the field were originally of primordial origin.

Imagine that in the protogalaxy from which our galaxy formed there were initially a large scale uniform weak field, of magnitude B_{in} and that the initial primordial density were ρ_{in}. Assume flux freezing during the collapse of the proto¡galaxy to form the galactic disk. The collapse goes in two phases. One an initial isotropic collapse to a density ρ'' and then a collapse along the axis of rotation by a factor of about one hundred to the current density of $\rho_0 = 1/\mathrm{cm}^3$. Then the magnetic field would be amplified to a value of $(10\rho_{in}/\rho_0)^{2/3}B_{in}$ since the field is proportional to $\rho^{2/3}$ during the first collapse, and to ρ during the second collapse. Thus, if $\rho_{in} = 10^{-5}\mathrm{cm}^{-3}$ then the original field is amplified by a factor of 10^4 during the initial formative stages of our galaxy.

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2. The Evolution of the Field in the Disk

Let us consider what happens to the magnetic field subsequent to these stages. We assume that the field continues to be frozen into the interstellar plasma, and that it is completely unaffected by any dynamo action at all. We ignore any turbulent motions in the interstellar medium and only consider the systematic motions of the medium. These are of two types: the differential rotation of the galaxy, and the ambipolar motion of the ionized part of the interstellar medium through the neutral medium. The latter motion is produced by the force which the magnetic field exerts on the ions and electrons in the plasma because the magnetic field is confined to the galactic plane. Since there is no corresponding force on the neutrals there arises a differential motion of the ions and electrons through the neutrals in the vertical direction perpendicular to the galactic disc to balance this differential force. The mean amount of this differential velocity v_d has been estimated (Kulsrud (1986)). It is found that, because of the presence of clouds in the ISM in which the fraction of ionization is very low v_d is much larger than it would be for the case of a homogeneous medium. Because of symmetry of the galactic disc v_d should vanish when $z = 0$ where z is the height above the galactic plane. Thus one can write

$$v_d = v_{d1} z/D \tag{1}$$

where D is the mean thickness of the galactic disc. The magnitude of v_{d1} depends on the parameters of the ISM and is given in order of magnitude by

$$v_{d1} \approx \frac{B^2}{4\pi} \frac{\ell}{Rh} \frac{1 + 8\pi p_{cos}/B^2}{\rho_i \nu_{in}} \tag{2}$$

where ℓ is the mean distance between clouds along a magnetic field line, R is the radius of the clouds h is the scale height of the density p_{cos} is the cosmic ray pressure, and ρ_i is the plasma density and ν_{in} the ion-neutral collision rate in the clouds. One finds for a choice of parameters corresponding to conditions in the interstellar medium at the present time, that v_{d1} is about .03 km/sec or about 100 pc. in a 3×10^9 years. Because of our assumption that the field is is frozen in the plasma, we can write the equation for the evolution of the magnetic field as

$$\partial \mathbf{B}/\partial t = \nabla \times (\mathbf{v} \times \mathbf{B}) \tag{3}$$

where

$$\mathbf{v} = R\Omega(R)\hat{\theta} + v_d(z/D)\hat{\mathbf{z}} \tag{4}$$

where $\hat{\theta}$ and $\hat{\mathbf{z}}$ are unit vectors in the azimuthal and vertical directions, respectively.

Now, let us consider the effect of the two velocities on the magnetic field. In general, since there need not be a relation between the direction of **B** and the direction of the angular velocity of the galaxy, we may expect that the field which is initially collapsed into the disk has both B_r and B_θ components. In addition, the field will have a B_z component, since it is still connected to the extragalactic medium. If the field is weak, the v_{d0}, the initial value of v_{d1} will be negligible, and the field will be stretched in the azimuthal direction. As the stretching proceeds, the field strength grows, and v_d becomes important. The plasma move vertically away from the central plane carrying the field lines with it. The field lines will be pulled out of the galactic disk, and shorten at the same rate as they are being lengthened by the differential rotation. Eventually, the vertical velocity wins and the field strength weakens.

To make these considerations quantitative, consider the field to be initially in the radial direction. Then, from the equations for the motion of the plasma in the mean velocity field,

$$dr/dt = 0 \quad (5)$$

$$d\theta/dt = 0 \quad (6)$$

$$dz/dt = 0 \quad (7)$$

To these equations we add the equation for the field strength B,

$$dB/dt = \frac{r d\theta/dt}{\Delta r} B \quad (8)$$

where Δr is the initial extent of the line in the r direction. This relation states essentially that the field strength is proportional to the length of the line in an infinitely conducting plasma.

From these equations one can show that

$$\frac{B^2}{B_0^2} = \frac{(\Delta\Omega)^2 t^2}{1 + \frac{2}{3}(v_{d0}/D)(\Delta\Omega)^2 t^3} \quad (9)$$

where B_0 is the field after collapse into the disk, and v_{d0} is the initial value of v_{d1}. $\Delta\Omega \equiv r d\Omega/dt$. (We have made the simplifying assumption that $p_{cos} \propto B^2$, since a stronger field should trap more cosmic ray pressure.)

Eq.(9) bears out the description given above for the evolution of the field strength B. If v_{d0} is small, the denominator is one at first and B increases as t. Later, after v_{d1} becomes larger, B decreases because part of the line is being lifted out of the galaxy faster than the remainder of the line is being stretched.

It should be noted that the entire line of force is not removed from the galaxy since part of the line is lifted upward from the galactic disk, while another part leaves the disk downward. This results from the antisymmetry of v_d. Also we have assigned an outward velocity to the plasma, but the plasma need not leave the disk because it is continually recombining and reionizing so the position of the plasma remains fixed. However the motion of the plasma ions and electrons does carry the line outward.

Let us solve for B when t is large. If the initial field B_0 is sufficiently large ($> 10^{-8}$ gauss), then for $t = t_H$, the Hubble time, the 1 in the denominator of Eq.(9) is small and we have

$$B^2 \approx \frac{3 B_0^2 D}{2 v_{d0} t_H} \quad (10)$$

But from Eq.(2), v_{d0}/B_0^2 is independent of the value of B_0 so we may substitute the present values for v_{d0} and B_0 in Eq.(10). Thus,

$$B^2 \approx \frac{3}{2}\frac{B_d^2}{v_{d,now}t_H/D} \approx \frac{1}{2}B_{now}^2 \tag{11}$$

for the same choice of parameters in Eq.(2) as made in the first paragraph. We see that B naturally evolves under the two mean motions, to a value dependent only on the properties of the interstellar medium which turns out to be close to the present observed value for the interstellar field. This value is independent of the initial value of the field provided that it is stronger than about 10^{-8} gauss. This is true even if the initial field B_0 is greater than its present value B_{now}. In addition we can say that the usual argument against the primordial origin for B, that it will be amplified indefinitely by differential galactic rotation is defeated by the vertical ambipolar velocity v_d. To draw a conclusion with respect to the magnitude of the present intergalactic field necessary for a primordial origin we should note first that the field is amplified by a factor of about 10^4 above the value present at the formation time of the galaxy, and that this field is about 10 times larger than its present value, $B_{intergalactic}$. Thus, the minimum necessary value of the current field is $B_{intergalactic} = 10^{-13}$ gauss.

However, the amount of wrapping up of the line of force, that is its final angular extent $\Delta\theta$, is

$$\Delta\theta \approx \frac{B_{now}}{B_0} \tag{12}$$

so that in fact B_0 must be considerably larger than 10^{-8} gauss to avoid undue wrap-up of the lines, contrary to observations.

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4. Reference

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