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Origin of electric and magnetic fields in the early universe*

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Abstract. A fundamental unanswered question of cosmology is the origin of the magnetic fields observed in the various types of astrophysical bodies. It is still argued whether these magnetic fields are primordial or whether they have been amplified from an initial small seed field. We shall show that a large-scale magnetic field is generated by motions of an electric field in the plasma that constituted the early Universe at the time of decoupling of matter from radiation. This primordial electric field is a consequence of temperature and pressure gradients that produce charge separation in the plasma of electrons and protons. We calculate the magnitude of these primordial fields using expected galactic size and streaming velocities as well as values of temperature and pressure gradients that are observed near the time of decoupling. We calculate the large-scale primordial magnetic flux and use the conservation of magnetic flux to determine the magnitude of dynamo amplification of this seed field that has occurred during the formation of the various astrophysical bodies.

1. Introduction

Recently, microwave observations have measured the temperature perturbations in the early Universe near the time of decoupling of matter from radiation. Such temperature variations can be expected to have attendant velocity perturbations and density and pressure gradients. Above a temperature of about 4000° K the matter of the early Universe is a plasma of electrons and ions whose main constituent is protons. Temperature and pressure gradients cause the constituent electrons and ions whose main constituent is protons. Temperature and pressure gradients cause the constituent electrons and protons to diffuse at different rates thereby creating a charge separation which acts to set up an opposing electric field. This field grows to a size sufficient to establish an equilibrium state wherein there is no further separation of charges and no velocity difference between the electrons and protons in the plasma of the early Universe.

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Because of velocity perturbations and the associated streaming motions of the plasma, the electric field locked in the plasma will also have motion. We invoke the usual Biot-Savart electrodynamic law to determine the magnetic field that is generated by the motions of this electric field in the early Universe. Associated with this large-scale primordial magnetic field is a magnetic flux that will be conserved in non-dynamo astrophysical processes. We obtain a range of values for this primordial magnetic field and flux by substituting in the functional expression the appropriate values for the temperature and pressure gradients and the velocity and size of the density perturbations in the early Universe. We compare the primordial magnetic flux values so obtained with those magnetic fluxes observed in radio galaxies and their relics in clusters and in more normal astrophysical bodies such as the Sun, magnetic stars, white dwarfs and pulsars. These results indicate a formation history of these astrophysical bodies that necessitates amplification of this primordial magnetic seed field by dynamo activity.

2. Electric field generation

The constituent plasma of the early Universe is considered to consist of electrons and protons which are subject to the prevailing temperature and pressure gradients and external forces. These forces cause diffusion of the electrons relative to the protons, the relative velocity being given by the following relation derived in detail by Aller and Chapman (1960) :

$$w_p - w_e = -D \left[\frac{(m_e - m_p),}{(c_p m_p + c_e m_e)} \cdot \frac{1}{P} \cdot \frac{dP}{dr} + \frac{\alpha}{T} \cdot \frac{dT}{dr} - \frac{m_p m_e}{(c_p m_p + c_e m_e)} \cdot \frac{(F_p - F_e)}{kT} \right] \qquad (1)$$

where we have ignored concentration gradients and where :

w_e , w_P = Velocity of electron and proton respectively,

D = Diffusion Coefficient,

$m_e m_p$ = Mass of electron and proton respectively,

c_e, c_p = Concentration of electrons and protons respectively.

P, T = Pressure and absolute temperature, whose gradients arep taken in the r direction.

α = Thermal Diffusion Factor

k = Boltzmann's Constant,

Fe, Fp = Forces per unit mass acting on electrons and protons respectively.

Thus the prevailing temperature and pressure gradients cause the electrons and protons to separate and in so doing they set up an electric field that acts as an internal force, given by :

$$F_p - F_e = Ee\left(\frac{1}{m_p} + \frac{1}{m_e}\right) \qquad (2)$$

where e is the unit charge. As the charges continue to separate, this electric field will grow to a size sufficient to create an equilibrium state wherein there is no further charge separation and no velocity difference between the electrons and the protons. In this state the effect of the temperature and pressure gradients balances the forces due to the electric field whose functional dependence at equilibrium is thus :

$$\left[\frac{m_p + m_e}{(c_p m_p + c_e m_e)} \cdot \frac{Ee}{kT} = \frac{(m_e - m_p)}{(c_p m_p + c_e m_e)} \cdot \frac{1}{P} \cdot \frac{dP}{dr} \cdot \frac{\alpha}{T} \cdot \frac{dT}{dr}\right] \tag{3}$$

Using the fact that protons are much more massive than electrons, $m_p >> m_e$, and assuming similar concentrations, $c_p = c_e$, this relation for the primordial electric field becomes :

$$E = \frac{-kT}{e} \cdot \left[\frac{1}{p} \cdot \frac{dP}{dr} + \frac{0.8}{T} \cdot \frac{dT}{dr}\right] \tag{4}$$

where we have used the value of the Thermal Diffusion Factor for protons and electrons from Aller and Chapman (1960). Thus any clumping in the plasma of the early Universe which produces perturbations in density with associated pressure and temperature gradients will produce also a primordial electric field given by this simple relation.

3. Magnetic field generation

Any motion of an electric field will produce an associated magnetic field whose magnitude is given by Biot and Savart's relation :

$$B = E \frac{v}{c} \tag{5}$$

where v is the velocity of the electric field that we assume moves with the plasma, c is the velocity of light and electrostatic units are employed for the electric field and electromagnetic units (gauss) for the magnetic field. Substituting the relation (4) for the electric field, we obtain the final relation for the primordial magnetic field :

$$B = \frac{-kT}{ec} \cdot v \cdot \left[\frac{1}{P} \cdot \frac{dP}{dr} + \frac{0.8}{T} \cdot \frac{dT}{dr}\right] \tag{6}$$

The velocity of plasma motion, its temperature and its gradients of pressure and temperature thus define the strength of the generated magnetic field. In general, this magnetic field is not necessarily conserved in any astrophysical process but the associated magnetic flux , Φ, given by :

$$\Phi = B \cdot R^2$$

is conserved in a process where no dynamo amplification occurs. Here R is taken to be the distance over which the magnetic field is produced by the temperature and pressure gradients.

4. Astrophysical applications

The plasma in the early Universe at the time of decoupling of matter from radiation possessed a temperature of about 4000° K. Recent microwave observations of the early Universe indicate the presence of large-scale temperature variations, $\Delta T/T$, of the order of 10^{-5} and we can expect the associated pressure perturbations to be of similar magnitude. These observations and the present large-scale distribution of matter indicate that these early density perturbations were of galactic cluster size. Adjusting for the expansion since that era, we assume a typical length scale of the order of 100 kiloparsec. Observation and analyses of motions in and of these clusters indicate that, in the early Universe, they possessed streaming velocities of the order of 100 km/sec or more. Putting these values into the relation for the magnetic field where we use cgs units and a value of $4.8. \times 10^{-10}$ esu for electron charge, we obtain an electric field strength of 10^{-32} esu and a primordial magnetic field of the order of 10^{-35} gauss in the large-scale plasma density perturbations near the time of decoupling. For the primordial magnetic flux we obtain a value approximately 10^{13} gauss cm^2 though these estimates could change by a couple of orders of magnitude given more accurate knowledge of the density perturbations in the early Universe.

In contrast, radio galaxies and other relics observed in clusters have fields of the order of microgauss and thus magnetic fluxes of about 10^{39} gauss cm^2 indicating, as expected, that these particular galaxies have been subject to intense dynamo activity in the past. In comparison, the magnetic flux of the Sun is in the range of 10^{23} to 10^{25} gauss cm^2 while nearby magnetic A stars, white dwarfs, and pulsars are observed to have flux values at the high end of this range. This indicates that the matter composing these astrophysical bodies, whether during their formation and /or during the genesis of our galaxy, has been subject to much less though still significant dynamo amplification.

We have shown that a primordial electric field is produced by gradients of temperature and pressure in the early Universe. Motions of this electric field generate the primordial magnetic field and its conserved flux. Whether other forces producing charge separation and associated electric fields were active in the early Universe is not known. Many authors have considered the importance of a primeval magnetic field in the formation of galaxies, such a seed field having to be present at the time of decoupling, Pebbles (1980). As the magnetic field of the galaxy could not persist for 10^{10} years because of its dynamical instability toward leaving the galaxy in a much shorter time, it has been argued that a dynamo is needed to maintain the field in the galaxy which was generated initially from a very weak seed field, Parker (1975). These arguments are consistent with our results showing that temperature gradients in the early Universe will produce electric and magnetic seed fields.

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The author wishes to dedicate this research to the memory of his father, Sidney Davies, who was killed in action in the Second World War in 1943 and is buried on the Indian subcontinent.

References

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