Seed magnetic fields generated by primordial supernova explosions

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ABSTRACT
The origin of the magnetic field in galaxies is an open question in astrophysics. Several mechanisms have been proposed related, in general, to the generation of small seed fields amplified by a dynamo mechanism. In general, these mechanisms have difficulty in satisfying both the requirements of a sufficiently high strength for the magnetic field and the necessary large coherent scales. We show that the formation of dense and turbulent shells of matter, in the multiple explosion scenario of Miranda & Opher for the formation of the large-scale structures of the Universe, can naturally act as a seed for the generation of a magnetic field. During the collapse and explosion of Population III objects, a temperature gradient not parallel to a density gradient can naturally be established, producing a seed magnetic field through the Biermann battery mechanism. We show that seed magnetic fields \(10^{-12} - 10^{-14}\) G can be produced in this multiple explosion scenario on scales of the order of clusters of galaxies (with coherence length \(L \sim 1.8\) Mpc) and up to \(4.5 \times 10^{-10}\) G on scales of galaxies \((L \sim 100\) kpc).

Key words: magnetic fields – galaxies: magnetic fields – cosmology: theory – early Universe – large-scale structure of Universe.

1 INTRODUCTION
The origin of primordial magnetic fields is one of the most important problems in astrophysics (Peebles 1993) and, as pointed out by Barrow, Ferreira & Silk (1997), is still a mystery. Various processes have been proposed for the primordial origin of a seed field. In particular, several mechanisms on small dimensions have been suggested such as fluctuations in the primordial plasma, creation in phase transitions in the inflation era, etc. However, no satisfactory theory has been proposed that creates a sufficiently intense magnetic field on the large scales of galaxies and clusters of galaxies.

The basic idea of a seed field is that, once produced, it can be later amplified by a dynamo process (e.g. Zel’Dovich, Ruzmaikin & Sokolov 1983). However, it is necessary to generate a seed field with a sufficient intensity such that a dynamo process can amplify it to the present observed values. Another aspect that should be satisfied by the proposed mechanism is that the magnetic field should have a sufficiently large coherence length so that it can be amplified by the dynamo mechanism (e.g., be at least of galactic dimension such that the differential galactic rotation can amplify it).

Harrison (1973) proposed a mechanism for the generation of magnetic fields before the recombination epoch. Assuming the existence of turbulence with non-zero vorticity, he arrived at a magnetic field \(10^{-18}\) G on galactic scales. Rees (1987) pointed out, however, that the significant vorticity required by the model of Harrison is difficult to reconcile with the expected predominance of irrotational density perturbations that should become dominant in the post-recombination epoch. Another mechanism suggested in the plasma epoch, but without requiring vorticity, was proposed by Tajima et al. (1992). Based on the fluctuation–dissipation theorem, they studied the electromagnetic fluctuations present in plasma in thermal equilibrium and showed that in the plasma epoch \((1s < \tau < 10^{13}s, \text{ where } \tau \text{ is the cosmic time}),\) a high-intensity magnetic field exists at \(\omega \sim 0\) (i.e., zero frequency). It is difficult to exactly quantify the present intensity of this magnetic field, but it could be as high as \(10^{-12}\) G. However, a more detailed treatment of the plasma processes by Opher & Opher (1997a,b) showed that the magnetic field at zero frequency is appreciably less than that predicted by Tajima et al. (1992).

Some authors suggested that magnetic fields could be created during inflation (Turner & Widrow 1988; Ratra 1992). These scenarios can lead to sufficiently large coherence scales for the fields because inflation can lead to mechanisms acting on horizon scales. However, the predicted amplitudes are extremely sensitive to the parameters used. Another suggestion is the creation of magnetic fields in phase transitions. Quasnock, Loeb & Spergel (1988) proposed a seed field generating mechanism during the quark–hadron phase transition (assuming a first-order transition). The field strength obtained is \(10^{-17}\) G on a scale \(10^{10}\) cm at the recombination epoch. This scale is of order 1 au at the present time, very small compared with galactic scales. More recently, Sigl, Olinto & Jedamzik (1997) obtained for the seed field, generated in a first-order phase transition, strengths \(10^{-20}\) G on a 10 Mpc scale for the electroweak transition and \(10^{-20}\) G for the QCD transition.

The generation of primordial magnetic fields in the early Universe, as a consequence of the electroweak phase transition, has been studied more recently by Törnkvist (1997, 1998) and Olesen...
(1998). In particular, Olesen showed that at the electroweak scale, considering that the magnetic field is essentially random, it is necessary to produce a field $B < 10^{-15}$ G such that at the present time we have a primordial magnetic field of order $10^{-15}$ G on a scale of 100 kpc.

Barrow et al. (1997) have obtained, through a statistical analysis of the four-year COBE data, an upper limit of $B_0 < 3.4 \times 10^{-16}$ G for the present strength of any primordial homogeneous magnetic field. This limit is important because it restricts the value of the seed field during the pre-recombination epoch.

Opher & Wichoski (1997) suggested that the origin of the magnetic field is due to a non-minimal electromagnetic–gravitational coupling. Assuming that the magnetic dipole moment is proportional to the angular momentum with the proportionality constant normalized to existing observations, Opher & Wichoski (1997) obtained galactic magnetic fields comparable to those observed $(\gtrsim \mu$ G).

For stars, a totally spontaneous mechanism of generating magnetic fields, not requiring seed fields, was suggested. It is the Biermann mechanism (Biermann 1950) that depends on the differential rotation in stars. As pointed out by Kemp (1982), what creates the Biermann effect is the difference in the acceleration imparted to the electrons, as compared to the ions, by the differential pressures. The difference in acceleration results in currents generating a double toroidal magnetic field, with the magnetic fields being oppositely circulating in the upper and lower hemisphere (the upper and lower hemispheres are defined with respect to the rotation axis).

Several works deal with this mechanism (e.g., Mestel & Roxburgh 1962 and Roxburgh 1966). In particular, Roxburgh (1966) analysed whether or not there is a meridional circulation in stars.

Recently, Kulsrud et al. (1997) suggested a mechanism of generating protogalactic magnetic fields by a Biermann-type mechanism on shocks in the intergalactic medium. Their mechanism generates a seed field of $10^{-22}$ G.

We present here an alternative model to generate a seed magnetic field of magnitude $\sim 10^{-14}$ to $5 \times 10^{-10}$ G which is many orders of magnitude greater than many of the previously suggested scenarios. It also is created over a relatively large scale making it relatively easy to amplify by galactic differential rotation. It is based on the supernovae explosion model of Miranda & Opher (1996, 1997) for large-scale structure formation. Whereas, for example, the Kulsrud et al. (1997) scenario requires a very strong dynamo action to amplify the seed magnetic field of $\sim 10^{-21}$ G to presently observed values of $\sim 10^{-6}$ G, our scenario requires only a relatively mild amplification.

The mechanism proposed here for generating seed magnetic fields is based on the study of Lazarian (1992). It is a Biermann-type mechanism because it requires that the electronic temperature and density gradients are not parallel so that the limit of the anisotropy observed in the cosmic background radiation. The multiple explosion scenario was recently retaken by Miranda & Opher (1996, 1997). They showed that, within the limits of their model, the multiple explosion scenario can produce large voids with Compton-$y$-distortions compatible with the COBE limits.

In Section 2, we show that it is possible to generate seed magnetic fields $\sim 10^{-12} - 10^{-14}$ G on scales of galactic clusters and in Section 3 up to $\sim 4.5 \times 10^{-10}$ G on $\sim 100$ kpc scales. These seeds can be amplified during galactic formation to the observed values $\sim 1 \mu$ G by a dynamo mechanism. Our discussion and conclusions are presented in Section 3.

2 THE MODEL

When magnetic fields are present, we use magnetohydrodynamics to follow their effects. In this work we consider that the electrical conductivity is infinite. Thus, using Ohm’s law in the Faraday equation, we have

$$\frac{\partial B}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B})$$

(1)

On the other hand, Miranda & Opher (1996, 1997) showed that the multicycle explosion scenario produces voids with characteristic radii $\sim 18 - 40$ Mpc (with the present value of the Hubble constant $h = 0.5$, in units of $100 \text{ km s}^{-1} \text{Mpc}^{-1}$). In this turbulent ambient medium formed by the explosions of Population III objects, we have a high probability for the formation of a temperature gradient not parallel to the density gradient.

The process proposed by Biermann (1950) is an efficient battery mechanism (compared with, for example, the battery mechanism based on Compton drag) because it can act on scales smaller than the galactic scale. Thus, we include an additional term in the prior equation given by (see Lazarian 1992)

$$\frac{\partial B}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \frac{4k_B T}{\pi e} \left[ \nabla n_e (r) \times \nabla T (r) \right] T$$

(2)

where $n_e$ is the electron density, $T$ is the temperature and $\mathbf{v}$ is the velocity of the shock front.

The second term on the right-hand side of equation (2) is similar to the original Biermann mechanism, with the difference that we do not require rotation of the medium (as proposed by Biermann). It is worth stressing that an electromotive force can also be generated if there is a non-symmetric distribution of ions with different masses (e.g. the study made by Mestel & Roxburgh 1962).

For a fluid in which shocks and photoheating can occur, temperature and density gradients are naturally not parallel so that $\nabla T \times \nabla n_e \neq 0$. As shown by Miranda & Opher (1996, 1997), the multicycle explosive scenario for void formation produces a sequence of supernova explosions at high and moderate redshifts, beginning from the collapse of a Population III object.

At redshifts $z > 8$, the main mechanism for cooling the shell of matter is the Compton cooling mechanism. This mechanism quickly produces a dense shell of matter where globules (that is, new gravitationally bound objects) are formed. These globules could be composed of stellar clusters of high mass, because the short Compton cooling time and the absence of metals favours the fragmentation of the globules into stars of high mass (that have a short lifetime). Thus, the explosion of these ‘stellar clusters’ produces a turbulent medium where gradients of density and temperature that are not parallel can appear.

When the mass contained in a sphere of radius half the shell thickness is equal to the Jeans mass, objects (or globules) of mass $\sim m$ within the shell begin to collapse. The mass of these objects is
obtained from
\[ \delta m = \left( \frac{M_S}{4\pi R_S^2} \right) \frac{4\pi}{3} \left( \frac{\xi}{2} \right)^3 \]  
(3)
where \( \xi \) is the shell thickness, \( M_S \) is the total mass contained inside the shell and \( R_S \) is the radius of the shock front.

The temperature gradient exists inside the shell in the time interval from the explosion of the globules until the thermalization of the shell. Assuming that when the globules explode the characteristic separation distance between two globules is of the order of the shell thickness, we have
\[ \nabla n(r) = \frac{\Delta n}{n} = \frac{1}{\xi f_n} \]  
(4)
and
\[ \nabla T(r) = \frac{\Delta T}{T} = \frac{1}{\xi f_T} \]  
(5)

In equations (4) and (5), the density gradient occurs over a distance \( \xi f_n \) and the temperature gradient over a distance \( \xi f_T \). In general, \( f_n \) and \( f_T \) are less than 1/2 (and can be very much less). We then have \( f_n f_T = 0.25 F \) with \( F \leq 1 \). In the present investigation we consider that \( F \) is in the interval 0.01 to 1.

Thus, we obtain from equation (2)
\[ \frac{\partial B}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B}) + \frac{16k_0 cT}{\pi \xi^2 F} \left[ \frac{\Delta n}{n_c} \frac{\Delta T}{T} \sin(\phi) \right], \]  
(6)
where \( \phi \) is the angle between the temperature and density gradients. The value \( \phi = \pi/2 \) determines the upper limit to the seed magnetic field produced in the multiple explosion scenario. After the explosion of the globules, we assume that the strong shock condition is maintained. Thus, from the usual Rankine–Hugoniot relation, we have \( \Delta n_1 n_2 = 4 \). The temperature gradient occurs over the distance \( \xi f_T \) in equation (5) and, over this distance, we may expect \( \Delta T \sim T \) owing to the fact that immediately after the explosion of the globules the temperature of the shock front is \( \sim 10^8 \) K while the temperature of the material external to the shock front is several orders of magnitude lower. Thus, we obtain in equation (6)
\[ \frac{\partial B}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B}) + \frac{64k_0 cT}{\pi \xi^2 F}. \]  
(7)

It is worth stressing that the angle \( \pi/2 \) produces an upper limit to the seed magnetic field produced in this scenario, as mentioned above. On the other hand, when the globules are formed within the shell of matter, these objects have sufficiently small cross-sections such that the external medium does not impede their propagation. The objects formed maintain their peculiar velocity \( V_p = V_S - V_H \), where \( V_H \) is the Hubble flow (see Miranda & Opher 1996). In this situation, when the expansion of the globules occurs, the density gradient is in the direction of the shell expansion, while the temperature gradient is situated between the globules (until the thermalization of the shell). In this case, the angle between the two gradients is not much smaller than \( \pi/2 \).

When the globules are formed and begin to collapse, the first term on the right side of equation (7) is not active. On the other hand, during this phase of evolution, the magnetic field is frozen in the matter of the globules and from the conservation of the magnetic flux we need to include an additional term on the right-hand side of equation (7) to take into account the variation with time of the area of the globules during the shell collapse. Thus
\[ \frac{\partial B}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B}) + \frac{64k_0 cT}{\pi \xi^2 F} - \frac{2B}{\xi} \frac{d \xi}{dt}. \]  
(8)

It is worthwhile noting that the three terms on the right-hand side of equation (8) act during well-defined phases. The first term acts during the shell expansion phase. The second term acts during a short time after the explosion of the globules when a temperature gradient exists in the shell. The third term acts during the collapse of the globules when the temperature inside the shell is lower than the Jeans temperature.

By the conservation of magnetic flux, a magnetic field present in the Universe decreases as a function of the scalefactor \( (B \propto a^{-2}) \). On the other hand, during the shell expansion phase, when the first term on the right-hand side of equation (8) is important, the shell expands with a velocity greater than the expansion rate of the Universe. Thus, as a result of the fact that the field is frozen into the matter, it decreases as \( B \propto R_S^{-2} \), where \( R_S \) is the radius of the shock front.

In the last explosion cycle of our model, the seed magnetic field is increased owing to the growth of the density contrast of the globules (which may collapse to form quasars and galaxies) in relation to the ambient medium (that is \( \delta \rho / \rho \sim 10^5 \), where \( \rho \) is the ambient density). The final collapse can increase the intensity of the seed magnetic field by a factor \( \sim 3000 \). Our final (present) seed magnetic field takes this factor into account.

In Table 1 we have the present value of the seed magnetic field produced by the collapse and explosion, at an initial redshift \( z_i \), of a Population III object with mass \( M_0 \). The evolution in explosion cycles generates large shells of matter with a Compton y-distortion within the limit imposed by the COBE satellite (\( y \leq 1.5 \times 10^{-5} \), see Miranda & Opher 1996, 1997). The explosion models, presented in Table 1, produce voids within the range 18–26 Mpc. The last column of Table 1 shows the coherence length \( L \) of the magnetic field. The magnetic field \( B \) in the table is for \( F = 0.01 \). For other values of \( F \), the magnetic field \( B \) is approximately proportional to \( F^{-1} \).

3 DISCUSSION AND CONCLUSIONS

The results presented in Table 1 show that seed magnetic fields with intensity \( \sim 10^{-12}–10^{-14} \) G (for values of \( F \) within the interval 0.01 – 1) can naturally be produced in the multicycle explosion scenario, without any previous seed magnetic field in the beginning of the explosions. The intensity of this seed field is sufficiently high to produce, by future dynamo amplification (for example the \( \alpha - \omega \) dynamo), a magnetic field with intensity \( \sim \mu G \) (on the order of typical galactic magnetic fields). The coherence length \( L \) of these seed fields is \( \sim 1.8 \) Mpc, the typical dimension of clusters of galaxies.

As a result of the low values of the seed magnetic fields produced by the previous suggested mechanisms, it is questionable if the dynamo mechanisms have enough time to amplify the suggested

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<th>Table 1. Seed magnetic field.</th>
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<td>( M_0(M_0) )</td>
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The present value of the seed magnetic field \( B \), and its respective coherence length \( L \), produced by the collapse and explosion, at initial redshift \( z_i \), of a Population III object with mass \( M_0 \).
seed fields to the observed values. The amplification time-scale in
the protogalactic disc is of the order of the rotation period of the
disc, ~3 × 10³ yr. Our proposed mechanism creates relatively high
values of the magnetic field over a large coherence length so that the
dynamo mechanism can be effective.

Because of the large initial magnetic field, the dynamo action
needs to operate only over a relatively short time. Comparing with
the models previously proposed for the production of magnetic
fields, our mechanism produces seeds of the greatest intensity. In
this model, the generation of the magnetic field occurs after the
recombination era as a result of the formation of the structures of the
Universe.

The generation of seed magnetic fields, as a consequence of the
explosive scenario for the formation of the large-scale voids, is
consistent with the detection of a large-scale intercluster magnetic
field, found in the Coma supercluster, with an estimated strength of
0.3–0.6 μG. This detected magnetic field could be the result of a
primordial field, generated and amplified during the formation of
the supercluster (Kim et al. 1989). It is worth mentioning that
coherence of the magnetic field over a large scale (e.g., the Coma
supercluster) could occur via reconnection over causally uncon-
neected regions (Hogan 1983).

It is interesting to note that the magnetic field can have several
effects on the history of the Universe (e.g. Kronberg 1994). The
question of whether magnetic fields are amplified is relevant in
several areas related with the formation and evolution of galaxies
(e.g Rees 1978; Coles 1992). For example, stellar formation can
change for different values of the magnetic field. That is, the star
formation rate and the distribution of stellar masses can be modi-
cated, because the magnetic field alters the Jeans mass and is
important in the loss of angular momentum during protostellar
collapse. Also, as shown by Wasserman (1978), and more recently
by Kim, Olinto & Rosner (1996), a primordial magnetic field can
have a direct effect on triggering galaxy formation. Early creation
of magnetic fields can also play an important role in particle
cosmology by modifying the clustering properties of dark matter
particles sensitive to the presence of a magnetic field (Enqvist
1998).

Although in Table 1 we present only models that produce
large voids with present radii RŞF > 18 Mpc, an interesting
characteristic of the multiple explosion scenario is that, indepen-
dent of the radius of the void formed, a seed field can naturally
be produced. For example, in the multipycle explosion model,
the explosion of an object with initial mass 10⁹ M☉ (a typical
mass of a globular cluster) at redshift z = 25 produces a small
void with a present diameter 1.5 Mpc but with a magnetic field
of strength 4.5 × 10⁻¹⁰ G (with F = 0.01) and a coherence length
~100 kpc.

A void with radius 1.5 Mpc certainly makes a small contribution
to the formation of the large-scale structures of the Universe.
However, on the other hand, these small voids formed by explosions
can be very important for the generation of seed magnetic fields on
galactic scales.

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