Origin of the Magnetic Field in Young Galaxies

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Abstract. The primordial origin of magnetic fields in young galaxies is a challenging problem. Several mechanisms have been proposed, in general, concerning the generation of small seed fields later amplified by a dynamo processes. Miranda & Opher (1996) studied the explosion of Population III objects as the origin of the large scale voids and the young galaxies in their shells. The explosion creates a shock wave that compresses the matter in front of it creating a dense shell. This shell eventually becomes gravitationaly unstable, fragmenting into objects that form a new generation of supernovae. This occurs several times generating the voids. We present a mechanism of magnetic field generation in these shells based on a Biermann type mechanism. We obtain galactic magnetic fields $B \sim 10^{-16} \, G$ that can act as a seed field for further amplification by a dynamo mechanism.

1. Introduction

The origin of primordial magnetic fields is one of the most important problems in astrophysics. There are evidences from Faraday rotation for the presence of magnetic fields in $\La$ clouds at $z \geq 2$. Magnetic fields can affect the formation of galaxies (Rees 1978; Coles 1992) and primordial nucleosynthesis (Cheng et al. 1993). Several models have been suggested for the primordial origin of a seed field that would be amplified by the dynamo mechanism. Harrison (1970) proposed a mechanism in which a battery would operate before the recombination epoch. But it requires that the primordial perturbations would have a non-zero vorticity. His mechanism generates a field $\sim 10^{-18} \, G$. Tajima et al (1992) proposed that a magnetic field would be generated due to electromagnetic fluctuations that exist in a primordial plasma in thermal equilibrium. The resultant field is of the order of $\sim 10^{-18} \, G$. Turner and Widrow (1988) proposed that inflation could generate the seed field. Quashnock et al. (1989) proposed a generation mechanism during the quark-hadron phase transition. Their mechanism produces at $\sim 10^{-17} \, G$.

We investigate the origin of the primordial magnetic field in young galaxies in the explosive scenario for the creation of large voids in the universe. The explosive scenario was initially suggested by Cowie & Ostriker (1982) and most recently studied by Miranda & Opher (1996).
2. The Model

We use the multicycle explosive model developed by Miranda & Opher (1996). A Population III object collapses (and explodes) creating a shock. The shock sweeps up matter, increasing its density (by a factor of 4 for a strong shock) and heats the material to a high temperature. The swept up material cools down, and eventually spheres of radii equal to half the shell thickness form. The spheres collapse and then explode. Later, the supernovae shells coalesce and transfer their energy to the large shock forming the void. The model take into account energy loss processes such as Compton and radiative cooling.

We know (e.g., Lazarian 1992) that a Biermann type effect appears when there exists gradients of temperature and density that are not parallel. A magnetic field is then created at a rate

$$\frac{\partial B}{\partial t} = \frac{4k_Bc T}{\pi e} \left[ \frac{\nabla n(x)}{n} \times \frac{\nabla T(x)}{T} \right], \quad (1)$$

where $c$ is the velocity of light, $T$ the temperature as a function of the distance $x$ and $n$ the density, also a function of the distance.

In our case, the Biermann effect acts behind the shell, after the explosion of the supernovae where a gradient of temperature exists. The density gradient is perpendicular to the shock front. The temperature gradient is between the diverse globules in the shell. The two gradients are almost perpendicular to one another. We assume that the distance between the globules $\sim$ the shell thickness $\sim 1/12R_*$. We have

$$\frac{\nabla n(x)}{n} \sim \frac{\Delta n}{\Delta x n} \sim \frac{\Delta n}{n} \frac{1}{\xi}; \quad \frac{\nabla T(x)}{T} \sim \frac{\Delta T}{\Delta x T} \sim \frac{\Delta T}{T} \frac{1}{(R_*/24)}, \quad (2)$$

and Eq. (1) becomes,

$$\frac{\partial B}{\partial t} = \frac{4k_Bc T}{\pi e} \frac{1}{\xi} \left( \frac{24}{R_*} \right) \left[ \frac{\Delta n}{n} \frac{\Delta T}{T} \sin \phi \right], \quad (3)$$

For a strong shock, $\frac{\Delta n}{n} = 3n/n = 3$. We take $\frac{\Delta T}{T} = 0.5$.

From magnetic flux conservation, an additional term has to be added to Eq. (3), taking into account the change in area with time. Eq. (3) then becomes,

$$\frac{\partial B}{\partial t} = K(t) - B(t) \left[ \frac{1}{R_*(t)} \frac{dR_*}{dt} + \frac{1}{\xi(t)} \frac{d\xi}{dt} \right], \quad (4)$$

where $K(t)$ is the term due to the Biermann effect, given by Eq. (3), and the second term is due to the variation of area ($\propto R_* \xi$) with time. $\xi$ is related to the anomalous scattering due to turbulence in front of the shock. The magnetic field appears in the thickness $\xi$. We assume that eventually the magnetic field is spread throughout the shell thickness and the final result for the magnetic field is independent of $\xi$. 

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2.1. Compton y-distortion

The explosive model generates distortions in the spectrum of the cosmic background radiation (CBR). The Compton y-distortion per unit length is

$$\frac{dy}{dl} = \frac{n_e(r,t)k_B T_e(r,t)\sigma_T}{m_e c^2},$$

(5)

where \(n_e(r,t)\) is the electron number density and \(T_e(r,t)\) the temperature inside the shell.

The average of the change in y per unit length is

$$\langle \frac{dy}{dl} \rangle = \frac{\sigma_T}{m_e c^2 V_s(t)} \int V_s(t) n_e k_B T_e dV,$$

(6)

where the integral is over the volume of the shell. The shell has a thickness \(R_s/12\) during the entire time of evolution of the shock. We obtain,

$$\langle \frac{dy}{dl} \rangle = \frac{n_e k_B T_e \sigma_T}{4 m_e c^2}.$$

(7)

Defining the filling factor \(F(t)\) as the fraction of the volume of the universe occupied by the shells forming voids we have

$$F(t) = F_f \left(\frac{1}{1+z}\right)^3 \left(\frac{R_s(t)}{R_{st}}\right)^3,$$

(8)

where \(F_f\) is the filling factor at \(z = 0\).

The distortion of the CBR is then

$$y_{comp} = \int_{z_i}^{z_f} \langle \frac{dy}{dl} \rangle F(t) \frac{dl}{dt} dz,$$

(9)

where

$$\frac{dl}{dz} = -c H_0^{-1}(1+z)^{-2}(1+\Omega_0 z)^{-1/2}.$$

(10)

3. Results

We calculate the magnetic field generated in two of the models of Miranda & Opher (1996) that generate a Compton y-distortion compatible with COBE, \(y_{comp} \leq 1.5 \times 10^{-5}\). For the mass of the seed object \(M_0 = 10^7 M_\odot\) and the redshift when the first explosion occurred \(z_{init} = 145\), the magnetic field generated at the present time was found to be \(B = 1.3 \times 10^{-16} G\) with the radius of the shell at the present time \(R_{SF} = 21.0 \ Mpc\). For \(M_0 = 10^8 M_\odot\) and \(z_{init} = 120\) the magnetic field generated was \(B = 0.9 \times 10^{-16} G\) with \(R_{SF} = 24.2\). We used \(h_0 = 0.5\) and \(\Omega_0 = 0.1\) in these calculations.

The collapse to form a galaxy increases the magnetic field. The density contrast of a galaxy with respect to the ambient density is \(\sim 10^5\). The collapse then increases the magnetic field by a factor of \(\sim 3000\). Our seed magnetic field takes this factor into account. From the results above, we see that the seed galactic magnetic field found is \(B \sim 10^{-16} G\) which can be later amplified by the dynamo mechanism.
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References

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