Origin of Magnetic Fields in the Universe due to Nonminimal Gravitational-Electromagnetic Coupling

Reuven Opher[1,*] and Ubirajara F. Wichoski[2,3,†]
[1]Instituto de Astronomia e Geofísica, Universidade de São Paulo, Av. Miguel Stefano, 4.200, CEP 04301-904, São Paulo, SP, Brazil
[2]Department of Physics, Brown University, Providence, Rhode Island 02912
[3]Depto. Física-Matemática, Instituto de Física, Universidade de São Paulo, Caixa Postal 66318, CEP 05389-970, São Paulo, SP, Brazil
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Basically the only existing theories for the creation of a magnetic field (**B**) in the Universe are the creation of a seed field $\sim 10^{-20}$ G in spiral galaxy which is subsequently supposedly amplified up to the observed 10^{-6}–10^{-5} G by a dynamo process or a seed intergalactic field of $\sim 10^{-12}$–10^{-10} G which is amplified by collapse and differential rotation. No satisfactory dynamo theory, however, exists today. We show that a $\sim 10^{-6}$–10^{-5} G magnetic field in spiral galaxies is directly obtained from a nonminimal gravitational-electromagnetic coupling, without the need of significant dynamo amplification. [S0031-9007(97)02296-5]

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As far as we know, cosmic magnetic fields pervade the Universe. Nevertheless, we still do not know their origin, which has been pursued according to two basic possibilities, namely, cosmological (i.e., primordial origin) [1] and Biermann-type battery seed effects [2].

Several alternatives have been suggested to account for the cosmological origin of the seed magnetic field, among them are the following: (i) It could arise during cosmological phase transitions which took place in the early Universe [3,4]. (ii) It could be generated during an early epoch of inflation in inflationary Universe models [5]. (iii) It could emerge in string cosmology from the amplification of the electromagnetic vacuum fluctuations due to a dynamical dilaton background [6]. In any case, however, its strength is constrained by the abundances of the elements formed in big-bang nucleosynthesis [7]. Later, this seed field could possibly be amplified either through a dynamo mechanism from an initial strength of $\sim 10^{-20}$ G [1], or through protogalactic collapse and differential rotation from an initial strength of $\sim 10^{-12}$–10^{-10} G [8,9], to the presently observed 10^{-6}–10^{-5} G [1].

The Biermann-type battery seed effect [2] is based on the fact that a magnetic field could be generated as long as electronic temperature and density gradients are not parallel, generally in a rotating medium. Harrison [10] suggested a pregalactic origin where a cosmic battery could operate before the recombination epoch creating a weak field. This idea has not been pursued because the primordial vorticity required by this mechanism could not be sustained in view of whirls decaying during cosmic expansion (see also [11–13] for a galactic origin of the seed magnetic field in early stages of the galaxy formation).

In the case of a dynamo process, it is generally assumed that the seed field $\sim 10^{-20}$ G is subsequently amplified up to the observed 10^{-6}–10^{-5} G in a spiral galaxy, i.e., an amplification of over 14 orders of magnitude. No satisfactory dynamo theory, however, exists today. Field [14] recently discussed the origin of magnetic fields in spiral galaxies starting from a seed field which is subsequently amplified by dynamo action. The first term of the dynamo equation for the increase of the magnetic field describes the transformation of a poloidal magnetic field into a toroidal magnetic field; the second term, the α term, describes the transformation of the toroidal field back into a poloidal field; and the third term, the β term, describes turbulent diffusion. Field [14] indicates that the traditional values of α and β are $\alpha \sim 10^4$ cm s^{-1} and $\beta \sim 10^{26}$ cm^2 s^{-1}. However, for $\alpha = \alpha_0 \sin(\pi x h^{-1})$ (with h the height of the disk and x the distance perpendicular to the disk) and $\alpha_0 = 2.1 \times 10^4$ and $\beta \cong 10^{26}$, we have the growth rate less than zero (i.e., no dynamo amplification). The dynamo action is thus extremely sensitive to the exact value of α and β used. In general, turbulent velocities are assumed to determine α and β, rather than determining α and β self-consistently (i.e., making sure that the derived α and β create the turbulent velocities assumed). Another problem [15] is that it is assumed in dynamo theory that we have $\sim 10^{10}$ yr to amplify the seed field, but in high redshift (z) systems there is evidence of $B \sim 10^{-6}$ G, requiring dynamo action possibly in $\sim 10^9$ yr.

The other mechanism, distinct from the dynamo and probably the most likely explanation for the galactic magnetic field to date, is the amplification of a seed field by anisotropic protogalactic collapse and differential rotation [8,9,16,17] (and references therein). In this case, a seed field $\sim 10^{-12}$–10^{-10} G, frozen into the galactic gas, is needed. In particular, for spiral galaxies the field has to be also oblique to the rotation vector. Inflation is a good candidate to produce a seed field of this magnitude (e.g., [5] and references therein).

We argue in favor of a protogalactic origin for the $\sim 10^{-6}$ G magnetic field which originates from the angular momentum of the protogalaxies through the nonminimal gravitational-electromagnetic coupling (NMC) between gravitational and electromagnetic fields. Gravitational nonminimal coupling has long been considered in the literature [18–20]. In particular, a lot of work has been done on the nonminimal coupling between gravitational and electromagnetic fields. It has been motivated in part, by the Schuster-Blackett (S-B) conjecture. This conjecture, as Schuster [21] first stated at the turn of the century, says that the magnetic fields of planets and stars arise only from their rotation. In other words, neutral mass currents generate magnetic fields implying the existence of a NMC between gravitational and electromagnetic fields.

An early attempt to encompass the S-B conjecture in a gravitational theory was made by Pauli [22] in the 1930s. During the 1940s and 1950s, after Blackett [23] resuscitated the conjecture, many authors such as Bennett *et al.* [24], Papapetrou [25], and Luchak [26] also attempted to encompass the S-B conjecture in a gravitational theory. Later in the eighties, Barut and Gornitz [27] tried to accomplish this objective as well. The majority of these works were based on the five—dimensional Kaluza-Klein formalism. This formalism was used in order to describe a unified theory of gravitation and electromagnetism with NMC in such a way that the S-B conjecture would be obtained. More recently, De Sabbata and Gasperini [28] proposed a theory where the relation between neutral mass currents and magnetic fields are due to the initial conditions of the Universe, provided that torsion is introduced according to the Einstein-Cartan theory, and the large-number hypothesis of Dirac is assumed. Wesson [29] and De Sabbata and Gasperini [30], based on the relation between magnetic fields and angular momentum as implicated by the S-B conjecture, argued that there is a possible connection between atomic physics and gravitational physics.

Nonminimal gravitational-electromagnetic coupling indicates the relation between the angular momentum $\mathbf{L}$ and the magnetic dipole moment $\mathbf{m}$

$$\mathbf{m} = \left[\beta \frac{\sqrt{G}}{2c} \right] \mathbf{L} . \qquad (1)$$

where β is a constant, G is the Newtonian constant of gravitation, and c is the speed of light. It is important to mention that the relation (1) is speculative and the observational and experimental evidence that exists on its behalf is still not conclusive.

The observational and experimental effort supporting the S-B conjecture includes the early work of Blackett [23], Wilson [31], and Swann and Longacre [32]. More recently, the observational evidence of the S-B conjecture is based on the works of Sirag and Woodward. Sirag [33] compared the predictions of Eq. (1) to the observed values of the ratio of magnetic moment to angular momentum for the Earth, Sun, the star 78 Vir, the Moon, Mercury, Venus, Jupiter, Saturn, and the neutron star Her X-1. The minimum data for β for these objects was 0.12, 0.02, 0.02, 0.11, 0.37, 0.04, 0.03, 0.03, and 0.07, respectively. Excluding the star 78 Vir, the maximum data for β was 0.77 for the planet Mercury (see also [34,35]). Woodward [36] examined the S-B conjecture in the context of pulsar gyromagnetic ratios, for short-period pulsars. He found that (1) β is not the same for all pulsars, (2) young pulsars evolve with their individual value of β, constant for a discernible period of time, and (3) β lies in the range 0.001 to 0.01. In the present paper we suggest that β for galaxies is in the range of 0.01 to 0.1, consistent with the data of Sirag [33] and Woodward [36].

We apply the relation (1) to protogalaxies just after they acquired angular momentum. In order to use this relation for a protogalaxy, we have to discuss the origin of its angular momentum.

At the present moment, it is believed that the angular momentum of galaxies was acquired during the protogalaxy stage through the tidal torques by neighboring protogalaxies [37–39]. The best results are accomplished through N-body simulations [39–42]. In the simulation the angular momentum is written in terms of the spin parameter [41]

$$\lambda = \frac{\omega}{\omega_{\mathrm{sup}}} = \frac{L|E|^{1/2}}{GM^{5/2}} , \qquad (2)$$

that is, the ratio between the actual angular frequency ω of the system and the hypothetical angular frequency ω_{sup} needed to support the system against gravity purely by rotation. Here $|E| \simeq GM^2R^{-1}$ is the binding energy of the system, where R is the radius and M is the total mass of the protogalaxy. From simulations [42] it is obtained that the median value of λ ($\lambda_{\mathrm{med}} \sim 0.05$) for collapsed objects is insensitive to the shape of the initial power spectrum of density fluctuations or the magnitude of its initial overdensity. Spiral galaxies indicate an observed value of the spin parameter $\lambda_0 \sim 0.5$ [41]. It is necessary thus to reconcile the angular momentum due to tidal torques $\lambda_{\mathrm{med}} \sim 0.05$ with the observed value. It is accomplished considering the existence of a halo of dark matter so that the increase of the spin parameter is due to the increase of the binding energy E in Eq. (2) because of the collapse [41]. In this process angular momentum remains constant; i.e., the angular momentum acquired up to the time protogalaxies became far apart (protogalactic decoupling time) is conserved.

We assume that the protogalaxy had a total mass $M \sim 10^{13} M_{\odot}$ corresponding to a large spiral galaxy possessing a halo of dark matter $\sim$10 times the mass of the luminous matter $M_{\mathrm{L}} \sim 10^{12} M_{\odot}$. We also assume that the angular momentum of a protogalaxy increased, until the protogalaxies became sufficiently far apart and

TABLE I. Density $[\rho(z_d)]$, radius $[R(z_d)]$, magnetic field $[B_{\rm NMC}(z_d)]$, angular momentum $[L(z_d)]$, magnetic moment $[m(z)]$ at the decoupling redshift (z_d), and the present magnetic field $B_0(R_{\rm L}, z_d)$ at a radius $R_{\rm L} \simeq 10$ kpc $\simeq 3.1 \times 10^2$ cm for a protogalaxy of total mass $M \sim 10^{13} M_\odot$.

z_d	$\rho(z_d)$ [g cm^{-3}]	$R(z_d)$ [cm]	$B_{\rm NMC}(z_d)$ [G]	$L(z_d)$ [g cm^2 s^{-1}]	$m(z)$ [erg G^{-1}]	$B_0(R_{\rm L}, z_d)$ [G]
100	1.1×10^{-23}	7.6×10^{22}	4.0×10^{-9}	4.0×10^{75}	1.7×10^{61}	5.8×10^{-7}
10	1.4×10^{-26}	7.0×10^{23}	1.5×10^{-11}	1.2×10^{76}	5.2×10^{61}	1.8×10^{-6}
5	2.3×10^{-27}	1.3×10^{24}	3.4×10^{-12}	1.6×10^{76}	7.0×10^{61}	2.4×10^{-6}
2	2.8×10^{-28}	2.5×10^{24}	6.0×10^{-13}	2.3×10^{76}	10.0×10^{61}	3.4×10^{-6}
0.5	3.6×10^{-29}	5.1×10^{24}	1.0×10^{-13}	3.3×10^{76}	1.4×10^{62}	4.8×10^{-6}
~0	1.0×10^{-29}	7.6×10^{24}	3.8×10^{-14}	4.0×10^{78}	1.7×10^{62}	5.9×10^{-6}

decoupled from the other protogalaxies, preserving their angular momentum, **L**, acquired from the tidal interaction with the other protogalaxies. We do not know when protogalaxies decoupled; we thus consider the decoupling redshifts $z_d = 100$, 10, 5, 2, 0.5, and ~ 0. We assume that up to the time of protogalaxy decoupling the mean density of the protogalaxy was roughly that of the Universe $\rho(z) = (1 + z)^3 \rho_0$, where ρ_0 is the present matter density of the Universe ($\rho_0 \sim 1.057 \times 10^{-29}$ g cm^{-3} with $H_0 = 75$ km s^{-1} Mpc^{-1}). The radius of the protogalaxy $R(z)$ is then $R(z) = [(3/4\pi) M \rho(z)^{-1}]^{1/3}$. The angular momentum $L(z)$ acquired by a protogalaxy is

$$L(z) \cong \tfrac{2}{5} \lambda_{\rm med} [G M^3 R(z)]^{1/2}. \qquad (3)$$

As noted above, we assume that $L(z)$ in (3) and consequently $\mathbf{m}(z)$ in (1) are conserved after the decoupling redshift z_d. The magnetic field in the vicinity of the protogalaxy is obtained approximately through the relation $\mathbf{B}_{\rm NMC}(z) \cong \mathbf{m}(z) R(z)^{-3}$. Assuming that the magnetic field of the magnetic dipole is frozen into the plasma part of the galaxy which collapses to a present radius $R_{\rm L} \simeq 10$ kpc $\simeq 3.1 \times 10^{22}$ cm, we obtain a present magnetic field at the radius $R_{\rm L}$, $\mathbf{B}_0(R_{\rm L}, z_d) \cong \mathbf{B}_{\rm NMC}(z_d) [R(z_d)/R_{\rm L}]^3$. Assuming a protogalaxy total mass $M \sim 10^{13} M_\odot$, we present in Table I, at the decoupling redshift z_d, the density of the protogalaxy, $\rho(z_d)$ ($\sim$ambient density), the radius of the protogalaxy $R(z_d)$, the magnetic field $B_{\rm NMC}(z_d)$ taking $R \sim R(z_d)$, the angular momentum $L(z_d)$, the magnetic dipole moment $m(z_d)$, and the present magnetic field $B_0(R_{\rm L}, z_d)$. We have to take into account an additional amplification due to the differential rotation which ranges from 10 to 100.

In Table I we use for β in Eq. (1) $\beta = 0.1$. We also take into account an additional amplification due to differential rotation of order 10. Hence, we obtain for a decoupling redshift $z_d \lesssim 10$ the present magnetic field

$$B_0(R_{\rm L}, z_d) \sim 10^{-6} - 10^{-5} \text{ G}. \qquad (4)$$

As noted above, we suggest a value for β for galaxies 0.01 to 0.1, which is consistent with the observational data of Sirag [33] and Woodward [36]. For β equals 0.01 with an amplification due to differential rotation of 100, we obtain the same values of $B_0(R_{\rm L}, z_d)$ as given in relation (4). We note that for a value of β on the order of unity or greater than unity, the field predicted by NMC mechanism becomes inconsistent with the observations.

We assume that this poloidal field (4) is transformed into a toroidal field by the differential rotation of the spiral galaxy. However, it is possible that a large scale dynamo has influenced only the geometry more than the strength of magnetic fields [1], so transforming poloidal fields into toroidal fields. Nonetheless, we note from (4) that no appreciable dynamo action is necessary to explain the presently observed magnetic field strength for decoupling redshifts $z_d \lesssim 10$.

For a galaxy of total mass less than $10^{13} M_\odot$ we would have a smaller magnetic field. We note from Table I that we have an estimate for the intergalactic magnetic field (the field between protogalaxies) for $z_d \lesssim 2$, $B_{\rm NMC}(z_d) \sim 10^{14} - 10^{-12}$ G. This is consistent with our knowledge of the intergalactic magnetic field [1].

The above discussion was for the origin of magnetic fields in spiral galaxies. We assume that the origin of magnetic fields in other types of galaxies is due to the merger of spiral galaxies or the diffusion of the magnetic field out of spiral galaxies.

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*Electronic address: Opher@vax.iagusp.usp.br
†Electronic address: Wichoski@het.brown.edu

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