On the origins of galactic magnetic fields

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Abstract

We present a five dimensional unified theory of gravity and electromagnetism which leads to modified Maxwell equations, suggesting a new origin for galactic magnetic fields. It is shown that a region with nonzero scalar curvature would amplify the magnetic fields under certain conditions.

1 Introduction

A large number of astrophysical observations based on Faraday rotation, Zeeman splitting, polarization of optical starlight and synchrotron emission prove the existence of magnetic fields in galaxies. A variety of such observations suggest that these magnetic fields are present in all galaxies and galaxy clusters. The properties of these magnetic fields are characterized by their huge spatial coherence scale which is less than 1 Mpc and a modest strength which is of the order of \((10^{-7} - 10^{-5}) G\) [1]. Today, the best numbers obtained for the total strength of the magnetic field in galactic disks give 6 - 7 \(\mu G\) [2, 3]. Also, extra-galactic magnetic fields with large scales which have strengths of \(\sim \mu G\) have been detected by both synchrotron emission and Faraday rotation in clusters like Coma Cluster. Furthermore, beyond clusters, in sparser regions, astonishing magnetic fields of \(\sim 0.1 \mu G\) were measured [4, 5]. In our galaxy, average magnetic fields of the interstellar medium of order \(\sim 5 \mu G\) is detected [6, 7].

Up until now the primordial field theory and dynamo theory have been the main ingredients used to explain the origin of galactic magnetic fields. In the former, galactic magnetic fields which we observe today would be the relics of a coherent magnetic field existing in the early universe before galaxy formation. One can imagine that in a collapsing protogalaxy, the lines of force of the ambient magnetic field (which tend to be frozen into the highly conductive gas) would have been compressed by the gas motions associated with this collapse, and from then on, the differential rotation of the galaxy would have wrapped them up about its center. In the absence of any other process, the galactic magnetic field would be wound up 50 to 100 times the present time, i.e., much more than indicated by observations. The traditional way of resolving this inconsistency is to take into account the magnetic diffusion. But if magnetic diffusion is sufficiently present parallel to the galactic plane to avoid a tight wind-up of magnetic field lines, it must also be true perpendicular to the plane for field lines to diffuse out of the disk. Under these conditions, galactic magnetic fields would have completely decayed away by now, without ever reaching the observed strengths of a few \(\mu G\) [8, 9, 10, 11]. Primordial models are unrealistic since they also neglect deviations from axisymmetric rotation of the gas, such as spiral...
density waves. Furthermore, such models suffer from a fundamental problem; shear by differential rotation increases the average field strength, not the magnetic flux, while magnetic flux is lost into intergalactic space by magnetic diffusion. Estimation of turbulent diffusion leads to a decay time of the field of only $10^8$ yr, meaning that to have a field amplification, one must seek another processes such as field amplification by gas flows or a dynamo effect [10, 12]. In dynamo theory, according to Faraday’s law of induction, moving a conductor through a magnetic field (seed field) induces a current from which a new magnetic field can arise (Ampere’s law). There are different views on the origin of this seed field. One possibility is due to astrophysical processes, such as Bierman battery effect in which the magnetic field is produced by an electric current due to the non-coinciding surfaces of constant pressure and density [2, 13, 14] and the other possibility can be cosmological (primordial origin). A truly cosmological magnetic field is one that cannot be associated with collapsing or virialized structures. Cosmological magnetic fields can include those that exist prior to the epoch of galaxy formation as well as those that are coherent on scales greater than the scale of the largest known structures in the Universe, i.e., $\geq 50$ Mpc [1]. If the last possibility was true then all galaxies would have the same seed field but the field strength in galaxies today would be different because this mechanism depends on the galaxy characteristics such as age, structure, etc. The magnitude of this seed field according to a calculation based on the age of a typical galaxy must have been about $10^{-20} G$ [12, 15]. It seems as if the true combination of the flows of the fields amplifies the original induced field which would then lead to the field amplification that we measure in our observations. In the dynamo model, it is assumed that large scale magnetic fields observed in disk galaxies and spiral galaxies arise from the combined action of differential rotation ($\omega$) and helical turbulence ($\alpha$), a process known as the $\alpha \omega$ dynamo wherein, new field is regenerated continuously by the combined action of these two effects [1]. In this model, the small-scale cyclonic turbulent motions which have acquired a preferred sense of rotation under the action of the Coriolis force stretch and twist the magnetic field lines, imparting a net rotation, whereby the magnetic field is created in the direction perpendicular to the prevailing field which is known as the “alpha-effect.” Thus, in dynamo theory, the large-scale differential rotation stretches magnetic field lines in the azimuthal direction about the galactic center, while small-scale cyclonic turbulent motions regenerate, via the alpha-effect, the meridional component of the field from its azimuthal component. It is the combination of these two complementary mechanisms that leads to magnetic field amplification in galaxies [8, 16].

There are, however, fundamental questions concerning the nature of the dynamo. Magnetic fields are abundantly present in elliptical galaxies and their presence is revealed through observations of synchrotron emission. The standard $\alpha \omega$ dynamo however does not explain the existence of magnetic fields in non-rotating or slowly rotating systems such as elliptical galaxies and clusters. In addition, the time scale for field amplification in the standard $\alpha \omega$ dynamo could be too long to explain the fields observed in very young galaxies [1]. Even if the dynamos work properly, they still need a small seed magnetic field. Therefore, the conventional $\alpha \omega$ dynamo theory may not be able to explain the amplification of the weak seed magnetic fields $\sim 10^{-18} G$ to micro Gauss strengths after $10^9$ years. The basic difficulty is that the growth rate of a large scale dynamo is typically some fraction $\xi$ of the angular velocity $\Omega$ of the galaxy. Typical numbers are $\Omega = 30 Gyr^{-1}$ and $\xi \approx 0.1 - 0.5$. Even in the most optimistic case, the amplification factor after $t = 1$ Gyr is just $\exp(0.5 \Omega t) \approx 10^{6.5}$ [17].

In this work we present an alternative mechanism for explaining the origin of galactic magnetic fields. This is based on the applications of the results obtained from a fresh look at the unification of gravity and electromagnetism. Such a unification, as is well known, was introduced in the early part of the last century by Kaluza and Klein. Over the years, a large number of works centering around the original ideas of Kaluza and Klein have appeared. Our unification scheme is no exception, but leads to Maxwell equations which are modified relative to the standard theory. Surprisingly, such modifications could be used to account for the the origin of galactic magnetic fields for which, as of now, no completely satisfactory explanation exists. We therefore start by a brief introduction to the theory whose results are of great importance in explaining this phenomena. For detailed account, the reader should consult [19].
2 Unification of gravity and electromagnetism

Let us begin by considering a charged particle in the presence of gravitational and electromagnetic fields in free fall with kinetic energy defined as [18]

\[
\frac{1}{2}mV^2 = \frac{1}{2}mg_{\mu\nu}\dot{x}^\mu\dot{x}^\nu - \frac{1}{2}qA_\mu\dot{x}^\mu + \phi',
\]

(1)

\[V^2 = \left(\frac{ds}{d\tau}\right)^2 = g_{\mu\nu}\dot{x}^\mu\dot{x}^\nu - \frac{q}{m}A_\mu\dot{x}^\mu + \phi.
\]

(2)

As for the metric describing the space-time, we write

\[ds^2 = g_{\lambda\beta}dx^\lambda dx^\beta + f_\mu dx^\mu dl + \phi dl dl,
\]

(3)

and assume that \(\frac{df_\mu}{d\tau} = -1\), with \(f_\mu = \frac{q}{m}A_\mu\) being a vector and \(\phi\) a scalar, both in 4-dimensional space-time and \(\dot{x}^\mu = \frac{dx^\mu}{d\tau}\). Also, let us define

\[ds = (dx^0, dx^1, dx^2, dx^3, dl) \quad \text{and} \quad V = (\dot{x}^0, \dot{x}^1, \dot{x}^2, \dot{x}^3, -1),
\]

(4)

and the five dimensional metric as

\[
\hat{g}_{AB} = \begin{pmatrix}
g_{\alpha\beta} & f_0 \\
f_1 & f_2 \\
f_0 & f_1 & f_2 & f_3 & \phi
\end{pmatrix},
\]

(5)

We now assume that all geometrical objects that we define are independent of the fifth coordinate and thus their derivatives with respect to the fifth coordinate is zero. We may then obtain the geodesic equation by minimizing the usual integral

\[\delta s = \delta \int ds = \delta \int V d\tau = 0,
\]

(6)

resulting in

\[
\ddot{x}^\kappa + \frac{1}{2}g^{\lambda\kappa}(g_{\lambda\beta,\alpha} + g_{\lambda\alpha,\beta} - g_{\alpha\beta,\lambda})\dot{x}^\alpha\dot{x}^\beta - \frac{1}{2}g^{\lambda\kappa}(f_{\lambda,\mu} - f_{\mu,\lambda})\dot{x}^\mu - \frac{1}{2}g^{\lambda\kappa}\phi,_{\lambda} = 0,
\]

(7)

where \(V\) is given by equation (2) and \(g_{\lambda\beta}g^{\lambda\kappa} = \delta_\beta^\kappa\). Knowing that \(\dot{x}^4 = -1\), \(f_\lambda = \dot{g}_{4\lambda}\), \(\phi = \dot{g}_{44}\) and partial derivatives with respect to \(x^4\) are zero, we can write (7) as

\[
\ddot{x}^\kappa + \Gamma^\kappa_{AB}\dot{x}^A\dot{x}^B = 0,
\]

(8)

where

\[
\Gamma^\kappa_{AB} = \frac{1}{2}g^{\lambda\kappa}(\dot{g}_{A\lambda,B} + \dot{g}_{B\lambda,A} - \dot{g}_{AB,\lambda}).
\]

(9)

If we write the Riemann tensor

\[
\hat{R}^A_{BCD} = \partial_C\Gamma^A_{BD} - \partial_D\Gamma^A_{BC} + \Gamma^E_{BD}\Gamma^A_{CE} - \Gamma^E_{BC}\Gamma^A_{DE},
\]

(10)

we can easily see that \(\Gamma^4_{AC} = 0\). We then have \(\hat{R}^4_{BCD} = 0\) and

\[
\hat{R}^\kappa_{BCD} = \partial_C\Gamma^\kappa_{BD} - \partial_D\Gamma^\kappa_{BC} + \Gamma^\delta_{BD}\Gamma^\kappa_{CE} - \Gamma^\delta_{BC}\Gamma^\kappa_{DE}.
\]

(11)
We also see that $\hat{R}^\alpha_{BCD}$ is a tensor in four dimensional space which is characterized by $g_{\alpha\lambda}$. Noting that
\[
\Gamma^\gamma_{\alpha\beta} = \frac{1}{2}g^{\lambda\gamma}(\hat{g}_{\alpha\lambda,\beta} + \hat{g}_{\beta\lambda,\alpha} - \hat{g}_{\alpha\beta,\lambda}),
\]
and that $\hat{g}_{\alpha\lambda} = g_{\alpha\lambda}$, we find that $\hat{R}^\alpha_{\beta\gamma\sigma} = R^\alpha_{\beta\gamma\sigma}$ where $R^\alpha_{\beta\gamma\sigma}$ is the usual Riemann tensor. We may now show that
\[
\hat{R}^\alpha_{\beta\gamma\sigma} = \frac{1}{2}\nabla_\alpha F_{\beta\gamma\sigma}.
\]
The first Bianchi identity is
\[
\hat{R}^\alpha_{\beta\gamma\delta} + \hat{R}^\gamma_{\alpha\delta\beta} + \hat{R}^\delta_{\beta\alpha\gamma} = 0,
\]
leading to
\[
\frac{1}{2}\nabla_\kappa F_{\alpha\beta} + \frac{1}{2}\nabla_\beta F_{\kappa\alpha} + \frac{1}{2}\nabla_\alpha F_{\beta\kappa} = 0,
\]
showing that, as expected, it results in the homogeneous Maxwell equations. It is worth mentioning that in other 5D theories, e.g. Kaluza-Klein, equation (14) does not lead to equation (15). Now, introducing the Ricci tensor as $\hat{R}_{BD} = \hat{R}^\alpha_{B\alpha D}$, we can easily see that
\[
\hat{R}^\alpha_{\beta\alpha} = \frac{1}{2}\nabla_\alpha F_{\beta\alpha}.
\]
The field equations can now be written as follows
\[
\hat{G}_{AB} = \hat{R}_{AB} - \frac{1}{2}\hat{g}_{AB}R = 8\pi\hat{T}_{AB}.
\]
The above equation can be cast into the 4D Maxwell and Einstein equations where $R$ is defined as
\[
R = g^{\lambda\alpha}R_{\lambda\alpha}, \quad R_{\lambda\alpha} = \hat{R}_{\lambda\alpha}.
\]
Let us introduce the five dimensional energy-momentum tensor according to
\[
\hat{T}_{AB} = \begin{pmatrix}
T_{\alpha\beta} & \frac{q}{m}\kappa j_0 \\
\frac{q}{m}\kappa j_0 & \frac{q}{m}\kappa j_1 \\
\frac{q}{m}\kappa j_1 & \frac{q}{m}\kappa j_2 \\
\frac{q}{m}\kappa j_2 & \frac{q}{m}\kappa j_3 \\
\frac{q}{m}\kappa j_3 & T_{44}
\end{pmatrix},
\]
where $\kappa$ is a coupling constant and $j$ is the current vector in the 4D space-time. The equation of continuity $j^\alpha_{\alpha} = 0$ now gives us the conservation law. If $A \rightarrow \alpha$ and $B \rightarrow \beta$, equation (17) reduces to the 4D Einstein equation since
\[
\hat{R}^\alpha_{\beta\sigma} = R^\alpha_{\beta\sigma}, \quad \hat{g}_{\alpha\lambda} = g_{\alpha\lambda}, \quad \hat{T}_{\beta\sigma} = T_{\beta\sigma}.
\]
However, if $A \rightarrow \alpha, B = 4$, equation (17) reduces to the Maxwell equations with a correction term
\[
\hat{G}^\alpha_{4\lambda} = \hat{R}^\alpha_{4\lambda} - \frac{1}{2}\hat{g}_{4\lambda}R = 8\pi\hat{T}^\alpha_{4\lambda} = 8\pi\frac{q}{m}\kappa j_\lambda,
\]
and
\[
\nabla_\alpha F^\alpha_\lambda - f_\lambda R = 16\pi\frac{q}{m}\kappa j_\lambda.
\]
Here we have used
\[
\hat{R}^\alpha_{\beta4} = \frac{1}{2}\nabla_\alpha F^\alpha_{\beta}, \quad \hat{T}^\alpha_{4\lambda} = \frac{q}{m}\kappa j_\lambda, \quad \text{and} \quad \hat{g}_{4\lambda} = f_\lambda.
2.1 Modified Maxwell equations

From (22) we can write the modified Maxwell equations as

\[ \partial_\alpha F^{\alpha\beta} + \Gamma^\alpha_{\alpha\lambda} F^{\lambda\beta} = R f^\beta + 16\pi \frac{q}{m} \kappa j^\beta, \]  

(23)

where

\[ F^{\alpha\beta} = \frac{q}{m} \begin{pmatrix} \sqrt{\mu_0 \epsilon_0} E_x & -\sqrt{\mu_0 \epsilon_0} E_y & -\sqrt{\mu_0 \epsilon_0} E_z \\ B_z & 0 & B_y \\ -B_y & B_x & 0 \end{pmatrix}, \]  

(24)

and

\[ f^\beta = \frac{q}{m} (\sqrt{\mu_0 \epsilon_0} \phi A_x A_y A_z), \]

\[ j^\beta = (\rho \sqrt{\mu_0 \epsilon_0} j_x \sqrt{\mu_0 \epsilon_0} j_y \sqrt{\mu_0 \epsilon_0} j_z). \]

3 Origin of galactic magnetic fields

We are now ready to use the results obtained above to show how the galactic magnetic fields are produced. Let us first suppose that our galaxy is disk-like, having a thickness 2\(d\), radius \(l\) which is assumed to be large. The \(z\) axis is taken as being perpendicular to the plane of the disk and the origin of coordinates is on the geometric center of the disk having a homogenous mass density \(\rho\). Now suppose that a plane wave is incident on the disk and passes through the galaxy at \(y = 0\) and \(z = -d\). This wave can be represented by

\[ f^\beta_{in} = \begin{pmatrix} 0 & 0 & 0 & A' \cos(k_2 y + k_3(z + d) - \omega t) \end{pmatrix}, \]

(25)

\[ f^\beta_{out} = \begin{pmatrix} 0 & 0 & 0 & A \cos(k_2 y + k_3(z + d) - \omega t) \end{pmatrix}. \]

3.1 Weak field approximation

We may now use the weak field approximation and write the metric as

\[ g_{mn} = \eta_{mn} + h_{mn}, \]

(27)

where \(\eta_{mn}\) is the Minkowski metric and \(h_{mn} \ll 1\). We then have

\[ \Gamma^\sigma_{\mu\nu} = \frac{1}{2} \eta^{\sigma\rho} (\partial_\nu h_{\rho\mu} + \partial_\mu h_{\rho\nu} - \partial_\rho h_{\mu\nu}), \]

(28)

\[ R = -\Box (\eta^{\sigma\rho} h_{\rho\sigma}) + \partial_\rho \partial_\mu (\eta^{\mu\nu} \eta^{\rho\lambda} h_{\nu\lambda}), \]

(29)

with

\[ h_{00} = h_{11} = h_{22} = h_{33} = h = \frac{-2\phi}{c^2}, \]

(30)

where \(c\) is the speed of light and \(\phi\) is the Newtonian potential. Newtonian potential for the galaxy model described above can be easily written as follows

\[ \phi_{in} = 2\pi G \rho z^2, \quad \phi_{out} = 4\pi G d \rho z - 2\pi G \rho d^2, \]

(31)
where the indices refer to the inner and outer galaxy regions. Then we have

\begin{align*}
  h_{\text{in}} &= -\frac{4\pi G \rho z^2}{c^2}, \\
  R_{\text{in}} &= \frac{8\pi G \rho}{c^2}, \\
  h_{\text{out}} &= -\frac{8\pi G \rho dz}{c^2} + \frac{4\pi G \rho d^2}{c^2}, \\
  R_{\text{out}} &= 0,
\end{align*}

(32)

\( \Gamma_{\text{in} \alpha} = \Gamma_{\text{in} \alpha_0} = \Gamma_{\text{in} \alpha_1} = \Gamma_{\text{in} \alpha_2} = 0 \), \quad \Gamma_{\text{out} \alpha} = \Gamma_{\text{out} \alpha_0} = \Gamma_{\text{out} \alpha_1} = \Gamma_{\text{out} \alpha_2} = 0,

\( \Gamma_{\text{in} \alpha_3} = -\frac{8\pi G \rho z}{c^2}, \quad \Gamma_{\text{out} \alpha_3} = -\frac{8\pi G \rho d}{c^2} \).

for more detailed description see [20]. If \( k_3 \) is arbitrarily small and \( \omega \) tends to zero, equations (25) and (26), to a good approximation, are the solutions of equation (23) and we have

\begin{align*}
  k_2^2 &= \frac{\varphi^2}{c^2} (1 + h_{\text{out}}) \left( \frac{1}{1 - h_{\text{out}}} \right), \\
  k_2' &= \frac{\varphi^2}{c^2} (1 - h_{\text{in}}) + \frac{R}{1 - h_{\text{in}}}, \\
  \end{align*}

(33)

where the terms containing higher orders of \( \frac{G \rho}{c^2} \) have been neglected.

\section*{3.2 Continuity of currents}

Since currents must satisfy continuity equations, so does our new current. This means that we must have

\[ \nabla_\beta (R f^\beta) = 0. \quad (34) \]

By neglecting higher orders of \( \frac{G \rho}{c^2} \) we are led to

\[ R \partial_\beta f^\beta = 0. \quad (35) \]

Since \( R \) is very small, this equation is approximately satisfied.

\section*{4 Boundary conditions}

Since the metric should be continuous across the the boundaries \( y = 0 \) and \( z = -d \), we find from equations (25) and (26) that \( A = A' \). If our goal is to find the ratio of the field strengths, we can neglect the terms containing \( \frac{G \rho}{c^2} \) in the Faraday tensor. Therefore, from equations (25) and (26) we find

\begin{align*}
  F_{\text{in} 03}^{03} &\approx A' \frac{\varphi}{c} \sin(k_2' y + k_3' (z + d) - \omega t), \\
  F_{\text{out} 03}^{03} &\approx A' \frac{\varphi}{c} \sin(k_2 y + k_3 (z + d) - \omega t), \\
  F_{\text{in} 23}^{23} &\approx A' k_2' \sin(k_2' y + k_3' (z + d) - \omega t), \\
  F_{\text{out} 23}^{23} &\approx A k_2 \sin(k_2 y + k_3 (z + d) - \omega t).
\end{align*}

(36)

Now it is clear that

\[ h_{\text{in}} = h_{\text{out}}|_{\text{boundary}}, \quad \frac{E_{\text{in}}}{E_{\text{out}}} = 1|_{\text{boundary}}, \quad \frac{B_{\text{in}}}{B_{\text{out}}} = \frac{k_2'}{k_2}|_{\text{boundary}}. \quad (37) \]

We finally obtain the desired relation

\[ \frac{B_{\text{in} x}}{B_{\text{out} x}} \approx \sqrt{1 + \frac{R c^2}{\omega^2}}. \quad (38) \]

Now for the average density of a galaxy [21], \( \bar{\rho} \sim 10^{-21} km^{-3} \), the seed magnetic field which is of order of \( \sim 10^{-20} G \) would be amplified to \( \sim 10^{-6} G \), if we take \( \omega \sim 10^{-29} Hz \). This indicates that galactic magnetic fields are almost static.
5 Conclusions

In this paper we have employed a theory resulting from a fresh look at the unification of gravity and electromagnetism, developed previously, to explain one of the most intriguing phenomena at the galactic scales, namely the origins of the unexpectedly large magnetic fields which one measures within galaxies. We showed that if an electromagnetic field is incident upon a galaxy parallel to its plane, it would be amplified because of the coupling of the vector potential to the scalar curvature produced by the mass distribution in the galaxy. We have also shown that the amplification occurs for magnetic fields which are almost static, an assumption common in such investigations.

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