GALACTIC MAGNETIC FIELDS: A GENERIC PREDICTION OF INFLATION

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Introduction

Observed Galactic Magnetic Fields: $B_0 \sim \mu$Gauss

Generated by Dynamo: Seed Field Required with:

Strength: $B_{\rm seed} \sim 10^{-(20-30)}$Gauss
Coherence: $l \sim 100$ pc (turb. eddy)

Astrophysical Seed Fields

- Biermann Battery: large-scale radio-jets
- Stellar Fields: hen-egg problem
- Vorticity: strong ionization of plasma

Primordial Seed Fields

Magnetic Field generation ⇒ NO Thermal Equilibrium
- Thermal photon distribution ⇒ ∄ long-range currents
- Long-range magnetic field breaks isotropy

- **Phase Transitions**
  Causal production ⇒ Generated seed field extremely incoherent due to small comoving size of Horizon

- **Magnetic Fields during Inflation**
  Conformal invariance of electromagnetism ⇒ $B \propto a^{-2}$ during Inflation ⇒ $|B|$ exponentially suppressed

We show that ∃ natural breaking of conformal invariance during inflation ⇒ enhances generation of field strength enough to successfully seed the galactic dynamo

Inflation and Magnetic Fields

Inflation in brief

Spatially-Flat Friedman Equation: $\Rightarrow \dot{a} = (8\pi G/3)\sqrt{\rho}\, a$

Inflation: $\rho \simeq V(\phi) \simeq$ const. $\Rightarrow\ a \propto e^{Ht}$ $(H \equiv \dot{a}/a \simeq \text{const.})$

During inflation: $T \propto a^{-1} \rightarrow 0$ (Supercooling)

Reheating: $V_{\rm end} \rightarrow$ Thermal bath of HBB $(T_{\rm reh} \sim V_{\rm end}^{1/4})$

Solves: Horizon, Flatness, Monopole + LSS & CMBR

Magnetic Fields by Inflation

Inflated quantum fluctuations of gauge fields $\Rightarrow$ long-range gauge fields with superhorizon correlations.

Basic idea: Conformal invariance breakdown of massive Z_μ generates a substantial superhorizon Hypermagnetic field which projects onto the photon at EW-transition.

During Inflation: Supercooling $\Rightarrow$ all symmetries broken

Typically $T_{\rm reh} > 100$ GeV $\Rightarrow$ EW-restored $(A_\mu, Z_\mu \rightarrow Y_\mu)$

Hypercharge: $Y_\mu = \cos\theta_W A_\mu - \sin\theta_W Z_\mu$

Hypermagnetic field: $\boldsymbol{B}^Y \equiv \boldsymbol{\nabla} \times \boldsymbol{Y}$

Possible hyperelectric component = Debye screened

Y_μ: Abelian $\Rightarrow B_\mu^Y$ freezes in reheated plasma $\Rightarrow B^Y \propto a^{-2}$

Non-Abelian W_μ's screened (Magnetic mass: $M_T^2 \approx 0.28 g^2 T$)

EW-transition $Y_\mu \rightarrow A_\mu$: $A_\mu = \cos\theta_W Y_\mu + \sin\theta_W W_\mu^3$

Magnetic field at EW-transition: $B_\mu \simeq \cos\theta_W B_\mu^Y$

Z production during Inflation

Initial amplitude at Horizon crossing

Quantum fluctuation: $\Delta\mathcal{E} \cdot \Delta t \simeq 1$

Compton wavelength > Horizon $\Leftrightarrow\ M_Z < H\ \Rightarrow$

$\Delta\mathcal{E} \sim [\partial(\delta Z)]^2 \Delta V$ with $\left.\begin{array}{l}\Delta V \sim H^{-3}\\ \Delta t \sim H^{-1}\end{array}\right\}$ (Horizon crossing)

$\partial \sim \Delta t^{-1} \sim H$ (randomness)

$$\delta Z \simeq \frac{H}{2\pi} \quad \text{(Gibbons Hawking T)}$$

Particle Horizon in Inflation $\Leftrightarrow$ Event Horizon of inverted Black Hole

Self-similarity of De-Sitter space: $\delta Z =$ indept of $t_{\rm x}$

After Horizon-crossing: fluctuation $\rightarrow$ classical object $\Rightarrow Z$: produced gravitationally on superhorizon scales

Superhorizon evolution during inflation

Classical equation of motion: $[D_g \equiv \det(g_{\mu\nu})]$

$$[\partial_\mu + (\partial_\mu \ln\sqrt{-D_g})][g^{\mu\rho}g^{\nu\sigma}(\partial_\rho Z_\sigma - \partial_\sigma Z_\rho)] + M_Z^2 g^{\mu\nu} Z_\mu = 0$$

Spatial component: $[g_{\mu\nu} = \text{FRW} \Rightarrow D_g = -a^6]$

$$\partial_t^2 Z_i - \partial_t\partial_i Z_t + H(\partial_t Z_i - \partial_i Z_t) + a^{-2}(\partial_j\partial_j Z_i - \partial_i\partial_j Z_j) + M_Z^2 Z_i = 0$$

Fluctuation = causally connected at Horizon-crossing +
FRW = Homogeneous and Isotropic $\Rightarrow$ Ignore ∂_i

$$\ddot{Z} + H\dot{Z} + M_Z^2 Z = 0$$

Solve with $Z_x = H/2\pi$, $\dot{Z}_x = -H^2/2\pi$ and $M_Z \simeq$ const.

$$Z(t) = -\tfrac{H}{4\pi\nu}(\tfrac{1}{2}-\nu)\, e^{-H\Delta t(\frac{1}{2}-\nu)} + \tfrac{H}{4\pi\nu}(\tfrac{1}{2}+\nu)\, e^{-H\Delta t(\frac{1}{2}+\nu)}$$

$\Delta t = t - t_x$ & $\nu \equiv \sqrt{\frac{1}{4} - (\frac{M_Z}{H})^2} \simeq \frac{1}{2} - (\frac{M_Z}{H})^2 \quad (M_Z \ll H)$

Self-similarity of De-Sitter space $\Rightarrow$ independent of t_x

$$a \propto e^{Ht} \Rightarrow \quad k(t) = \tfrac{a(t_x)}{a(t)} H \quad \Rightarrow \quad e^{-H\Delta t} = \frac{k(t)}{H}$$

$$Z(k) \;=\; -\frac{H}{2\pi}\left(\frac{M_Z}{H}\right)^2 \left(\frac{k}{H}\right)^{(M_Z/H)^2} + \frac{H}{2\pi}\left(\frac{k}{H}\right)$$

Superhorizon spectrum: $k = k(t_{\rm end})$, $(k < H \Leftrightarrow t_x < t_{\rm end})$

Photon versus Z

In inflation: $M_Z = g_Z\sqrt{\langle\Psi^\dagger\Psi\rangle} = g_Z(\frac{H}{2\pi})\sqrt{\Delta N} \propto \sqrt{\ln(k/k_0)}$

Ψ = EW-Higgs, $g_Z = g/\cos\theta_W$, $\Delta N = \ln(a_0/a_x)$

Every e-folding $\delta\psi \sim H/2\pi \Rightarrow \sqrt{\langle\Psi^\dagger\Psi\rangle}$ corresponds to random walk in inner space of ΔN steps $\Rightarrow \sqrt{\Delta N}$ factor

$$(\tfrac{M_Z}{H})^2 = (\tfrac{g_Z}{2\pi})^2 \ln(k/k_0) \sim 0.01 \gg (k/H) \Rightarrow$$

$$Z(k) \simeq \frac{H}{2\pi}\left(\frac{M_Z}{H}\right)^2 \left(\frac{k}{H}\right)^{(M_Z/H)^2} \sim \frac{H}{2\pi}\left(\frac{M_Z}{H}\right)^2$$

Superhorizon Z-spectrum $\simeq$ scale invariant (+ log tilt)

Photon case: $M_A = 0 \Rightarrow \quad A(k) = k/2\pi \quad \ll Z(k)$

Magnetic field at galaxy formation

$Y = \sin\theta_W Z$, $B = \cos\theta_W B^Y$ and $B^Y_{\rm rms}(t_{\rm end}) = k(t_{\rm end}) Y_{\rm rms}$

$$k(t) \propto a^{-1} \propto T \quad \Rightarrow \quad k(t_{\rm end}) = \frac{2\pi}{\ell}\left(\frac{T_{\rm reh}}{T_{\rm CMB}}\right)$$

$$B(t) \propto a^{-2} \propto T^2 \quad \Rightarrow \quad B_{\rm rms}(t_0) = \cos\theta_W \, B^Y_{\rm rms}(t_{\rm end}) \left(\frac{T_{\rm CMB}}{T_{\rm reh}}\right)^2$$

Back to galaxy formation using: $a_0/a_{\rm gf} = 1 + z_{\rm gf}$

$$B_{\rm rms}(t_{\rm gf}) \;=\; \pi \sin(2\theta_W)(1+z_{\rm gf})^2 \frac{T_{\rm CMB}}{\ell}\frac{Z_{\rm rms}}{T_{\rm reh}}$$

Galactic collapse amplification: $(\rho_{\rm gal}/\rho_0)^{2/3} \approx 5 \times 10^3$

$$B^{\rm gal}_{\rm rms} \;=\; 8.3 \times 10^{-28} \left(\frac{1\ {\rm Mpc}}{\ell}\right) \frac{Z_{\rm rms}}{T_{\rm reh}} \ {\rm Gauss}$$

Comoving scale of largest turbulent eddy: $\ell \sim 10$ kpc

GUT-scale Inflation: $B_{\rm seed} \sim 10^{-30}$Gauss

Sufficient to trigger galactic dynamo for dark energy dominated, spatially flat Universe ($\Omega_\Lambda \simeq 0.65, \Omega_{\rm tot} = 1$)

Conclusions

- All GUT-scale inflationary models generate magnetic fields of enough strength and coherence to successfully seed the galactic dynamo and explain thereby the observed galactic magnetic fields

- The magnetic field is generated due to the gravitational production of the Z-boson field, whose conformal invariance is naturally broken during inflation

- The superhorizon spectrum of Z is approximately scale invariant and is projected onto the Hypercharge field at reheating when EW-symmetry is restored. The corresponding hypermagnetic field freezes into the plasma and evolves satisfying flux conservation until galaxy formation. At the EW-transition the hypermagnetic field is projected onto a regular magnetic field

- Extra amplification ($\sim 10^2$) may be achieved by Preheating. Also, additional enhancement of field strength may be due to deviations from the $B \propto a^{-2}$ scaling law, when considering inverse cascade or turbulent helicity phenomena during its evolution.

- This is a **model independent magnetic field generation mechanism** and can be thought of as being a feature of inflationary theory itself. Since GUT-scale inflationary models are the most typical realisations of the inflationary paradigm (due to COBE normalization), **accounting for the observed galactic magnetic fields can be considered as another generic success of inflation**