Primordial Magnetic Fields from Inflation

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Introduction

Magnetic fields (MF) are widely observed in the Universe at all redshifts, from the solar system to galaxies, clusters, filaments, etc...

Their origin is still unknown, and we have two possibilities: they are created before the recombination period (hence primordial) or after.

If MF are primordial, we may observe them in large-scale structure voids. The Fermi and H.E.S.S. satellites estimated the lower bound of these intergalactic MF strength $B \approx 10^{-17} G$

$\rightarrow$ in favor of the primordial hypothesis.

However, the electromagnetic (EM) field is conformally invariant, so a primordial MF created by the standard particle physics model will not be enhanced by inflation. A way-out is to consider an EM model beyond the standard one, in the inflationary case, that breaks such invariance while preserving gauge invariance.

How can we constrain a primordial magnetogenesis model?
By computing the spectrum of primordial perturbations, and compare it to data from the CMB.

A modified electromagnetic model

We start from a two-part Lagrangian:

$$\begin{aligned}\mathcal{L} &= \mathcal{L}_{inf} + \mathcal{L}_{EM} \\ &= \frac{1}{2}\left(\partial^{\mu}\phi\right)\left(\partial_{\mu}\phi\right) - V\left(\phi\right) \\ &\quad + I(\tau)^2\left(-\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{\xi}{8n}F_{\mu\nu}\tilde{F}^{\mu\nu}\right)\end{aligned} \tag{1}$$

$I(\tau)$: coupling EM/inflation (through τ because we consider a deSitter background during inflation). Generates electromagnetic field by breaking conformal invariance.

$F_{\mu\nu}\tilde{F}^{\mu\nu}$: helical EM field $\rightarrow$ allows energy transfers to cosmological scales through inverse cascade processes.

ξ : constant parameter, used to keep control over the EM field amplitude.

Dynamics of the EM part give the formal solution:

$$\tilde{A}''_{\pm} + \left(k^2 \pm 2\frac{k}{\tau}\xi - \frac{n(n+1)}{\tau^2}\right)\tilde{A}_{\pm} = 0 \tag{2}$$

k^2 : Harmonic modes

$2\frac{k}{\tau}\xi$: Exponential amplification of one helicity mode

$\rightarrow$ generates the helical field

$\frac{n(n+1)}{\tau^2}$: Large-scales amplification

We only keep $\tilde{A}_{+}$ as it will be exponentially enhanced, and the other contribution exponentially suppressed. We find an approximate solution:

$$\tilde{A}_{+}\left(\tau, \vec{k}\right) \simeq \sqrt{-\frac{2\tau}{\pi}}e^{\pi\xi}K_{-2n-1}\left(\sqrt{-8\xi k\tau}\right) \tag{3}$$

Power spectrum of inflaton perturbations

During inflation, the amplification of quantum effects can attain the amplitude of the CMB stochastic fluctuations. These effects are perturbations from the vacuum and the EM field.

The curvature evolution equation is then sourced, and gives:

$$\delta\phi'' + 2\frac{a'}{a}\delta\phi' - \delta\phi \approx J\left(\tau, \vec{x}\right) \tag{4}$$

with a the scale factor, and J a source term. Resolving this equation allows us to determine the Gaussian spectrum of perturbations:

$$\left\langle \delta\phi_{\vec{k}}\delta\phi_{\vec{k}'}\right\rangle = \delta\left(\vec{k} + \vec{k}'\right)\frac{e^{4\xi\pi}}{\xi^6}\frac{1}{\dot{\phi}_0^2}\frac{H^6}{k^3}\theta(n) \tag{5}$$

and using the relation between curvature and perturbations:

$$\zeta\left(\tau, \vec{x}\right) = -\frac{H}{\dot{\phi}_0}\delta\phi\left(\tau, \vec{x}\right) \tag{6}$$

we obtain the power spectrum for the EM field:

$$P_{\zeta,EM}(k) = 2(2\pi)^2\frac{e^{4\pi\xi}}{\xi^6}\theta(n)P^2_{\zeta,vac}(k) \tag{7}$$

Conclusion

We can now constrain the model, knowing that CMB observations give $P_{\zeta,vac} \approx 10^{-10}$, and that EM field contributions should be small compared to the vacuum ones, this gives

$\rightarrow \xi \approx \mathcal{O}(10)$ and $-2 < n \leq 0$.

We need a MF strength $B \approx 10^{-16}G \times \sqrt{1Mpc/L_0}$, where L_0 is the actual correlation length of the MF, to be a valuable MF seed. In the best case $n = 0$, we obtain this value for an inflationary scale $\approx 10^{10}$ GeV. In the worst case considered $n = -1.95$, we obtain $\approx 10^{5}$ GeV.