Title: Cosmological seed magnetic field from inflation

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Abstract: I describe an inflation model that can generate a cosmological magnetic seed field of nG strength on Mpc length scales today that could explain observed few microG large-scale galactic magnetic fields. I also summarize some of the extensions of this model that have been developed over the last two decades, as well as open questions about such models.

# Outline

Late time motivation (observational, theoretical)

Previous cosmological seed magnetic field models

Exponential potential scalar field inflation

Maxwell $L_{U(1)} \sim \sqrt{-g}\, F^{\mu\nu} F_{\mu\nu}$ does not work

Modify $L_{U(1)}$ (toy model)

Inflation, radiation, baryon epoch computations

Results, numbers, consequences

What remains to be done, generalizations

Some observable consequences

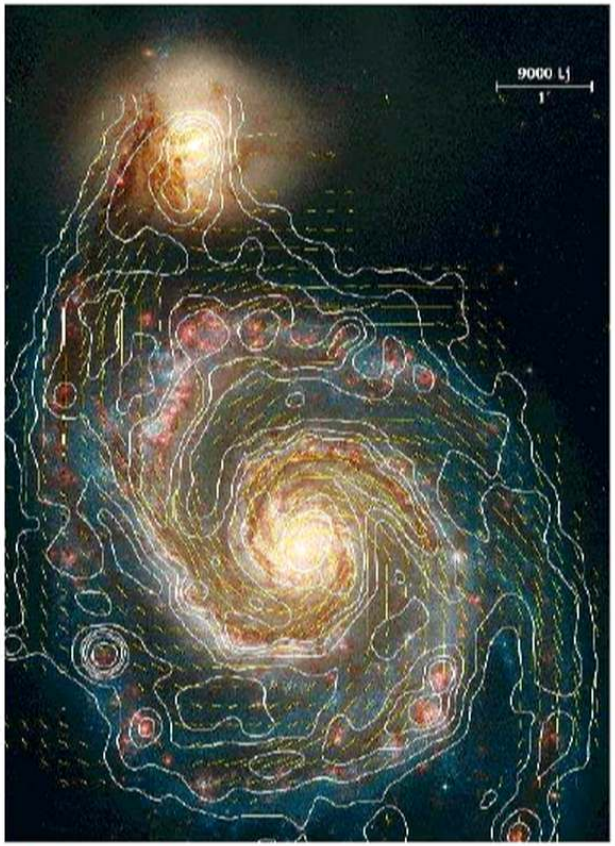
BR ApJL 391 (1992) (rejected by PLB)

+ Caltech preprint (rejected by PRD) at www.phys.ksu.edu/personal/ratra
(backreaction discussed in detail in Caltech preprint; it is not a problem.)

# Observations

Use Faraday effect on polarized radiation from background object (pulsar, quasar,..) to determine magnetic field in foreground object.

Aside from a random component of similar magnitude, there are uniform (on scales ~ 10 kpc), few μG magnetic fields in: galactic disks and halos; low redshift galactic clusters; and possibly in higher redshift (< 3) protogalactic disks.




HST image of the spiral galaxy M 51, overlaid by contours of the intensity of total radio emission at 6.2 cm wavelength and B–vectors, combined from data from the VLA and Effelsberg 100m telescopes and smoothed to 15" resolution (Fletcher & Beck, in prep.) (Graphics: Sterne und Weltraum. Copyright: MPIfR Bonn and Hubble Heritage Team). R. Beck, AIP Conf. Proc. 1085, 83 (2009).

# Need a primordial "seed" field

Universe is a good conductor now so MHD is a good approximation:

$$\partial_t \mathbf{B} = \boldsymbol{\partial}_x \times (\mathbf{v} \times \mathbf{B}) + \partial_x^2 \mathbf{B}/(4\pi\sigma)$$

No source: $\mathbf{B}(t_i) = 0 \Rightarrow \mathbf{B}(t_i + \Delta t) = 0 \Rightarrow$ Initial (non-MHD) seed field needed if we are to explain current B fields.

Observed galactic and other magnetic fields might be the result of amplification of an earlier, small, "seed" magnetic field.

Galactic seed field might be:

Small-scale, "bottom up" (stars, star clusters, galactic nuclei, ...); can only use in dynamo amplification model

Large-scale, "top down" (cosmological)

# Phenomenological Amplification Models

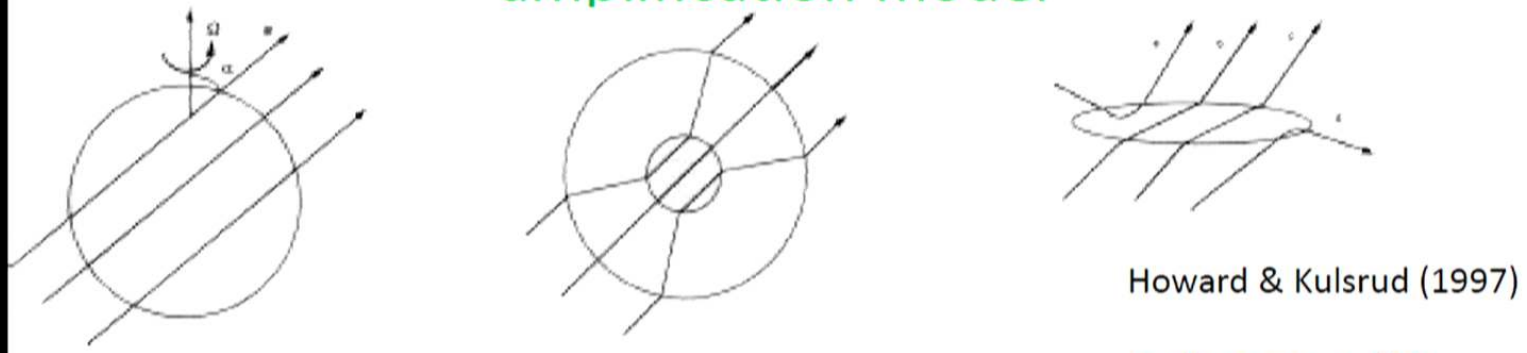
Anisotropic protogalactic collapse and differential rotation model (less effective amplifier, but does most of it quickly).

Piddington (1970); Kulsrud (1986). Needs $10^{-13} - 10^{-11}$ G seed field.

Galactic dynamo model (no consistent model; amplifies exponentially on rotation time scale; enough rotations result in large field; high-z objects have many fewer rotations).

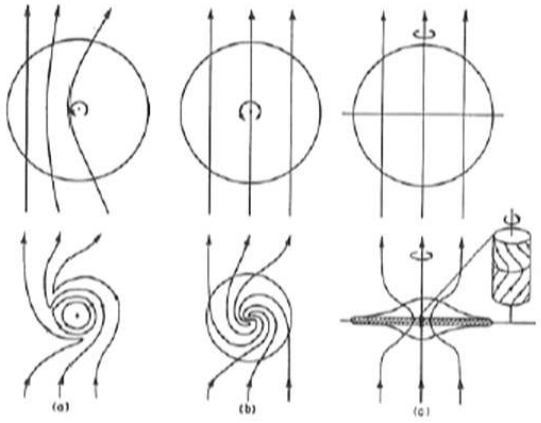
Parker (1971); Vainshtein & Ruzmaikin (1971). Needs $10^{-24} - 10^{-16}$ G seed field.

# Protogalactic collapse and differential rotation amplification model



Howard & Kulsrud (1997)

Before collapse ⟶ "Spherically" collapsed ⟶ Collapse to a disk



Amplified field structures (bottom row) generated from different large-scale protogalactic fields (top row) in a differentially rotating disk: (a) non-uniform field perpendicular to the rotation axis, (b) uniform perpendicular field, (c) uniform field parallel to the rotation axis (from Sofue 1990).

Disk is approx $10^6$ times denser than average baryon density; magnetic field amplified by $10^4$ during collapse and probably another factor of 10 or so during differential rotation => seed field ~ $10^{-12}$ G

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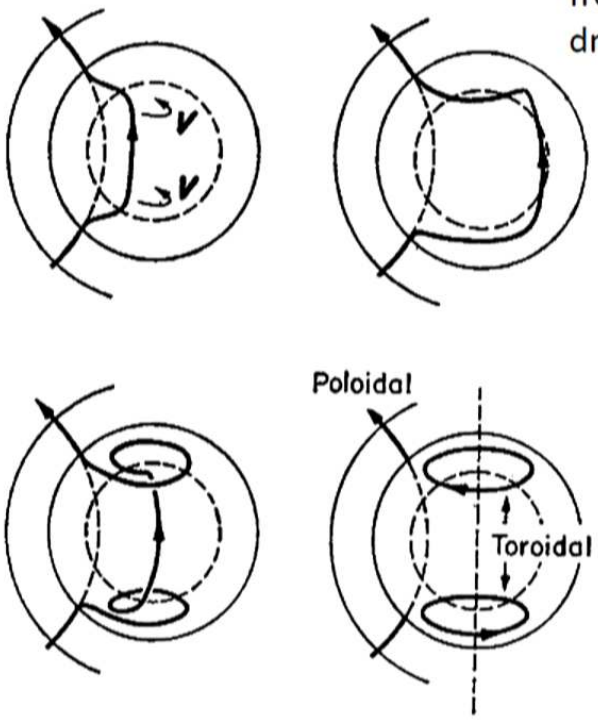
# Planetary/stellar dynamo amplification model




Nonuniform rotation generates toroidal field from poloidal field, which is amplified, dragged-in seed field.

Then convection and cyclonic turbulence generates poloidal field from toroidal field.

Nonlinear process that presumably exponentially amplifies the field on the rotation time scale. $e^{40} \sim 10^{17}$ => seed field ~ $10^{-23}$ G. Very naïve as this ignores dissipation.

People have argued that on galactic scales this model does not generate a smooth large-scale field; rather, that it generates a large small-scale field. Too early to draw firm conclusions.

# Some cosmological seed field models:

If there is large-scale vorticity in the radiation epoch, ions spin down relative to the Thomson coupled e's and CMB γ's resulting in an IGMF of $10^{-23}$ G. Harrison(1969) Barely large enough for the dynamo; no vorticity in inflation-based models.

Early universe phase transitions (PTs):

QCD PT: $10^{-38}$ G on 1 Mpc Hogan (1983); Quashnock et al (1989)

Electroweak 2nd order PT: $10^{-31}$ G on 1 Mpc Vachaspati (1989)

Too small, but can get variants to give larger values, but almost certainly not large enough.

Try inflation …

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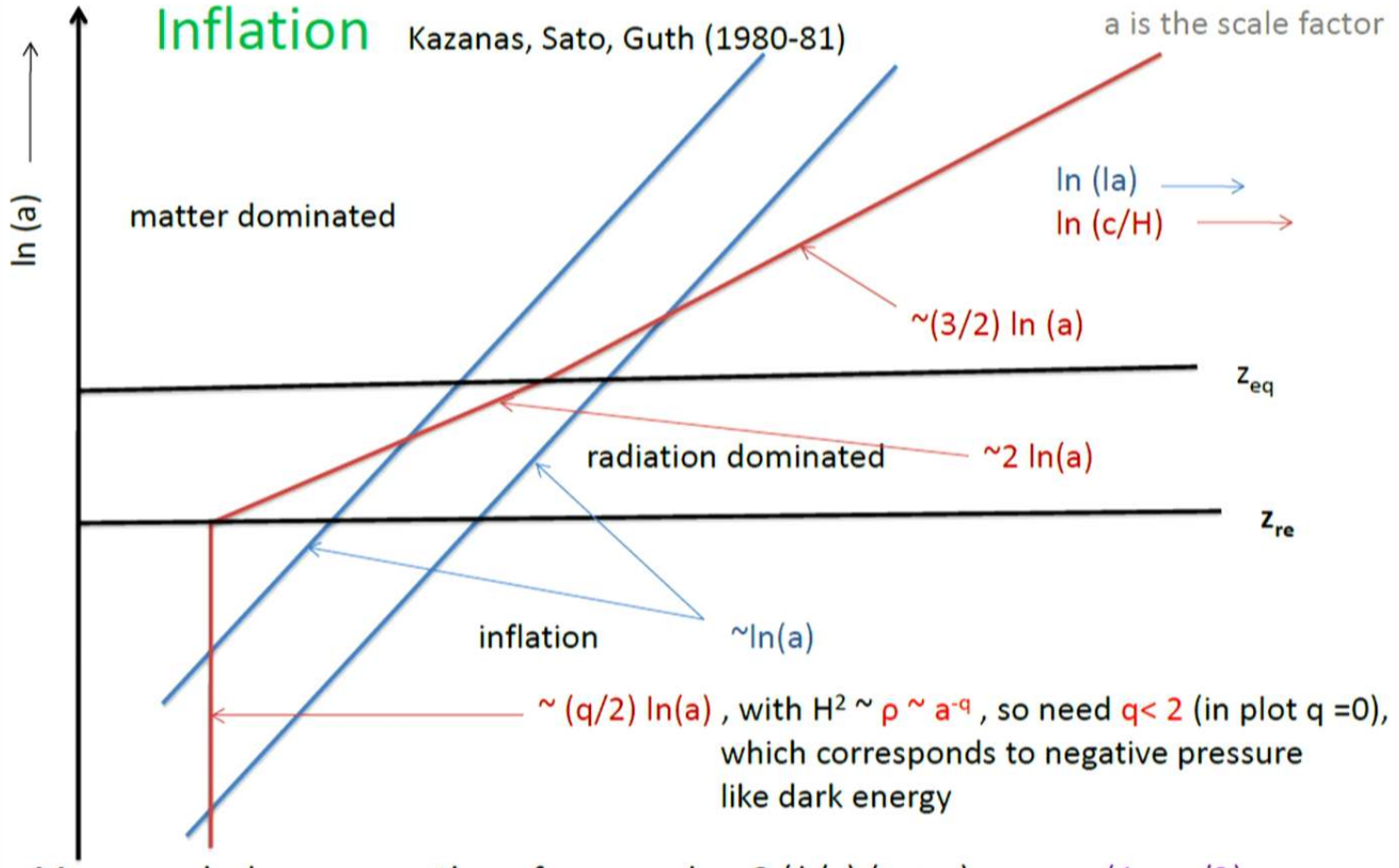
# Inflation

Kazanas, Sato, Guth (1980-81)

a is the scale factor




More precisely, conservation of energy, $\dot{\rho} = -3\,(\dot{a}/a)\,(\rho + p)$ => $p = (1 - q/3)\,\rho$

So, to model inflation use a scalar field ....

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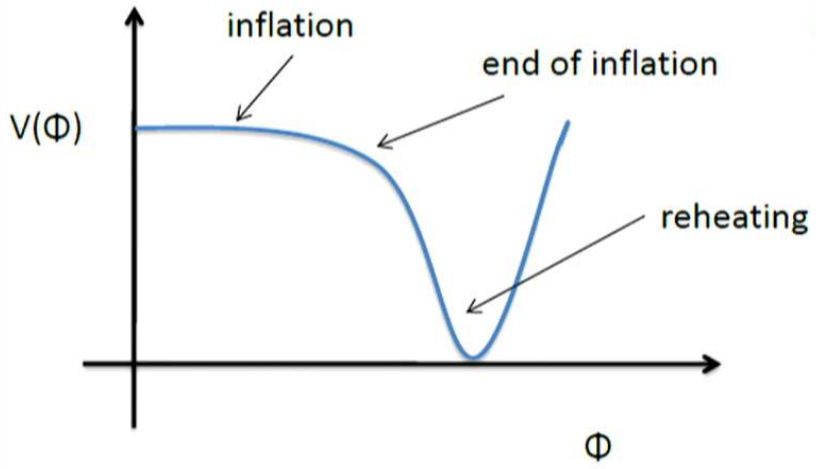



Spatially homogeneous background $\Phi(t)$

$\rho_\Phi \sim 1/2(d\Phi/dt)^2 + V \sim V$

$p_\Phi \sim 1/2(d\Phi/dt)^2 - V \sim - V$

$\Rightarrow p_\Phi = - \rho_\Phi$ (negative pressure)

$\dot{\rho} = -3\,(\dot{a}/a)\,(\rho + p)$

$\Rightarrow \rho_\Phi$ = constant

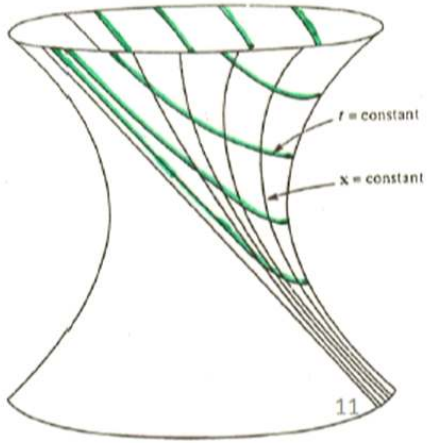
$\Rightarrow$ H = constant

Friedmann equation $\ddot{a}/a = -(4\pi G/3)(\rho + 3p) > 0$

$\Rightarrow$ accelerated expansion, like dark energy.

Simplest solution is spatially-flat de Sitter with $a(t) \sim \exp(Ht)$.

More generally, instead of a flat potential we can have $V(\phi) \sim \exp(-\sqrt{q/2}\,\phi)$, then free parameters are q and $z_{re}$, and $a(t) \sim t^{2/q}$.



No direct evidence for the inflaton scalar field, however there is persuasive indirect evidence.

## Spatial irregularities

During inflation, quantum mechanics generates small-scale zero-point fluctuations (gravity modifies the usual ground state in a manner similar to what happens for the Casimir effect).

These are stretched by the expansion to cosmological length scales in the late time universe.

Hawking, Starobinsky, Guth & Pi (1982)

This happens for any field present during inflation.

Inflation epoch gravity & scalar field action:

$S = \int dt\, d^3x\, \sqrt{-g}\, [\, -R + \tfrac{1}{2}\, g^{\mu\nu}\, \partial_\mu \phi \partial_\nu \phi - V(\phi)]$

To this add the electromagnetism action:

$S_{EM} = \int dt\, d^3x\, \sqrt{-g}\, (1/\hat{e}^2)\, F^{\mu\nu}\, F_{\mu\nu}$

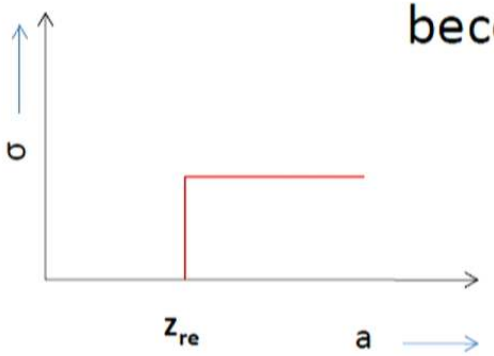
Flux (~ $|\mathbf{B}|$ X area) is conserved =>

$|\mathbf{B}|$ ~ 1/area ~ $a^{-2}$

Model charged particles at reheating.

Two free parameters: $z_{re}$ and q.

At $z_{re}$ $E \rightarrow 0$ as the universe becomes a good conductor.



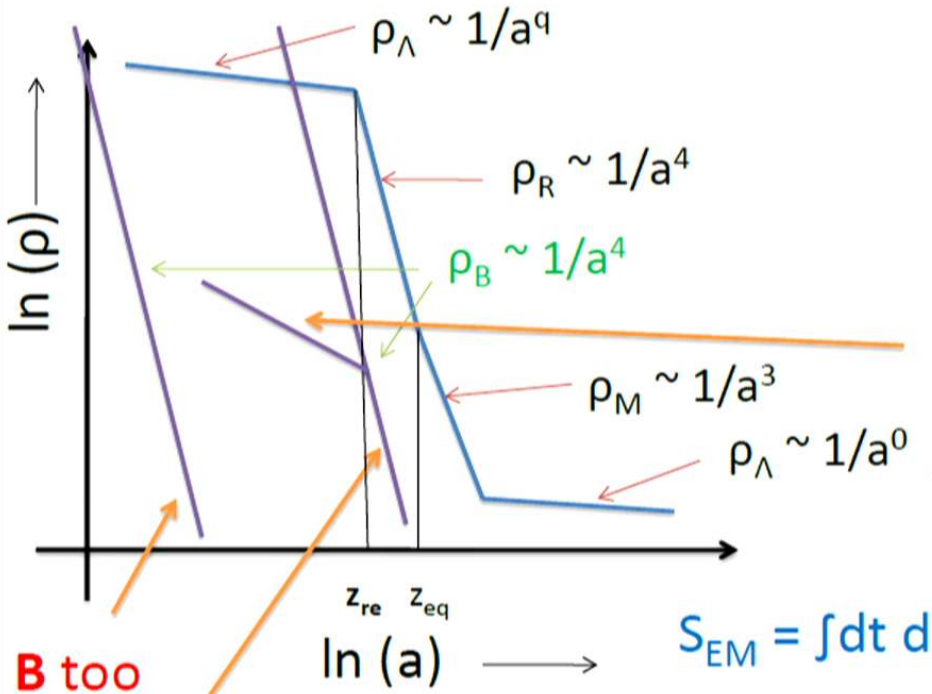

At present, in wavenumber k space

$< |B(k)|^2 > \sim k/a^4$,

so $<B^2(r = 10^{-3}/H_0)>^{1/2} = 10^{-59}$ G now.

Too small.

# The problem and a solution




So change relation between **B** and ρ during inflation by making coupling constant time variable through a dilaton-like coupling:

$$S_{EM} = \int dt\, d^3x \sqrt{-g}\, (1/\hat{e}^2)\, e^{\alpha\phi} F^{\mu\nu} F_{\mu\nu}$$

**B** too small.

Increase **B**, but then no inflation.

$\rho_B \sim T_{00} \sim \mathbf{B}^2/\mu$. During inflation: $\mu \sim e^{-\alpha\phi} \sim \varepsilon^{-1}$. After inflation, Φ freezes at VEV, $\mu = 1 = \varepsilon^{-1}$ and standard U(1) is recovered.

Three free parameters: $z_{re}$ , q and α.

Synchronous and temporal gauge: Inflation Epoch

$$\ddot{A}_i + (\dot{a}/a + \alpha\dot{\phi}_b)\dot{A}_i + (\partial_i\partial_j A_j - \partial_j\partial_j A_i)/a^2 = 0, \qquad \partial_i\dot{A}_i = 0.$$

Solve for $A_i$. Initial conditions determine constants of integration. On small scales, inside the Hubble radius, appropriately rescaled $A_i$ modes should be in the harmonic oscillator ground state in terms of conformal time.

Then on large scales magnetic field

$$B \sim \begin{cases} a^{-2}\, k^{1-\nu} & \text{for } \nu \geq 0 \text{ or } \alpha \geq -(2-q)/(2\sqrt{(2q)}) \\ a^{-(6-q+2\alpha\sqrt{(2q)})/2}\, k^{1+\nu} & \text{for } \nu \leq 0 \text{ or } \alpha \leq -(2-q)/(2\sqrt{(2q)}) \end{cases}$$

where $\nu = \frac{1}{2} + \alpha\sqrt{(2q)}/(2-q)$. Compared to ordinary electromagnetism, where $B \sim a^{-2}\, k^{1/2}$, power is shifted to the infrared for $\nu > \frac{1}{2}$ & $\nu < -\frac{1}{2}$.

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And on large scales electromagnetic energy density

$$\varepsilon \sim \begin{cases} a^{-(4+\alpha\sqrt{(2q)})}\, k^{2\nu} & \text{for } \alpha < 0 \\ a^{-(4-\alpha\sqrt{(2q)})}\, k^{2(1-\nu)} & \text{for } \alpha > 0 \end{cases}$$

where $\nu = \frac{1}{2} + \alpha\sqrt{(2q)}/(2-q)$. Compared to ordinary electromagnetism where $\alpha = 0$, for $\alpha \neq 0$ the U(1) energy density increases slower than $a^{-4}$ as $a \to 0$.

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Normalize density perturbations to large-scale structure or CMB anisotropy observations. Then at the present time

$<|B(k)|^2> \sim k^{\hat{n}} a^{-4}$ $\quad -3< \hat{n}<2$

with amplitude range $10^{-65}\ G \leq <\mathbf{B}^2(r=10^{-3}/H_0)>^{1/2} \leq 10^{-9}\ G$.

At the upper end, $<|\delta(k)|^2> \sim k$, HPYZ scale-invariant energy-density spectrum, with a scale-invariant magnetic field spectrum, $<|B(k)|^2> \sim k^{-3} a^{-4}$ or $<\mathbf{B}^2(r)>^{1/2} \sim r$ and normalization $<\mathbf{B}^2(r=10^{-3}/H_0)>^{1/2} \sim 10^{-9}\ G$.

Close to this limit, the model provides energy-density perturbations that are observationally consistent and seed magnetic field amplitude strong enough even for the collapse and differential rotation amplification scenario!

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# Extensions and Other (Inflation) Options

Careful confirmation. Bamba & Yokoyama PR D69, 043507 (2004); Martin & Yokoyama JCAP 0801, 025 (2008). (Backreaction is not a problem: Demozzi et al JCAP 0908, 025 (2009).)

Use two scalar fields: an inflaton and dilaton-like one. This is also viable. Lemoine & Lemoine PR D52, 1955 (1995); Gasperini et al PRL 75, 3796 (1995); Bamba & Yokoyama PR D69, 043507 (2004).

Use trace anomaly to break conformal invariance. Might work in models with very many particle species. Dolgov PR D48, 2499 (1993).

Axion electrodynamics. Might be able to generate an interesting amount of small-scale magnetic helicity but not a large-scale magnetic field. Garretson et al PR D46, 5346 (1992); Prokopec astro-ph/0106247; Campanelli IJMP D18, 1395 (2009); Caprini & Sorbo JCAP 1410, 056; Cheng et al 1409.2656; Bamba PR D91, 043509 (2015); Fujita et al 1503.05802

Scalar electrodynamics. Inflation-generated current might produce a (too weak?) large-scale magnetic field. Turner & Widrow PR D37, 2743 (1988); Calzetta et al PR D57, 7139 (1998); Giovannini & Shaposhnikov PR D62, 103512 (2000); Calzetta & Kandus PR D65, 063004 (2002). (Massive fermions not yet studied much.)

Non-Einsteinian gravity or gravitational coupling to U(1) field. Probably can generate a large enough magnetic field but not yet clear this is consistent with general relativity tests. (Are we that desperate?) Turner & Widrow PR D37, 2743 (1988); Mazzitelli & Spedalieri PR D52, 6694 (1995); Lambiase & Prasanna PR D70, 063502 (2004); Akhtari-Zavareh et al PTP 117, 803 (2007); Campanelli et al PR D77, 123002 (2008).

Nonlinear electrodynamics (DBI, Heisenberg-Euler,...). There is probably enough freedom here also. Garousi et al PL B606, 1 (2005); Ganjali JHEP 0509, 004 (2005); Kunze PR D77, 023530 (2008); Campanelli et al PR D77, 043001 (2008).

Can also use extra spatial dimensions or extra gauge fields or bounces or branes or break gauge invariance or Lorentz invariance or do other things that some feel should not be discussed in public.

# Summary

Need a seed field, possibly a large-scale cosmological one; this could soon be settled by new data.

It seems we could be seeing the first indications of another beyond Standard Model physics phenomenon, to add to density perturbations, dark matter, neutrino and other masses and couplings, strong CP, matter-antimatter asymmetry, and dark energy. This could have very interesting implications.

There are a number of inflation models that can work. I discussed in some detail the simplest predictive mechanism that can generate a large enough magnetic seed field for probably any amplification model.

# Some potentially observable effects

Cosmological seed field can affect the polarized CMB through Faraday rotation of polarization plane and might be detected (and can be limited) through this effect. e.g., Sethi MNRAS 342, 962 (2003); Kosowsky et al PRD 71, 043006 (2005); Kahniashvili et al PRD 82, 083005 (2010)

Cosmological seed field can induce CMB temperature and polarization anisotropies and might be detected (and can be limited) through this effect. e.g., Subramanian & Barrow PRL 81, 3575 (1998); Seshadri & Subramanian PRL 87, 101301 (2001); Kahniashvili & Ratra PRD 82, 103006 (2005); Ballardini et al 1412.1836; Ade et al 1502.01594

Cosmological seed field can affect the formation of the first bound structures and might be detected (and can be limited) through this effect. e.g., Subramanian & Barrow PRD 58, 083502 (1998); Gopal & Sethi PRD72, 103003 (2005); Kahniashvili et al PRD 82, 083005 (2010); Pandey et al MNRAS 451, 1692 (2015)

Cosmological seed field can affect galaxy formation and might be detected (and can be limited) through this effect. e.g., Marinacci & Vogelsberger 1508.06631

Cosmological B field generated during inflation is uniform over large length scales and defines a preferred direction, breaking spatial isotropy and can possibly explain large angle WMAP "anomalies". e.g., Kahniashvili et al PRD 78, 063012 (2008)

# Open Questions

In the case of interest, when $\langle \mathbf{B}^2(r=10^{-3}/H_0)\rangle^{1/2} \sim 10^{-9}$ G, the model is strongly coupled early on. OK as is, but can (should) charged particles be present during inflation?

Does a quantum-mechanically consistent string theory result in this low energy effective semi-classical mechanism?

Can this phenomenological mechanism work in a more realistic model, inspired by high energy physics?

Need account for dark energy. Need improve reheating model.

Need account for electroweak transition. Field during inflation is hypercharge field, if there is no GUT or other model. √2 increase in B field amplitude.

Work out more (interesting!) observational predictions, derive limits.

# We are all agreed that your theory is crazy. The question that divides us is whether it is crazy enough to have a chance of being correct.

**Bohr to Pauli (1958)**

(Heisenberg-Pauli nonlinear field theory of elementary particles was not crazy enough.)

Better observational data will show if we are crazy enough.

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