Magnetogenesis in Cyclical Cosmology

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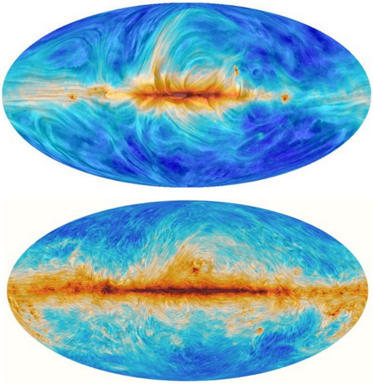
Outline

- Importance of magnetic fields
  - Ideas on generation of magnetic fields
- A different cosmological model
  - Shortcomings of ΛCDM and advantages of modified gravity
  - Electrodynamics in curved space
  - Conditions for contraction of Universe
- Magnetogenesis in contraction phase of a cyclic Universe
- Summary and conclusions

Magnetic Fields in the Cosmos

Magnetic fields are important!

- Evidence for the presence of magnetic fields at almost all observed scales
- Dictates evolution of various cosmological and astrophysical processes (e.g. large scale structure and propagation of charged particles)
- Detected structure and strength details rather uncertain



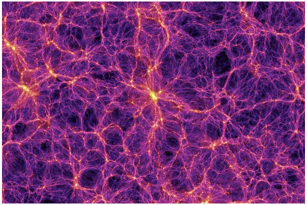
from PLANCK satellite

Magnetic Fields in the Cosmos

But how were magnetic fields generated?

cosmological origin

- inflation
- phase transitions



astrophysical origin

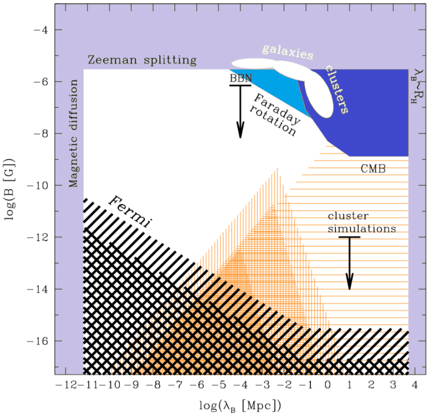
battery & small scale seeds

$+$

dynamos

Magnetic Fields in the Cosmos

Current bounds



Neronov & Vovk (2010)

- In the Universe's evolution, electric fields decay due to the high conductivity of the early Universe, but magnetic fields can leave remnants
- Magnetic fields decay with expansion $B(t) \propto a(t)^{-2}$
- If today $B(t_0) \sim 10^{-16} G$ in the early Universe the strengths were very high!

Modified Gravity

The need to go beyond General Relativity

- General Relativity is not a complete theory despite great performance in all tests
  - And there are even gravitational wave observations now!
- Big Bang paradigm introduces initial singularity (and thus creation *ex nihilo*) and problems that require further mechanism to be solved
- Assuming that singularities are to vanish in quantum gravity, the transition from Big Bang to a bouncing cosmological model is the most natural

Modified Gravity

What alternative can it offer us now?

- Initial singularity easily avoided by inclusion of simple corrections to curvature
- Universe evolution becomes tractable at all times without initial singularity
- No horizon and flatness problems to solve
- Chances of addressing ΛCDM dar energy and non-baryonic dark matter contributions without postulating those components but as a result from gravitational effects

Cyclical Universe

Historical contextualization

- First model proposed by Tolmann in 1930 (closed Universe based on GR) presented difficulties during the contraction phase and observations seem to favour flat Universe
- Renewed interest after 1998's discovery of accelerated expansion of Universe
- Research within modified gravity created several viable models:
    - Brans-Dicke gravity
    - $f(R)$ theories
    - $f(T)$ teleparallel gravity
    - Kaluza-Klein theories
    - Hořava-Lifshitz gravity

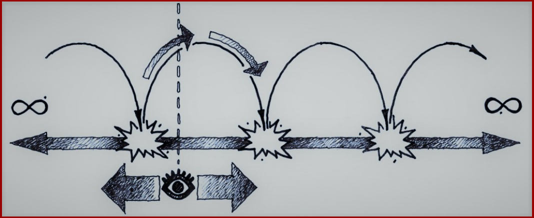
Cyclical Universe

Historical contextualization

Cyclical Universe

Implications for magnetogenesis

Looking at different epochs...



- K. Atmjeet (2014)
- F. Membiela (2014)
- P. Qian et al (2016)

Cyclical Universe

Description in terms of $f(R)$

- Simplest modification to the Lagrangian density in the Einstein-Hilbert action

$$S = \frac{1}{2\kappa} d^4x\sqrt{-g}f(R) \quad (1)$$

- Cyclic model of Pavlović & Sossich, PRD95, 103519 (2017)
- Obeys general covariance, the four-derivative gravity is renormalizable, ghost-free, free from Ostrogradsky instability
- Dark energy as zeroth contribution of the higher order curvature corrections
- standard spatially flat Universe (spatial curvature is of no concern in supporting a cyclical behaviour)

Electrodynamics in curved space

Minimal Maxwell's equations

$$S_{EM} = \int d^4x \sqrt{-g} \mathcal{L}_{EM} \,, \tag{2}$$

$$\mathcal{L}_{EM} = -\frac{1}{16\pi} F_{\mu\nu} F^{\mu\nu} + A_\mu J^\mu \,, F_{\mu\nu} = A_{\nu;\mu} - A_{\mu;\nu} \tag{3}$$

- Maxwell's equations obtained by varying action with respect to A_μ and using $*F^{\mu\nu} = \epsilon^{\mu\nu\alpha\beta} F_{\alpha\beta}/2$

$$\partial_i E^i = 4\pi\rho_q \tag{4}$$

$$\partial_t E^i + 3HE^i = \frac{1}{a}\epsilon^*_{ilm}\partial_l B^m - 4\pi J^i \tag{5}$$

$$\partial_i B^i = 0 \tag{6}$$

$$\partial_t B^i + 3HB^i = -\frac{1}{a}\epsilon^*_{ilm}\partial_l E^m \tag{7}$$

see K. Subramanian (2015)

Electrodynamics in curved space

Electromagnetic field

- Field configuration:

$$E_x = \phi(t)E(y,z)\,,\; E_y = \phi(t)E(x,z)\,,\; E_z = \phi(t)E(x,y)$$

$$B_x = \psi(t)B(y,z)\,,\; B_y = \psi(t)B(x,z)\,,\; B_z = \psi(t)B(x,y)$$

- Evolution of time component of fields:

$$\dot{\phi}(t) + 3H\phi(t) = w\psi(t) \quad (8)$$

$$\dot{\psi}(t) + 3H\psi(t) = u\phi(t) \quad (9)$$

$\phi(t)$ and $\psi(t)$ functions of time
$E_i \to -B_i \implies w = -u$

$$u = \frac{\partial_m E(i,m) - \partial_l E(i,l)}{B(l,m)}\,, w = \frac{\partial_l B(i,l) - \partial_m E(i,m)}{B(l,m)} \quad (10)$$

$$R = 6\dot{H} + 12H^2\,; \quad H \equiv \dot{a}(t)/a(t)\,, \tag{11}$$

Basic assumption: gravitationally bounded systems have been ripped apart after expansionary phase

↓

effectively empty Universe at beginning of contraction cycle

↓

$$\rho = p = 0$$

↓

vacuum electrodynamics is valid + same conditions at beginning of each cycle allow a truly eternal Universe

Contraction Phase

Modelling the Contraction Phase

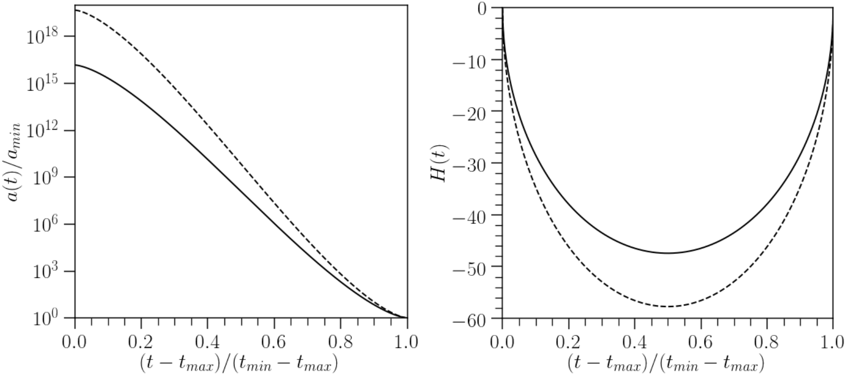
- Solve modified Friedmann's equation: $H^2(t) = \frac{\kappa}{3}(\rho + \rho_{eff}(t))$
- Effective energy density: describes the effect of non-Hilbertian term added to gravity's action
- Model it by an expansion in time:

$$\rho_{eff}(t) = b_0 + b_1 \frac{t - t_{max}}{t_{min} - t_{max}} + b_2 \left(\frac{t - t_{max}}{t_{min} - t_{max}}\right)^2 + \mathcal{O}(t^3)$$

- $t(a_{max}) = t_{max}$ and $t(a_{min}) = t_{min}$ correspond to the times of maximum and minimum of scale factor; b_i constants
- $b_0 = 0$ and for $\rho_{eff} > 0 \implies b_1 = -b_2 \rightarrow$ only one free parameter to fit
- initial conditions: fix $u = 1$, take a vanishing initial magnetic field and a small seed electric field

Contraction Phase

Scale factor and Hubble Parameter

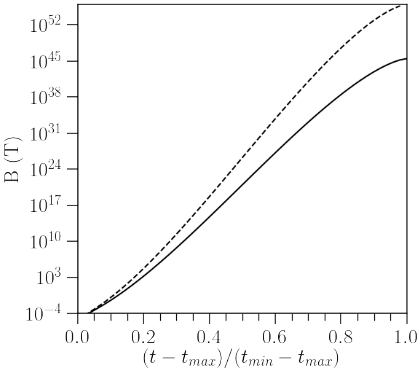


Estimated reproduction of lower bounds (solid curve) and upper bounds (dashed curves) on extragalactic magnetic fields

- Scale factor diminishes from the turnaround point until bounce $\implies H < 0$ during contraction + $H(t)$ must vanish at the points of a_{max} and a_{min}

Contraction Phase

Field Evolution

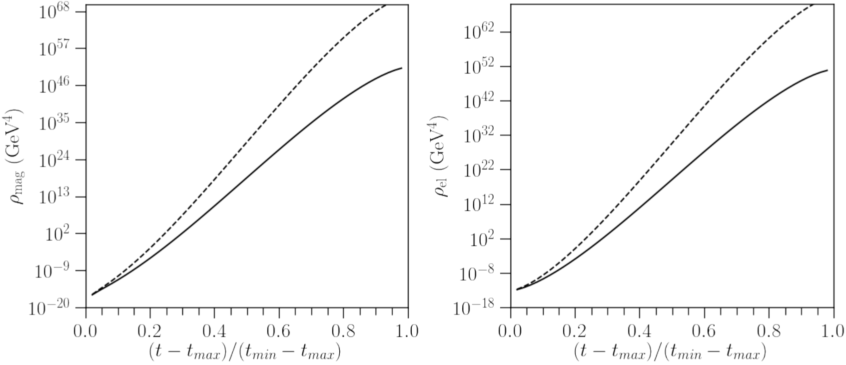


Estimated reproduction of lower bounds (solid curve) and upper bounds (dashed curves) on extragalactic magnetic fields

- Initially vanishing magnetic field + small initial seed electrical field $\rightarrow$ magnetic field creation and growth over contraction phase

Contraction Phase

Field Evolution



Estim

reproduction of lower bounds (solid curve) and upper bounds (dashed curves) on extragalactic magnetic fields

- Initially vanishing magnetic field + small initial seed electrical field $\rightarrow$ magnetic field creation and growth over contraction phase

Conclusions

In a cyclical, eternal, non-singular Universe that results from introducing higher order curvature corrections to general relativity:

- During contraction of Universe magnetic fields are created and amplified from a seed initial electric field in nearly-empty initial contracting conditions
- Generated fields well compatible with today's bounds on extragalactic magnetic fields

Thank you