Varying constants baryogenesis models

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Introduction

- **The baryon number asymmetry**
  The observed Universe manifests an asymmetry between the number density of baryons n_b and antybaryons $n_{\bar{b}}$:

$$\eta_B = \frac{n_B}{s} \simeq 8.6 \times 10^{-11}, \tag{1}$$

  where $n_B = n_b - n_{\bar{b}}$ and s is the entropy density.

- **The Sakharov conditions for baryogenesis** (A. Sakharov, 1967)
  1. baryon number violating interactions
  2. C and CP violation
  3. departure from thermal equilibrium

- **Spontaneous baryogenesis** (A. Cohen, D. Kaplan, 1987)
  It does not require 3^{th} Sakharov condition. The baryon asymmetry is produced by spontaneous breaking of the CPT symmetry in the early Universe. The CPT violation is mimicked by a time-dependent field.

- **Varying constants cosmology**
  Both dimensional and dimensionless fundamental constants may be represented by dynamical fields, i.e. Brans-Dicke theory. Their dynamics can provide a solution to the standard cosmological problems such as the horizon problem, the flatness problem or the Λ - problem.

Spontaneous barygenesis

- **Spontaneous baryon production in thermal equilibrium**
  We consider a theory in which a scalar field $\phi(x)$ is derivatively coupled to the baryon current J_B^σ:

$$\mathcal{L}_{eff} = \frac{\lambda}{M^2}\partial_\sigma \phi(x) J_B^\sigma \quad \longrightarrow \quad \mathcal{L}_{eff} = \frac{\lambda}{M^2}\dot{\phi} J_B^0 \,, \tag{2}$$

  where λ is a coupling constant, M is a cutoff scale and J_B^0 corresponds to n_B in the (flat) FRLW universe. The CPT symmetry is spontaneously broken by the term $< \dot{\phi} \neq 0 >$. The interaction (2) shifts the energy spectra of baryons with respect to that of antybaryons, which means that baryons and antybaryons equilibrate with different thermal distributions. This energy shift ΔE can be interpreted as a chemical potential $\mu = \frac{\lambda}{M^2}\dot{\phi}$.

- **The baryon to entropy ratio**

$$\eta_B = \frac{n_B}{s} = \frac{15\lambda}{4\pi M^2}\frac{g}{g_*}\frac{\dot{\phi}_{dec}}{T_{dec}} \tag{3}$$

  where n_B and the entropy s are given respectively:

$$n_B \simeq \frac{g}{6}\mu T^2, \quad s = \frac{2\pi g_*}{45}T^3 \tag{4}$$

  g- the the number of the internal degrees of freedom of a particle/antiparticle, so then the baryon to entropy ratio

Varying c barygenesis $\phi(t) = c^4(t)$

The field equations

We examine baryogenesis which is driven by a field ϕ derivatively coupled to the baryon current J^0_μ:

$$S = \frac{1}{16\pi G}\int d^4x\sqrt{-g}\left(\phi R - \frac{k}{\phi}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - \frac{\lambda}{M^2}\partial_\mu\phi J^\mu_B\right) \ , \tag{5}$$

where the evolution of the field is decribed by the equation of motion:

$$\ddot{\phi} + 3H\dot{\phi} = \frac{8\pi G}{2k+3}T_m - \frac{\lambda}{M^2}\left(\partial_\mu J^\mu_B + 3HJ^\mu_B + \frac{2}{\phi}\partial_\mu\phi J^\mu_B\right) \ . \tag{6}$$

The corresponding Friedmann equation for the flat universe reads as:

$$H^2 = \frac{8\pi G}{3}\varrho - H_\phi H + \frac{k}{6}H^2_\phi \ , \tag{7}$$

where ϱ is the energy density and $H_\phi = \dot{\phi}/\phi$. In order to calculate η_B we need to find an evolution of the ϕ during radiation dominated era. Since the source term in eq.(6) is negligible we have to solve the following equation:

$$\ddot{\phi} + 3H\dot{\phi} = 0 \ . \tag{8}$$

The dynamical c model

We adopt a specific ansatz for the speed of light:

$$c(t) = c_{in}\left(\frac{a}{a_{in}}\right)^n \ , \tag{9}$$

where c_{in} and a_{in} are initial values of the speed of light and the scale factor.

Varying c baryogenesis $\phi(t) = c^4(t)$

The equation of motion for the ansatz (9) reads as:

$$2(2n+1)\frac{\dot{a}}{a} + \frac{\ddot{a}}{\dot{a}} = 0 \,, \tag{10}$$

and it can be solved by the scale factor:

$$a(t) = a_{in} N(t)^{\frac{1}{4n+3}} \,, \tag{11}$$

where $N(t) = 1 + (t - t_{in})(4n-3)H_{in}$ and $H_{in} = \dot{a}_{in}/a_{in}$, which is a Hubble constant at the beginning of baryogenesis. Now we can find parameters H and H_ϕ:

$$H = \frac{\dot{a}}{a} = H_{in} N(t)^{-1} \,, \qquad H_\phi = 4nH_{in}N(t)^{-1} \,, \tag{12}$$

where $\phi(t)$ and $\dot{\phi}(t)$ depend on time in a following way:

$$\phi(t) = c_{in}^4 N(t)^{\frac{4n}{4n+3}} \,, \quad \dot{\phi}(t) = 4nc_{in}^4 H_{in} N(t)^{-\frac{3}{4n+3}} \,. \tag{13}$$

We can find **an realtion between time and temperature** by inserting eq. (12) to the Friedmann equation (7):

$$N(t) = H_{in}\left(1 + 4n - \frac{8k}{3}n^2\right)^{1/2}\left(\frac{8\pi G}{3}\frac{\pi^2}{30}g_*\right)^{-1/2} T^{-2} \,, \tag{14}$$

where we have used $\varrho = \pi^2 g_* T^4/30$. **The final baryon to entropy ratio takes a form:**

$$\eta_B = \frac{15}{4\pi GM^2}\frac{g}{g_*}\frac{\dot{\phi}}{T_{dec}} = \frac{15}{4\pi GM^2}\frac{g}{g_*}\frac{4nc_{in}^4 H_{in}\widetilde{N}(t_{dec})^{-\frac{3}{4n+3}}}{T_{dec}} \,. \tag{15}$$

Varying G baryogenesis $\phi(t) = \frac{1}{G(t)}$

We assume a following dynamics of the gravitational constants:

$$G(t) = G_{in} \left(\frac{a(t)}{a_{in}} \right)^q . \tag{16}$$

In this case the equation of motion of the field ϕ reads as:

$$(2-q)\frac{\dot{a}}{a} + \frac{\ddot{a}}{\dot{a}} = 0 , \tag{17}$$

which is solved by

$$a(t) = a_{in} \widetilde{N}(t)^{\frac{1}{3-q}} , \tag{18}$$

where $\widetilde{N}(t) = 1 + (t - t_{in})(3-q)H_{in}$. Following the procedure for the varying c we can find now a relation between time and temperature in this model:

$$\widetilde{N}(t) = \left[H_{in}^{-2} \left(1 - q - \frac{k}{6} q^2 \right)^{-1} \left(\frac{8\pi G_{in}}{3} \frac{\pi^2}{30} g_* \right) T^4 \right]^{\frac{3-q}{q-6}} . \tag{19}$$

The field ϕ is given by:

$$\phi = -\frac{q}{G_{in}} H_{in} \widetilde{N}(t)^{-\frac{q}{3-q}} \quad \text{and} \quad \dot{\phi} = -\frac{q}{G_{in}} H_{in} \widetilde{N}(t)^{-\frac{3}{3-q}} . \tag{20}$$

The final baryon to entropy ratio takes a form:

$$\eta_B = \frac{15}{4\pi M^2} \frac{g}{g_*} \frac{\dot{\phi}}{T_{dec}} = -\frac{15}{4\pi M^2} \frac{g}{g_*} \frac{q H_{in} \widetilde{N}(t_{dec})^{-\frac{3}{3-q}}}{G_{in} T_{dec}} . \tag{21}$$

Summary

- We investigate models of spontaneous c–varying and G–varying baryogenesis, where the baryon to entropy ratio is achieved by spontaneous CPT symmetry breaking in the Universe in thermal equilibrium.
- We consider the speed of light and the gravitational constant fields which produce the baryon asymmetry by coupling of their time derivatives to the baryon current.
- The dynamics of the fields is introduced by some specific parametrization (n,q parameters) which indicates on departure from the initial values of c and G.

References

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