Imprints of Gravitational Baryogenesis in $f(R, L_m, T)$ Gravity

Presented by

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Introduction

1. The dominance of matter over antimatter, a fundamental mystery in cosmology called **Baryogenesis.**

2. Supported by observations from the LSS, CMB and BBN.

3. After the **Big Bang**, the annihilation of matter–antimatter favored a small matter surplus, leaving behind the observable universe today.

Sakharov Conditions

1. B violation

Interactions must violate baryon number to create a net surplus.

2. C and CP violation

Otherwise any baryon producing process is exactly balanced by its mirror.

3. Out of equilibrium

In thermal balance, forward and backward rates are equal and erase any asymmetry.

Observed Baryon Asymmetry Ratio

1. Based on cosmological observations, the baryon number-to-entropy ratio is estimated to be:

$$\frac{\eta_B}{s} = \frac{n_B - n_{\bar{B}}}{s} \simeq 9.42 \times 10^{-11} \tag{1}$$

Significance

The small numerical value of the asymmetry ratio $\left(\frac{\eta_B}{s}\right)$ quantifies the tiny excess of matter over antimatter in the universe.

Different Routes to Baryogenesis

1. Several theoretical methodologies are there to explain the observed matter-antimatter asymmetry:

- **Electroweak Baryogenesis (1979)**
- **GUT Baryogenesis (1980)**
- **Affleck-Dine Baryogenesis (1985)**
- **Leptogenesis (1986)**
- **Spontaneous Baryogenesis (1989)**
- **Gravitational Baryogenesis (2004)**

Gravitational Baryogenesis

1. Gravitational Baryogenesis introduces a coupling between the derivative of the Ricci scalar and the baryonic matter current, which creates baryon asymmetry by CP-violation. The interaction term is as follows:

$$\mathcal{L}_{int} \sim \frac{1}{M_*^2}\,\partial_\mu R\, J^\mu \tag{2}$$

2. The time evolution of the Ricci scalar generates an effective chemical potential, favouring generation of baryon over antibaryon and thereby producing the observed baryon asymmetry.

$$\mu_B = \frac{\dot{R}}{M_*^2} \tag{3}$$

Gravitational Baryogenesis

1. Baryon asymmetry is generated when the universe cools below a critical threshold called the decoupling temperature $(T = TD)$.
2. The Baryon number-to-entropy ratio $\frac{\eta_B}{s}$ is approximated by:

$$\frac{\eta_B}{s} \simeq -\frac{15\, g_b}{g_*} \frac{\dot{R}}{M_*^2\, T_D} \tag{4}$$

3. The baryogenesis process is studied under the assumption that the universe remains in thermal equilibrium during the epoch of interest.

$f(R, L_m, T)$ Gravity

1. In $f(R, L_m, T)$ Gravity, Ricci Scalar (R) in Einstein-Hilbert Action S_{GR} is replaced by the function, $f(R, L_m, T)$.
2. Action in GR : $S_{GR} = \int d^4x\, R\, \sqrt{-g} + \mathcal{S}_m$
3. Action in $f(R, L_m, T)$: $S_{fRL_mT} = \int d^4x\, f(R, L_m, T)\, \sqrt{-g} + \mathcal{S}_m$

Field Equation

The respective field equations are obtained by varying the Action with respect to the metric tensor $(g_{\mu\nu})$.

Field Equation & Modified Firedmann Equation

1. The corresponding field equation takes the following form

$$R_{\mu\nu}f_R-(\nabla_\mu\nabla_\nu-g_{\mu\nu}\Box)f_R-[\frac{1}{2}(f_L+2f_T)+8\pi]T_{\mu\nu}+\frac{1}{2}[(2f_T+f_L)L_m-f]g_{\mu\nu}-f_T\tau_{\mu\nu}=0$$

2. An isotropic and homogeneous universe is described by FLRW metric of the form:

$$ds^2=a^2(t)(dx^2+dy^2+dz^2)-dt^2$$

3. For FLRW metric, the Modified Friedmann Equation are obtained as follows:

$$\dot{H}=\frac{1}{2f_R}(H\dot{f_R}-\ddot{f_R})-\frac{1}{2f_R}(\rho+p)(f_m+8\pi)$$

$$2H^2+\dot{H}=\frac{1}{2f_R}(\ddot{f_R}+3H\dot{f_R})-\frac{1}{3f_R}(2L_mf_m-f)+\frac{1}{6f_R}(3p-\rho)(8\pi+f_m)$$

Choice of L_m

$L_m=-\rho$ is chosen for radiation domination era.

GB & GGB in $f(R, L_m, T)$ Gravity

1. For the Standard case, the CP-violating interaction takes the form as:

$$\frac{1}{M_*^2}\int d^4x\,\sqrt{-g}\,\partial_\mu(R + L_m + T)J^\mu$$

2. While for the Generalized case, the CP-violating interaction takes the form as:

$$\frac{1}{M_*^2}\int d^4x\,\sqrt{-g}\,\partial_\mu f(R, L_m, T)J^\mu$$

Asymmetry ratio expression

The Corresponding expressions for asymmetry ratio are:

$$\frac{\eta_B}{s} \simeq -\frac{15}{4\pi^2}\frac{g_b}{g_*}\frac{(\dot{R} + \dot{L_m} + \dot{T})}{M_*^2 T_D}, \qquad \frac{\eta_B}{s} \simeq -\frac{15}{4\pi^2}\frac{g_b}{g_*}\frac{(\dot{R}f_R + \dot{L_m}f_{L_m} + \dot{T}f_T)}{M_*^2 T_D}.$$

$f(R, L_m, T)$ Gravity Model & Cosmic Evolution

1. The gravity model considered for this study is:

$$f(R, L_m, T) = \alpha R + \beta L_m + \gamma T$$

where, α, β and γ are model parameters. α has dimension of GeV^2, while β and γ are dimensionless parameters.

2. We assume the cosmic evolution to be governed by a scale factor of power-law behaviour:

$$a(t) = a_0 t^{\xi}$$

where, ξ is a positive & real constant defined as: $\xi = \frac{2}{3(1+\omega)}$.

Energy Density & Decoupling Time

1. The energy density behind the cosmic evolution of the universe while considering $f(R, L_m, T)$ gravity model can be derived using the dynamics of Friedmann Equation as follows:

$$\rho = \frac{2\alpha\xi^2}{t^4(-1-\omega)\left(\frac{\beta}{2}+\gamma+8\pi\right)}$$

2. At decoupling temperature (t_D), the baryon-generating interactions freeze out of thermal equilibrium and is found to be:

$$t_D = -\frac{2^{3/4} \times \sqrt[4]{15} \times \sqrt[4]{\alpha} \times \sqrt{\xi}}{\sqrt{\pi} \times \sqrt[4]{-g_* \times T_D^4(\omega+1)(\beta+2\gamma+16\pi)}} \tag{5}$$

Energy Density of the Cosmos during Radiation Domination $(\omega = \frac{1}{3})$

$$\rho = \frac{\pi^2}{30} g_* T^4 \tag{6}$$

Asymmetry Ratio for the Standard Case

1. The expression for Baryon asymmetry for standard case is given by:

$$\frac{\eta_B}{s} = \frac{g_b \sqrt[4]{g_*(\omega+1)(-\beta-2\gamma-16\pi)T_D^4}}{4\times 30^{3/4}\sqrt{\pi}\alpha^{3/4}g_* M_*^2\sqrt{\xi}T_D} \times \left(45\sqrt{2}(1-2\xi)\sqrt{g_*(\omega+1)(-\beta-2\gamma-16\pi)T_D^4} + 2\pi\sqrt{15}\sqrt{\alpha}g_*(2-3\omega)T_D^4\right)$$

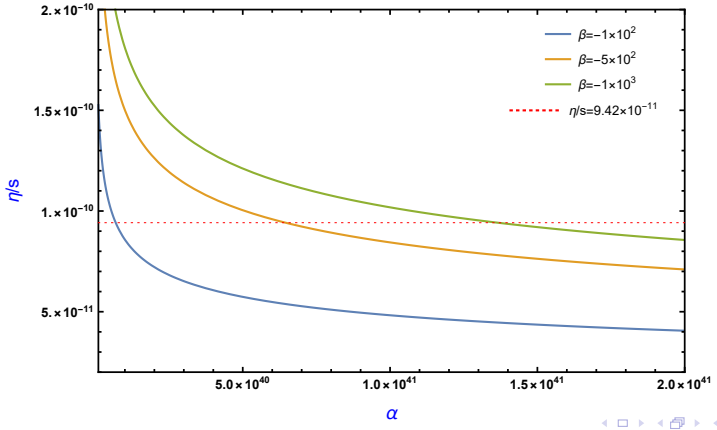
Parameter Values

The following parameter values are adopted for this study:

$$M_* = 2\times 10^{18}\ \text{GeV},\ T_D = 2\times 10^{16}\ \text{GeV},\ g_* \simeq 106,\ g_b \simeq 1$$

Graphical Analysis

1. The asymmetry ratio ($\frac{\eta_B}{s}$) versus α for the $f(R, L_m, T)$ model in radiation era ($\omega = \frac{1}{3}$) for three different β choices:



Asymmetry Ratio for the Generalized Case

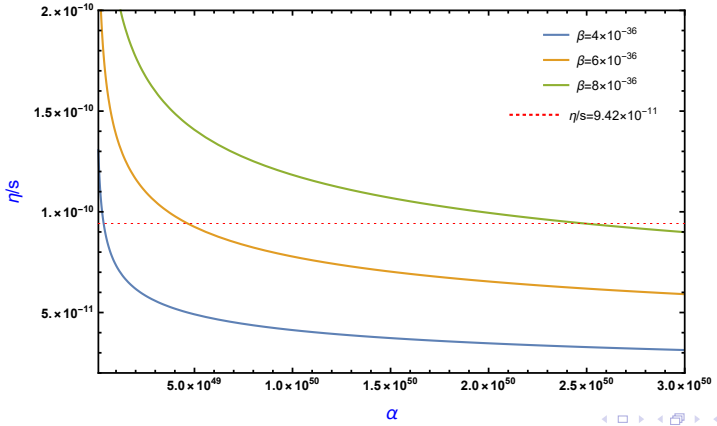
1. The expression for Baryon asymmetry for generalized case is given by:

$$\frac{\eta_B}{s}\Big|_{GGB} = \frac{g_b \sqrt[4]{g_*(\omega+1)(-\beta-2\gamma-16\pi)T_D^4}}{4\times 30^{3/4}\sqrt{\pi}\sqrt[4]{\alpha}g_* M_*^2\sqrt{\xi}T_D} \times \Bigg[45\times\sqrt{2\alpha}(2\xi-1) \times \sqrt{g_*(\omega+1)(-\beta-2\gamma-16\pi)T_D^4} - 2\sqrt{15}\pi g_* T_D^4(\beta-3\gamma\omega+\gamma)\Bigg]$$

2. Same set of parameter values adopted as in the standard case.

Graphical Analysis

1. The asymmetry ratio ($\frac{\eta_B}{s}$) versus α (generalized case) for the $f(R, L_m, T)$ model in radiation era ($\omega = \frac{1}{3}$) for three different β choices:



Results

1. **Results of GB analysis:**
   - The model successfully reproduces the observed baryon asymmetry during the radiation-dominated era for the standard case.
   - For $\gamma = 1$ and $-10^3 \leq \beta \leq -10^2$, the viable range of the curvature coupling parameter is $3.5 \times 10^{38} \leq \alpha \leq 4.25 \times 10^{41}$.
2. **Results of GGB analysis:**
   - The generalized interaction also yields baryon asymmetry consistent with observational constraints.
   - For $\gamma = 1$ and $-10^3 \leq \beta \leq -10^2$, the viable range becomes $3.5 \times 10^{46} \leq \alpha \leq 4.5 \times 10^{53}$.

Comparison with Other Modified Gravity Models

The table compares α, β and γ in $f(R, L_m, T)$ gravity with other modified gravity baryogenesis models.

Three-parameter models

Model	α	β	γ
$f(R, L_m, T) = \alpha R + \beta L_m + \gamma T$	1×10^{41}	-1×10^{3}	1
$f(R, L_m, T) = \alpha R + \beta L_m^2 + \gamma T^2$	6×10^{47}	1×10^{-27}	1
$f(R, G, T) = \alpha R^2 + \beta G - \gamma T$	6×10^{202}	$1.25 \times 10^{189.5}$	1

Two-parameter models

Model	α	β
$f(Q, L_m) = \alpha Q^n + \beta L_m$	-2×10^{86}	0.5
$f(T, \mathcal{T}) = \alpha T + \beta \mathcal{T}$	1×10^{160}	41.25
$f(T, \mathcal{T}) = \alpha T + \beta \mathcal{T}^2$	1×10^{142}	57.65×10^{-60}
$f(T, \mathcal{T}) = \alpha T^3 + \beta \mathcal{T}$	1×10^{274}	825
$f(G, T) = \alpha G^m + \beta T$	-5×10^{136}	0.5
$f(R, G) = \alpha R + \beta R^m G^n$	4×10^{32}	0.5
$f(R, G) = \alpha R + \beta \sqrt{G}$	5×10^{53}	-5×10^{136}

Conclusion

1. The $f(R, L_m, T)$ gravity model provides a viable framework for generating the observed baryon asymmetry through both Gravitational Baryogenesis and Generalized Gravitational Baryogenesis mechanisms.

2. Both mechanisms yield baryon-to-entropy ratios consistent with the observational value of $\eta_B/s \simeq 9.42 \times 10^{-11}$.

3. The obtained parameter constraints demonstrate the potential of geometry–matter coupling in explaining the matter–antimatter asymmetry of the universe.

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Full Length Article

Viability constraints on baryogenesis in $f(R, L_m, T)$ gravity

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ABSTRACT

Our study explores gravitational baryogenesis in the context of $f(R, L_m, T)$ gravity, where R is the Ricci scalar, L_m represents the Lagrangian density of the matter field and T stands for the metric contraction of $T_{\mu\nu}$. We focus on models: (i) $f(R, L_m, T) = \alpha R + \beta L_m + \gamma T$ and (ii) $f(R, L_m, T) = \alpha R + \beta L_m^2 + \gamma T^2$, to examine the parameter constraints for a successful baryon asymmetry generation in the radiation dominated era of the cosmos under the consideration of a power-law-type cosmic expansion. The computed baryon-to-entropy ratio is found to be consistent with the measured order of the asymmetry ratio 9.42×10^{-11}. In addition, the study is further extended to the generalised framework of gravitational baryogenesis, where the result shows strong agreement with the current observational data. Our findings indicate that the $f(R, L_m, T)$ framework ensures a compatible

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