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Gauss–Bonnet gravitational baryogenesis

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ABSTRACT

In this letter we study some variant forms of gravitational baryogenesis by using higher order terms containing the partial derivative of the Gauss–Bonnet scalar coupled to the baryonic current. This scenario extends the well known theory that uses a similar coupling between the Ricci scalar and the baryonic current. One appealing feature of the scenario we study is that the predicted baryon asymmetry during a radiation domination era is non-zero. We calculate the baryon to entropy ratio for the Gauss–Bonnet term and by using the observational constraints we investigate which are the allowed forms of the $R + F(\mathcal{G})$ gravity controlling the evolution. Also we briefly discuss some alternative higher order terms that can generate a non-zero baryon asymmetry, even in the conformal invariance limit.

1. Introduction

The excess of matter over antimatter in our Universe is one of the unsolved mysteries in cosmology, ever since cosmology became an autonomous research branch. The observational data coming from the Cosmic Microwave Background [2], supported by the Big Bang nucleosynthesis successful predictions [1], indicate an excess of matter over antimatter, and every viable cosmological description should in some way explain this excess in a successful way. One theoretically appealing mechanism for generating the baryon–anti-baryon asymmetry was given in Ref. [3], which was called as the “gravitational baryogenesis” mechanism. Later on, this mechanism was further studied and developed in Refs. [4–8]. The gravitational baryogenesis mechanism makes use of one of the Sakharov criteria [9], and the baryon–anti-baryon asymmetry is guaranteed by the presence of a $\mathcal{CP}$-violating interaction, which is of the form,

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

The term (1) can occur in the theory from higher order interactions coming from an underlying effective theory that controls the high energy physics. The parameter M_* in (1) denotes the cutoff scale of the underlying effective theory, while J^μ, g and R stand for the baryonic matter current, the trace of the metric tensor and the Ricci scalar respectively. In effect, for a flat Friedmann–Robertson–Walker (FRW) Universe, the baryon to entropy ratio η_B/s is proportional to $\dot{R}$. Notably, in the case that the matter fluid content of the flat FRW is controlled by relativistic matter with equation of state parameter $w = 1/3$, the net baryon asymmetry generated by the term (1) is zero.

The purpose of this letter is to investigate the consequences of a baryon asymmetry term related to other curvature invariants and specifically related to the Gauss–Bonnet invariant $\mathcal{G}$, which often appears in string-inspired gravities. Also we shall briefly discuss the effect of baryon asymmetry generating terms related to other higher order gravity terms. For the Gauss–Bonnet case, the $\mathcal{CP}$-violating interaction that will generate the baryon asymmetry of the Universe is of the form,

$$\frac{1}{M_*^2}\int d^4x\sqrt{-g}(\partial_\mu \mathcal{G})J^\mu\,. \tag{2}$$

This kind of terms can possibly occur in higher order gravities coupled with fundamental group fermion currents. As we demonstrate, for the Gauss–Bonnet baryon asymmetry term (2), there are differences in the resulting baryon to entropy ratio and in addition, the latter is non-zero even in the case that the Universe is filled with relativistic matter ($w = 1/3$). We shall investigate the cases that the Universe evolution is controlled by a matter fluid with

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a constant equation of state parameter $w = p/\rho$, and also we investigate the case that the evolution is controlled by an $R + F(\mathcal{G})$ theory of gravity in the presence of a matter fluid with constant equation of state w, with R being the Ricci scalar. Finally we shall discuss in brief how the baryon to entropy ratio becomes in the case of higher order gravity terms coupled with fermion currents.

The outline of this letter is as follows: In section 2 we briefly review the essential features of gravitational baryogenesis and we also investigate in some detail the implication of a Gauss–Bonnet baryogenesis term, by calculating the corresponding baryon to entropy ratio. We discuss the cases that the Universe's evolution is controlled by a perfect fluid and also the case that the evolution is controlled by a $R + F(\mathcal{G})$ theory plus a perfect matter fluid. At the end of section 3 we briefly discuss the case of higher order gravity gravitational baryogenesis terms and finally, the conclusions follow in the end of the paper.

2. Gauss–Bonnet baryogenesis

As we already discussed, the Cosmic Microwave Background observational data [2] and also the Big Bang nucleosynthesis predictions [1] indicate an excess of matter over antimatter. In addition to these, there are no matter–antimatter annihilation interactions which produce radiation, so this also supports the excess of matter over antimatter. The predicted baryon to entropy ratio is $\frac{\eta_B}{s} \simeq 9.2 \times 10^{-11}$ and according to Sakharov [9], there are three reasons that a baryon asymmetry can occur, firstly, if baryon number violating particle interactions occur, secondly if $\mathcal{C}$ and $\mathcal{CP}$ violating particle interactions exist, and thirdly if thermodynamical processes in the Universe are non-equilibrium thermodynamical processes. The baryon number violating interactions can in principle be quite slow for generating the observed baryon asymmetry, for example in $SU(5)$ grand unified theories, the proton decay interaction lasts 10^{22} billion years, which is almost twice the age of our Universe. Also the non-equilibrium processes are in principle quite difficult to model, so it is more easy to seek for $\mathcal{C}$ and $\mathcal{CP}$ violating particle interactions.

Effectively, in the process of the Universe's expansion, after the temperature of the Universe drops below the critical temperature T_D, the remaining asymmetry is approximately equal to [3],

$$\frac{n_B}{s} \simeq -\frac{15 g_b}{4\pi^2 g_*} \frac{\dot{R}}{M_*^2 T}\Big|_{T_D}\,, \tag{3}$$

where g_b is the number of the intrinsic degrees of freedom of the baryons. The critical temperature T_D is the temperature of the Universe at which the baryon asymmetry generating interactions occur.

In the analysis to follow we shall assume that a thermal equilibrium exists, so in all cases which we study, we will assume that the Universe evolves slowly from an equilibrium state to an equilibrium state, with the energy density being related to the temperature T of each state as,

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

where g_* denotes the number of the degrees of freedom of the effectively massless particles. So for the $\mathcal{CP}$ violating interaction of Eq. (2), the corresponding baryon to entropy ratio reads,

$$\frac{n_B}{s} \simeq -\frac{15 g_b}{4\pi^2 g_*} \frac{\dot{\mathcal{G}}}{M_*^2 T}\Big|_{T_D}\,. \tag{5}$$

Now depending on the matter content and the theory that controls the evolution, certain differences may occur, which we discuss in the following two sections.

2.1. The perfect fluid case

In the standard Einstein–Hilbert gravity framework used in Ref. [3], if the Universe is filled with a perfect matter fluid with constant equation of state parameter $w = p/\rho$, the Ricci scalar reads,

$$R = -8\pi G(1-3w)\rho\,, \tag{6}$$

where the Einstein equations are taken into account. Therefore, from Eq. (6) it can be seen that in the case of a radiation dominated era, the resulting baryon to entropy ratio is zero. In contrast to this, in our case the resulting baryon to entropy ratio is non-zero even in the radiation domination era. Consider a flat FRW background of the form,

$$ds^2 = -dt^2 + a(t)^2 \sum_{i=1,2,3} \left(dx^i\right)^2\,, \tag{7}$$

with $a(t)$ being the scale factor. Assume that the cosmic evolution is described by $a(t) = B\,t^\beta$, with $\beta = 2/(3(1+w))$, which is generated by an energy density $\rho \sim a^{-3(1+w)}$. In this case, for the FRW metric (7), the Gauss–Bonnet baryon to entropy ratio (5) reads,

$$\frac{n_B}{s} \simeq \frac{45 g_b\, 96\,(\beta-1)\beta^3}{12\pi^2 g_* T_D\, M_*^2\, t_D^5}\,, \tag{8}$$

where t_D is the decoupling time corresponding to the critical temperature T_D, and also we use the fact that for the flat FRW metric, the Gauss–Bonnet scalar is equal to,

$$\mathcal{G} = 24H^2\left(\dot{H} + H^2\right). \tag{9}$$

By using the equilibrium equation (4) for the energy density, and also that $\rho = \rho_0\, a^{-3(1+w)}$, the decoupling time as a function of the critical temperature T_D reads,

$$t_D = \left(\frac{\pi^2 g_*}{30\rho_0\, B^{4\beta}}\right) T_D^{1/\beta}\,, \tag{10}$$

and therefore the resulting baryon to entropy ratio reads,

$$\frac{n_B}{s} \simeq \frac{45 g_b\, 96\,(\beta-1)\beta^3}{12\pi^2 g_* T_D\, M_*^2} \left(\frac{\pi^2 g_*}{30\rho_0\, B^{4\beta}}\right)^{5/4\beta} T_D^{\frac{5}{\beta}-1}\,. \tag{11}$$

The radiation domination case corresponds to $\beta = 1/2$, and as it can be seen from Eq. (11), the resulting baryon to entropy ratio is non-zero, in contrast to the baryon to entropy ratio generated by the term (1). Depending on the matter content, the ratio (11) can be adjusted to satisfy the observational constraints, but the most interesting feature of a perfect fluid dominated Universe for the case of Gauss–Bonnet baryogenesis, is the fact that the ratio is non-zero in the radiation dominated case.

2.2. The $R + F(\mathcal{G})$ case

Now we shall calculate the baryon to entropy ratio in the case that the cosmological evolution is governed by an $R + F(\mathcal{G})$ theory of gravity, in the presence of a matter fluid with energy density ρ_m and pressure p_m. The gravitational action of the modified gravity theory is in this case [10,11],

$$\mathcal{S} = \frac{1}{2\kappa^2}\int \mathrm{d}x^4 \sqrt{-g}\,[R + F(\mathcal{G})] + S_m, \tag{12}$$

where $\kappa^2 = 8\pi G$ denotes the gravitational constant and S_m denotes the action of the matter fluids, which in our case consist of a simple perfect fluid with constant equations of state parameter